FAR-INFRARED SPECTROSCOPY OF NORMAL GALAXIES WITH ISO LWS

S. Malhotra[1,2,3], G. Helou[1], D. Hollenbach[4], M. Kaufman[4,5], S. Lord[1], J.R. Brauher[1], D. Dale[1], N.Y. Lu[1], C. A. Beichman[1], H. Dinerstein[6], D. A. Hunter[7], K. Y. Lo[8], R. H. Rubin[4], N. Silbermann[1], G.J. Stacey[9], H. A. Thronson Jr.[10], & M. W. Werner[11]

[1] I.P.A.C., Caltech, Pasadena
[2] N.O.A.O, Tucson
[3] Hubble Fellow
[4] NASA Ames Research Center, Moffett Field
[5] S.J.S.U
[6] U. Texas, Astronomy Department, Austin
[7] Lowell Observatory
[8] University of Illinois
[9] Cornell University, Ithaca
[10] NASA, Headquarters, Washington
[11] JPL, Pasadena

ABSTRACT

The deficiency of [CII] (158 μm) line emission in many normal and ultraluminous galaxies is one of the major surprises from ISO-LWS observations. We show that this is not an isolated phenomenon: there is a smooth decline in $L_{[CII]}/L_{FIR}$ ratio with increasing dust temperature (as indicated by far-infrared colors $F_\nu(60\mu m)/F_\nu(100\mu m)$, i.e. F60/F100) and star-formation activity (indicated by L_{FIR}/L_B), independent of their luminosity or morphology. In a sample of 60 normal galaxies, these trends span a factor of 100. Of the numerous explanations proposed for the $L_{[CII]}/L_{FIR}$ variation the leading ones are (a) optical depth and extinction, (b) softer radiation field from old stellar populations (c) inefficient photoelectric heating by charged grains when the UV radiation density per gas atom (G_0/n) is high.

We can rule out hypothesis (a) with the observations that the [OI]/[CII] line ratio increases for galaxies with higher F60/F100. This is contrary to the expectation that [OI] at 63 μm should be more severely affected by extinction because it is at a shorter wavelength. Optical depth should also affect [OI] 63 μm line more strongly because OI exists deeper (to $A_v = 10$) in the interior of clouds than [CII]. Hypothesis (b) explains the slight decrease in $L_{[CII]}/L_{FIR}$ seen in early type galaxies with low rates of star-formation and the lowest L_{FIR}/L_B in the sample. The dramatic fall in $L_{[CII]}/L_{FIR}$ for the warmest and most actively star-forming galaxies is best explained by hypothesis (c). In galaxies with warmer dust, there is less cooling via the [CII] line, while [OI] remains a major coolant. This trend is qualitatively explained in PDR models by an increase in radiation field G_0, which raises the dust temperature and the [OI]/[CII] line ratio.

1. INTRODUCTION AND SAMPLE

The [CII] (158 μm) and [OI] (63 μm) are dominant coolants of the neutral ISM, radiating typically 0.1 – 1% of the FIR luminosity and about 1500-4000 times more energy than the CO(1-0) line. The [CII] and [OI] (63μm) lines are able to cool the gas because C and O are abundant in neutral gas and because the excitation energy is low ($\Delta E/k = 91$K for C^+ and $\Delta E/k = 224$K for O). The [OI] line becomes effective at higher gas densities and temperatures. Comparing line strengths to models one can constrain physical conditions in the ISM (e.g., Tielens & Hollenbach 1985, Wolfire et al. 1990). Gas heating is dominated by photoelectron ejected from dust grains, following UV absorption (Watson 1972).

These lines arise in PDRs (Photon Dissociation Regions) including diffuse HI, and UV illuminated surface of molecular clouds; and in case of [CII], also ionized gas. For normal galaxy nuclei and star formation regions in the spiral arms, most of the observed [CII] arises from PDRs on molecular cloud surfaces (Crawford et al. 1985). 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).

The sample in the ISO key-project on ISM in normal galaxies consists of galaxies whose luminosity is dominated by star-formation and excludes AGNs (Helou et al. 1996). Sixty distant galaxies, for which all the FIR emission is within one LWS beam, and 9 nearby, resolved galaxies were observed with LWS (Clegg et al. 1996) aboard ISO (Kessler et

Proceedings of the Conference "The Universe as seen by ISO", Paris, France, 20–23 October 1998 (ESA SP-427, March 1999)

al. 1996). The sample spans a range of morphologies (irregular, spiral, S0 and ellipticals), far-infrared luminosity (Log($L_{FIR}/L_{\odot}$)=7.7-11.2), FIR color ($F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$), and ratio of the luminosities in far-infrared and B band (L_{FIR}/L_B). We observed up to 7 atomic and ionic fine structure lines for each galaxy: [CII] (158μm), [OI] (145μm), [NII] (122μm), [OIII] (88μm), [OI] (63μm), [NIII] (57μm) and [OIII] (52μm). The most common lines observed are [CII] (158μm), [OI] (63μm), and [NII] (122μm).

