ISO measurements of [CII] line variations in galaxies
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ABSTRACT

We report measurements of the [CII] fine structure line at 157.714 μm in 30 normal star-forming galaxies with the Long Wavelength Spectrometer (LWS) on the Infrared Space Observatory (ISO). The ratio of the line to total far-infrared luminosity, \( L_{[\text{CII}]} / L_{\text{FIR}} \), measures the ratio of the cooling of gas to that of dust; and thus the efficiency of the grain photoelectric heating process. This ratio varies by more than a factor of 40 in the current sample. About two-thirds of the galaxies have \( L_{[\text{CII}]} / L_{\text{FIR}} \) ratios in the narrow range of \( 2 - 7 \times 10^{-3} \). The other one-third show trends of decreasing \( L_{[\text{CII}]} / L_{\text{FIR}} \) with increasing dust temperature, as measured by the flux ratio of infrared emission at 60 and 100 μm \( (F_\nu(60\mu\text{m})/F_\nu(100\mu\text{m})) \); and with increasing star-formation activity, measured by the ratio of far-infrared and blue band luminosity \( L_{\text{FIR}} / L_B \). We also find three FIR bright galaxies which are deficient in the [CII] line, which is undetected with 3σ upper limits of \( L_{[\text{CII}]} / L_{\text{FIR}} < 0.5 - 2 \times 10^{-4} \).

The trend in the \( L_{[\text{CII}]} / L_{\text{FIR}} \) ratio with the temperature of dust and with star-formation activity may be due to decreased efficiency of photoelectric heating of gas at high UV radiation intensity as dust grains become positively charged, decreasing the yield and the energy of the photoelectrons. The three galaxies with no observed PDR lines have among the highest \( L_{\text{FIR}} / L_B \) and \( F_\nu(60\mu\text{m})/F_\nu(100\mu\text{m}) \) ratios. Their lack of [CII] lines may be due to a continuing trend of decreasing \( L_{[\text{CII}]} / L_{\text{FIR}} \) with increasing star-formation activity and dust temperature seen in one-third of the sample with warm IRAS colors. In that case the upper limits on \( L_{[\text{CII}]} / L_{\text{FIR}} \) imply a ratio of UV flux to gas density \( G_0/n > 10 \text{ cm}^3 \) (where \( G_0 \) is in the units of local average interstellar field). The low \( L_{[\text{CII}]} / L_{\text{FIR}} \) could also be due to either weak [CII] because of self-absorption or strong FIR continuum from regions weak in [CII], such as dense HII regions or plasma ionized by hard radiation of AGNs. The mid-infrared and radio images of these galaxies show that most of the emission comes from a compact nucleus. CO and HI are detected in these galaxies, with HI seen in absorption towards the nucleus.

Subject headings: radiation mechanisms: thermal, ISM: atoms, galaxies: ISM, infrared: ISM: lines and bands
1. Introduction

The $C^+$ fine structure transition at 157.714µm is an important coolant of the warm neutral interstellar medium. This is because carbon is the fourth most abundant element and has a lower ionization potential (11.26 eV) than hydrogen, so that carbon will be in the form of $C^+$ on the surfaces of far-UV illuminated neutral gas clouds. The depth of these photodissociation regions (PDRs) is determined by dust extinction, which is typically $A_v \leq 4$. Secondly, the 158µm [CII] line is relatively easy to excite ($\Delta E/k \simeq 91$ K), so that $C^+$ can cool warm neutral gas where the two most abundant atoms H and He cannot (cf. Tielens & Hollenbach (1985), hereafter TH85, Wolfire, Tielens & Hollenbach (1990), hereafter WTH90). Gas heating in PDRs is dominated by energetic photoelectrons ejected from dust grains following UV photon absorption (Watson 1972).

The [CII] line is roughly 1500 times more intense than the CO$(1 \rightarrow 0)$ rotational line in normal galaxies and Galactic molecular clouds; and 6300 times more intense than the CO$(1 \rightarrow 0)$ line in starburst nuclei and Galactic star formation regions (Crawford et al., 1985, Stacey et al. 1991). For normal galaxy nuclei and star formation regions in the spiral arms, most of the observed [CII] arises from PDRs on molecular cloud surfaces. However, integrated over the disks of normal spiral galaxies, a substantial fraction (up to 50%) may also arise from “standard” atomic clouds, i.e. the cold neutral medium (CNM) (Madden et al. 1993) or from extended, low density HII regions (Heiles 1994).

With the Long Wavelength Spectrometer (LWS, Clegg et al. 1996) on the Infrared Space Observatory (ISO, Kessler et al. 1996) it is now possible to measure the [CII] line emission from normal, not very infrared-bright galaxies (Lord et al. 1996). Observations of fine structure atomic and ionic lines in the far-infrared have been obtained for half the sample of about 60 galaxies in the US-ISO Key Project on Normal Galaxies. The galaxies were selected to span a range of morphologies: Irr-Sa in this paper, and Irr-E in
the complete sample (see Helou et al. 1996 for sample selection criteria), dust temperature (as indicated by the ratio of flux density at 60 µm and 100 µm), and star-formation activity (measured by the ratio of FIR to Blue luminosity). This paper offers a first look at statistical behavior of cooling via [CII] line in a diverse sample of galaxies, aimed at a better understanding of the physical conditions in the ISM of star-forming galaxies.

2. Observations

With the 80″ beam of LWS and spectral resolution of 0.6 µm we measure total line flux for the present sample of galaxies. The galaxies were selected to have FWHM < 0.5′ in FIR emission using deconvolved IRAS maps. LWS measures the total flux and not the brightness temperature so beam dilution is irrelevant. The [CII] line observations were planned to achieve (1σ) sensitivities of 5 × 10^{-5} × F_{FIR}, where F_{FIR} is the total far-infrared flux of the galaxy and is computed according to the formula F_{FIR} = 1.26 \times 10^{-14}[2.58 \times F_{\nu}(60 \mu m) + F_{\nu}(100 \mu m)] W m^{-2} (Helou et al. 1988), where F_{\nu}(60 \mu m) and F_{\nu}(100 \mu m) are flux densities in Jansky at 60 and 100 µm. For comparison, previous observations of Milky Way, starburst galaxies and galactic nuclei show that the line to continuum luminosity ratio L_{[CII]}/L_{FIR} = 1 − 10 \times 10^{-3} (Stacey et al. 1985, Wright et al. 1991, Crawford et al. 1985, and Stacey et al. 1991, Lord et al. 1996). In Galactic PDR sources associated with HII regions the L_{[CII]}/L_{FIR} ratio varies from \sim 3 \times 10^{-3} in PDRs (e.g. NGC 2023) to \sim 8 \times 10^{-5}, decreasing with HII region density and UV flux (cf. Crawford et al. 1985, Hollenbach, Takahashi & Tielens 1991).

The data were reduced and calibrated with the ISO pipelines OLP4.2 to OLP5.2. The line profiles were derived from several scans by running a median boxcar filter through typically six spectral scans per object. We use the median of the observed fluxes instead of the mean to reduce the influence of outlying points arising from cosmic ray hits. The flux in the [CII] line was determined by directly integrating under the line. The upper limits on non-detections were derived by calculating the flux from a hypothetical gaussian line with an amplitude of 3σ and the effective instrumental profile, since the line is unresolved for all sources.

The line fluxes suffer from calibration uncertainties mainly due to uncorrected fluctuations of detector responsivities with time. To estimate the calibration errors we compared the observed continuum levels at 158 µm with flux predicted from dust emission models made using IRAS 100 and 60 µm fluxes (Helou & Beichman 1990). This comparison shows that the mean ISO/IRAS continuum ratio at 158 µm is about 1.1 and the observed fluxes lie within a factor of two of the models. These values are conservative estimates of
the uncertainty in the line fluxes because the continuum levels, which are compared with IRAS flux densities, are affected by ill-determined dark currents (additive in nature) as well as detector responsivities (multiplicative), whereas the line fluxes are affected only by the detector responsivities. Thus we are confident of the trends in Figure 1 which span a factor of $\simeq 40$ in the $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio.