2. [CII]/FIR RATIO

The [CII] observations were designed to have (1σ) sensitivity of $5 \times 10^{-5} \times L_{FIR}$. This value should be compared to that of the $L_{[CII]}/L_{FIR} = 3 \times 10^{-3}$ in the Milky Way (Wright et al. 1991) and $L_{[CII]}/L_{FIR} = 1 - 3 \times 10^{-3}$ for normal and starburst galaxies (Lord et al. 1996, Stacey et al. 1991).

Theoretically, little variation in $L_{[CII]}/L_{FIR}$ ratio is expected because it is a measure of the fraction of energy absorbed by dust that goes into heating the gas via photoelectron ejection. There are two physical conditions that could change this ratio and both the effects are seen in the present sample. The first is positive charge on grains which raises the work function of the grains so the photoelectrons carry a smaller fraction of the incident energy. Second, a softer radiation also leads to lower $L_{[CII]}/L_{FIR}$ as only UV photons produce photoelectrons while both optical and UV photons heat the dust.

Most galaxies in the sample have [CII]/FIR in the range of $0.1 - 1\%$, consistent with previous observations and the models of PDRs where the gas is heated by the photoelectrons from dust. The $L_{[CII]}/L_{FIR}$ flux ratios observed in the present sample span a factor of 100. Galaxies with warmer infrared colors (i.e. higher $F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$ ratio) and higher FIR/Blue luminosity have smaller flux ratio (Figures 1 and 2). The $L_{[CII]}/L_{FIR}$ shows little dependence on FIR luminosity, most of which may be due to correlation between far-infrared color ($F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$) and FIR luminosity. Two galaxies, NGC 4418 and IC 0860, were not detected in [CII], [OI] or any other lines, and we show their 3σ upper limits for the [CII] flux.

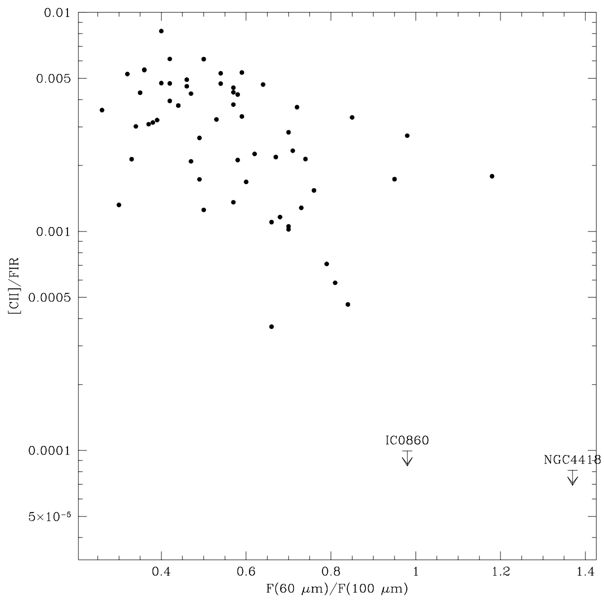

Figure 1. The ratio $L_{[CII]}/L_{FIR}$ is plotted against the ratio of flux densities at 60μm and 100μm measured by IRAS. There is a trend for galaxies with higher $F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$ (i.e. warmer dust) to have lower $L_{[CII]}/L_{FIR}$. Two galaxies in a sample of 60 have no detected [CII], for these the upper limit symbols show 3σ limits

3. REASONS FOR [CII] DEFICIENCY

(a) [CII] line could be optically thick or self-absorbing. For NGC 4418 this implies $N(H) = 4 \times 10^{22}$ and $A_v \simeq 20$ for $\tau = 1$. The total extinction towards the nucleus of NGC 4418 is $A_v > 50$. This implies a high ratio of PDR to cold molecular gas. Self-absorption by cooler foreground gas is a possibility, and has been seen towards Sgr B2 (Cox et al. these proceedings).

(b) High extinction: $\tau_{dust} = 1$ at 150 μm implies $A_v = 1,500$. This is insufficient to explain the [CII] deficiency and is unlikely even for very obscured starbursts like Arp220 (Fischer et al. these proceedings).

(c) Softer radiation from older/less massive stellar populations could lead to lower [CII]/FIR ratios (Luhman et al. 1998). This hypothesis also naturally explains the absence of FIR lines from ionized gas (Satyapal et al. in preparation).