3. Results and Discussion

The ratio of [CII] line to FIR continuum flux from neutral gas depends on the efficiency of heating of gas by photoelectrons from dust, and is expected to be sensitive to the physical conditions in the ISM. We therefore explore the dependence of $L_{\text{[CII]}}/L_{\text{FIR}}$ on the dust temperature (characterized by $F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$) and global star-formation activity in galaxies (characterized by $L_{\text{FIR}}/L_{\text{B}}$). The two quantities, $L_{\text{FIR}}/L_{\text{B}}$ and $F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$ are positively correlated with each other, i.e. galaxies with more active star-formation also have higher dust temperatures (Soifer & Neugebauer 1991). The present sample does not reflect this correlation as strongly as a randomly selected sample, as the galaxies were selected to span the parameter space in $L_{\text{FIR}}/L_{\text{B}}$ and $F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$. In Figure 1 the quantity log($L_{\text{[CII]}}/L_{\text{FIR}}$) is plotted as a function of the ratio of FIR and B-band luminosity $L_{\text{FIR}}/L_{\text{B}}$ of the galaxies, and as a function of flux density ratio at 60 and 100 $\mu m$ ($F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$). Three main results emerge from Figure 1, and are discussed in the next three subsections.

3.1. The modal value of $L_{\text{[CII]}}/L_{\text{FIR}}$:

About two-thirds of the galaxies (19 out of 30) have $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio between 0.2-0.7% (Figure 1). This is consistent with the value measured for the Milky Way, and both normal and starburst galaxies (Stacey et al. 1985, Crawford et al. 1985, Wright et al. 1991, Stacey et al. 1991, Madden et al. 1993, Lord et al. 1996). These observed ratios are well understood in terms of PDR models (TH85, WTH90). The [CII] line originates from warm neutral gas in the photodissociation regions. The efficiency of the photoelectric heating of gas is a fraction of a percent. In the data presented in this paper we see a confirmation of this model in galaxies spanning a range of morphologies, with dust temperatures and $L_{\text{FIR}}/L_{\text{B}}$ ratios which are not unusually high.
The ratio of FIR and [CII] line luminosities is plotted against the dust temperature characterized by the ratio of flux densities at 60\(\mu\)m and 100\(\mu\)m from IRAS measurements. The error bars indicate the dominant source of uncertainty, namely the calibration uncertainty of a factor of two. There is a trend for galaxies with higher \(F_\nu(60\mu\text{m})/F_\nu(100\mu\text{m})\) (warmer dust) to have lower \(L_{[\text{CII}]}/L_{\text{FIR}}\). Three galaxies in a sample of 30 have no detected [CII], they are identified and shown as upper limit symbols in the figure. (b) \(L_{[\text{CII}]}/L_{\text{FIR}}\) shows a similar trend with the ratio of FIR/Blue luminosity, which can be used as an indicator of star formation activity. Galaxies with higher \(L_{\text{FIR}}/L_B\) (more active star formation) have lower \(L_{[\text{CII}]}/L_{\text{FIR}}\).

3.2. Trends in the measured \(L_{[\text{CII}]}/L_{\text{FIR}}\):

About 1/3 of the present sample with higher FIR/Blue luminosity and warmer far-infrared colors (i.e. higher \(F_\nu(60\mu\text{m})/F_\nu(100\mu\text{m})\) ratio) show a trend of decreasing \(L_{[\text{CII}]}/L_{\text{FIR}}\) with \(F_\nu(60\mu\text{m})/F_\nu(100\mu\text{m})\) and \(L_{\text{FIR}}/L_B\) (Figure 1). Such a trend is also seen within our Galaxy (Nakagawa et al. 1995, Bennett et al. 1994). The trends in \(L_{[\text{CII}]}/L_{\text{FIR}}\) with \(L_{\text{FIR}}/L_B\) and with \(F_\nu(60\mu\text{m})/F_\nu(100\mu\text{m})\) could be due to the following. (Any reference to the trends refers only to the one-third of the sample with warm FIR colors which shows decreasing \(L_{[\text{CII}]}/L_{\text{FIR}}\) with \(L_{\text{FIR}}/L_B\) and with \(F_\nu(60\mu\text{m})/F_\nu(100\mu\text{m})\))

(a) For high ratios of UV flux to gas density \((G_0/n)\), the dust grains are positively charged and are less efficient at heating the gas because the potential barrier to photoejection
is higher (TH85). This leads to smaller PDR line to dust continuum ratios because, most of the UV energy is absorbed and reradiated in the FIR by grains, and a smaller fraction of the UV energy goes into gas heating, so the gas requires less cooling.

(b) At densities of \( n > 10^4 \text{cm}^{-3} \) \( C^+ \) ions become collisionally de-excited (TH85, WTH90) and an increasing amount of cooling is done through other channels; for example, the [OI] line at 63\( \mu \text{m} \). We see that this line cannot compensate completely for the decrease of \( L_{[\text{CII}]} / L_{\text{FIR}} \) in Figure 1, as the observed [OI](63\( \mu \text{m} \)) line flux does not exceed 3\times[CII] in this sample, whereas the ratio \( L_{[\text{CII}]} / L_{\text{FIR}} \) varies by a factor of 40. CO and CI lines can also cool the gas.

(c) In each galaxy we measure the total FIR and the total [CII] line emission arising from a collection of HI regions, PDRs, and diffuse atomic clouds. Galactic HI regions like W 51 and S 140 have smaller \( L_{[\text{CII}]} / L_{\text{FIR}} \) ratios compared to typical PDRs (Emery et al. 1996). A varying mix of these components will lead to variations in the \( L_{[\text{CII}]} / L_{\text{FIR}} \) ratio seen in Figure 1.

### 3.3. [CII] deficient galaxies:

In the extreme cases of NGC 4418, IC 0860 and CGCG 1510.8+0725, [CII] emission is undetected at the 3\( \sigma \) level of \( L_{[\text{CII}]} = 5 - 0.5 \times 10^{-4} L_{\text{FIR}} \). Emission in the other prominent PDR cooling line [OI] at 63\( \mu \text{m} \) is undetected at similar levels, as are [OIII] (88\( \mu \text{m} \)) and [NII] (122\( \mu \text{m} \)). In Figure 1 we show 3\( \sigma \) upper limits on the flux in the [CII] 158\( \mu \text{m} \) transition.

The absence of [CII] emission in these galaxies is very striking because the upper limits on the \( L_{[\text{CII}]} / L_{\text{FIR}} \) in these galaxies are up to 40 times smaller than the narrow range in \( L_{[\text{CII}]} / L_{\text{FIR}} \) measured for two-thirds of the sample. Yet these galaxies have normal atomic and molecular gas components. A comparable upper limit on \( L_{[\text{CII}]} / L_{\text{FIR}} \) was reported by Stacey et al. (1991) for the IR luminous galaxy NGC 660. Luhman et al. (1997) also report on weak [CII] emission from ultraluminous galaxies.

In order to understand the absence of the [CII] cooling line, let us review what is distinct about these three galaxies. They have among the highest \( L_{\text{FIR}} / L_{\text{B}} \) luminosity ratio and dust temperature \( F_{\nu}(60 \mu \text{m})/F_{\nu}(100 \mu \text{m}) \) in the sample, but are not ultraluminous IR sources. Their FIR luminosities vary from \( \log(L_{\text{FIR}} / L_{\odot}) = 10.05-10.24 \). The mid-infrared images at 7 and 15 \( \mu \text{m} \) are unresolved at 7\″ resolution of ISOCAM (Silbermann et al. 1997) and they are compact in radio continuum at 1.4 GHz (Condon et al 1990): NGC 4418 measures 0.5″ \times 0.3″(32h\(^{-1}\) pc), CGCG 1510.8+0725 measures 0.5″ \times 0.5″(85h\(^{-1}\) pc) and IC 860 0.4″ \times 0.3″(75h\(^{-1}\) pc). Two other galaxies in the present sample, NGC 3620 and
IRAS F10565+2448, have comparable FIR/Blue luminosity and $F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$ but do show weak [CII] emission lines. NGC 3620 is not compact in mid-IR emission and IRAS F10565+2448 is a point source at high redshift in the sample, so the size limits are less stringent (the size < 5.5 kpc). CGCG 1510.8+0725 shows a broad Hα line indicative of a Seyfert nucleus (Kim et al. 1995) but no Hβ, (possibly due to obscuration), causing it to be classified as a HII galaxy (Veilleux et al. 1995). NGC 4418 shows many indications of being a hidden Seyfert nucleus (Roche et al. 1986, Kawara, Nishida & Philips 1989), and has the distinction of having the most ’extinguished’ nucleus with $A_V > 50$ (Roche et al. 1986) as seen in the 9.7μm absorption feature.

There are several possible explanations for the [CII] deficiency in these three systems.

(A) For high ratios of UV radiation to density of the warm gas ($G_0/n$), the dust grains are positively charged and are less efficient at heating the gas (TH85). This is also a likely explanation for the trend of decreasing $L_{[CII]}/L_{FIR}$ discussed in section 3.2(a). Wolfire et al. (1990) predict $(F_{[CII]} + F_{[OI]})/F_{FIR} < 10^{-4}$ for $G_0/n > 10$ cm$^3$. A high $G_0/n$ can come about in low density or high radiation regions. CO observations of these galaxies show copious, compact, circumnuclear gas (Planesas, Mirabel & Sanders 1991, Kwara et al. 1990). This indicates that even though the density of the gas $n$ is high, $G_0/n$ is higher.

(B) The addition of a compact FIR source in the nucleus of galaxies, e.g. an obscured AGN, can lead to both a higher FIR/Blue luminosity ratio and a lower $L_{[CII]}/L_{FIR}$ ratio. This possibility is supported by the compact appearance of the mid-IR and radio continuum emission in these three galaxies. A buried AGN could produce a lot of FIR without much [CII] since the UV field will be inefficient at making [CII] both due to its hardness (higher ionization states for C will be common) and due to its strength (inefficiency of heating gas as discussed in point (A)).

(C) The [CII] line may be optically thick or the lines may be weak due to self-absorption by lower excitation $C^+$ foreground gas. Such self-absorption is seen in the 158μm line observed at high resolution (Boreiko & Betz 1997). This hypothesis is supported by the compactness of the mid-IR emission in the three galaxies. The [CII] line becomes optically thick at $N(C^+) = 5 \times 10^{17}$cm$^{-2}$ for a velocity width of 4 km/s (Russell et al. 1980). Assuming a velocity width of 120km/s for NGC 4418 (Sanders, Scoville & Soifer 1991) and $N(C^+)/N(H) \approx 3.7 \times 10^{-4}$, optical depth of one in the [CII] line is reached for column densities of $N(H) = 4 \times 10^{22}$ cm$^{-2}$. Roche et al. (1986) estimate the visual extinction towards the nucleus of NGC 4418 to be $120 > A_V > 50$. If the PDR gas has $\tau = 1$ it will contribute $A_V \approx 20$. This high a PDR contribution to the extinction would imply a high ratio of PDR to cold molecular gas, instead of the conventional picture where PDRs form a thin surface layer of molecular clouds. Since atomic oxygen is found in abundance in
dark clouds the non-detection of the [OI] 63\(\mu\)m line could easily be due to self-absorption as well (Poglitsch et al. 1996, Kraemer, Jackson & Lane, 1996). Compact concentrations of circumnuclear molecular gas in CGCG 1510.8+0725 and NGC 4418 (Planesas, Mirabel & Sanders 1991, Kwara et al. 1990) further support the scenario where the CII line is at high optical depth or self-absorbed.

(D) The dominant PDR cooling lines [CII] and [OI] could be weak or missing if most of the FIR emission is from dust in high density HII regions (c.f. point (c) in section 3.2). This hypothesis is disfavored because the dust temperatures derived from the continuum shapes are too low compared to HII regions in the Milky Way (e.g. S140, Emery et al. 1996).

(E) An aging starburst, and a weak UV field relative to a softer, optical/infrared field which heats the dust, is used to explain the [CII] line weakness in the Galactic Center (Nakagawa et al. 1995). This mechanism seems unlikely because the [CII] deficiency is systematically found in galaxies with warmer FIR colors and higher \(L_{\text{FIR}}/L_{\text{B}}\) ratios indicating younger starbursts, with the hotter dust pointing to the presence of massive stars and UV photons.

4. Summary and Conclusions

Three main results emerge in this study of [CII] fine structure transition at 158\(\mu\)m, a primary coolant of photodissociation regions in star-forming galaxies.

(1) About two-thirds of the observed galaxies show a ratio of \(L_{\text{[CII]}}/L_{\text{FIR}} = 0.2 - 0.7\%\). This is consistent with the models and efficiencies of heating of PDR gas by photoelectrons from dust grains illuminated by moderate UV fluxes.

(2) As the dust temperature and the star-formation rate in galaxies increase, the ratio of \(L_{\text{[CII]}}/L_{\text{FIR}}\) decreases. This is probably due to higher UV radiation fields in warmer galaxies causing dust grains to become positively charged, thus leading to a decrease in gas heating efficiency of photoelectrons from dust grains. This effect is seen in the warmer one-third of the sample.

(3) In the present sample there are three galaxies near the extreme end of this trend in the \(F_{\nu}(60\mu\text{m})/F_{\nu}(100\mu\text{m})\) ratio and in the ratio of \(L_{\text{FIR}}/L_{\text{B}}\) which show no detectable line emission in the [CII] and [OI] lines. Since the upper limits on \(L_{\text{[CII]}}/L_{\text{FIR}}\) for the three galaxies is 10-40 times smaller than the \(L_{\text{[CII]}}/L_{\text{FIR}}\) observed for most galaxies, we conclude that less than 10\% of the FIR emission in these galaxies arises from the typical PDR gas having moderate UV fluxes.
Upper limits on the [CII] line flux in the three galaxies with no detection are not very far from the trend of decreasing $L_{[\text{CII}]}/L_{\text{FIR}}$ with increasing star-formation activity and dust temperature. In our preferred scenario, both the trend in Figure 1 and the absence of PDR lines in the extreme galaxies can be naturally explained by a trend of increasing $G_0/n$ in the hotter, more active galaxies, and hence a lower efficiency of gas heating. A large contribution to the FIR flux by an active nucleus or dense HII regions could explain the absence of [CII] lines but not easily the trends in $L_{[\text{CII}]}/L_{\text{FIR}}$. The other scenarios where the absence of [CII] line is due to optically thick conditions, self-absorption or collisional de-excitation are not ruled out by the present data but other cooling channels for the gas need to be identified.

The [CII] line at 158$\mu$m has been used as a measure of star-formation activity (at least of massive stars) (e.g. Stacey et al. 1991). These ISO-LWS data allow us to probe the variations in the line strength and how sensitive they are to the physical conditions in the ISM. If the variations observed in this study are mostly due to AGN, then the [CII] line strength and its ratio to $L_{\text{FIR}}$ is mostly a diagnostic of whether the FIR luminosity of any given source is due to star-formation or active nucleus. However, if the decreasing $L_{\text{CII}}/L_{\text{FIR}}$ is caused by increasing $G_0/n$, then these ISO-LWS data allow us to probe the interplay between star formation and physical conditions in the ISM.

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