(d) An extraneous FIR source, e.g. an obscured AGN, can lead to both a higher FIR/Blue luminosity and a lower $L_{[CII]}/L_{FIR}$. This hypothesis is supported by the observed compactness of the [CII] deficient sources in the mid-IR emission. 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 as discussed next.

(e) For high levels of UV radiation (G_0/n), the dust grains are positively charged and are less efficient at heating the gas because of a higher potential barrier to photoelectric ejection (Tielens & Hollenbach 1985).

4. THE [OI]/[CII] LINE RATIO

The line ratio [OI](63 μm)/[CII] increases with $F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$, showing a tight correlation (Figure 4) (Malhotra et al. 1999), which is qualitatively explained by PDR models (Kaufman et al. 1999). The line ratio [OI]/[CII] and the dust temperature $F_{\nu}(60\mu m)/F_{\nu}(100\mu m)$ both increase with the UV radiation density G_0. However, PDR models underpredict [CII]/[OI] ratios observed. That is

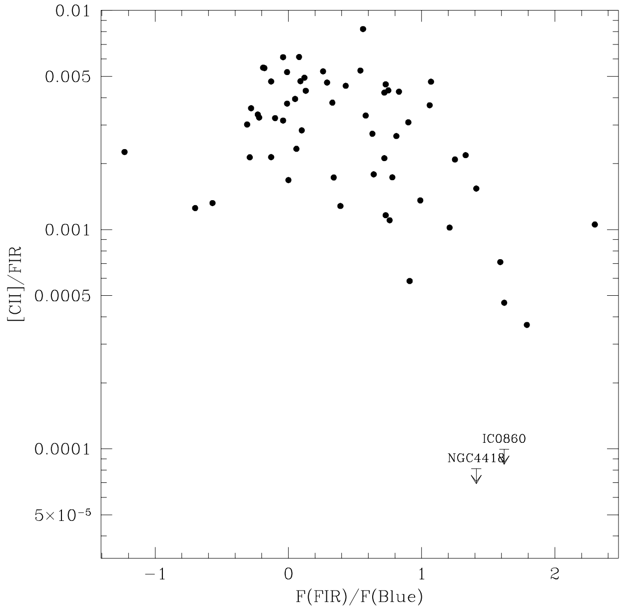

Figure 2. *The ratio* $L_{[CII]}/L_{FIR}$ *also decreases with higher ratio of FIR/Blue luminosity, which is a good estimator of star-formation activity. Galaxies at the low end of star-formation activity also show a less dramatic decrease in* $L_{[CII]}/L_{FIR}$. *The three galaxies with the lowest* L_{FIR}/L_B *are early type galaxies with a high proportion of old stars which produce softer radiation, leading to low* $L_{[CII]}/L_{FIR}$.

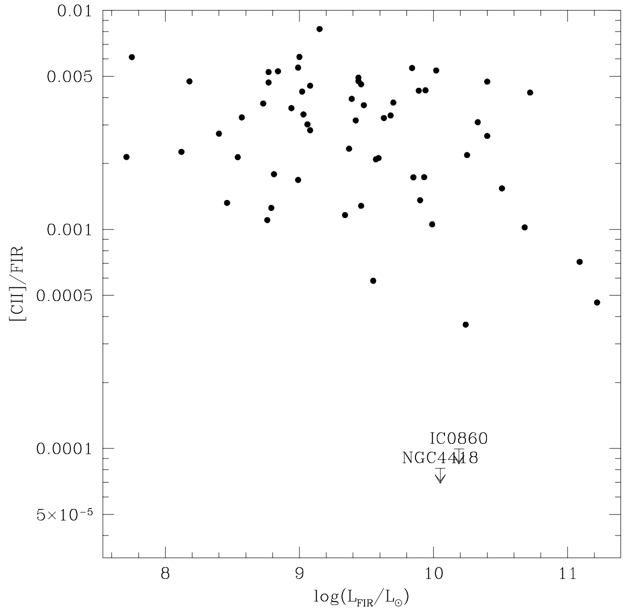

Figure 3. $L_{[CII]}/L_{FIR}$ *does not depend on the total FIR Luminosity. There is a weak tendency for the more luminous galaxies to be [CII] deficient, but that is probably due to a weak correlation between* $F_\nu(60\mu m)/F_\nu(100\mu m)$ *and* L_{FIR} *in the sample.*

because [CII] arises from ionized regions as well as neutral PDRs. Quantitative agreement between observations and PDR models of [OI]/[CII] line ratio is obtained by subtracting the [CII] emission due to ionized gas, estimated from the [NII] (122 μm) line (Malhotra et al. 1999).

This trend also rules out many of the hypothesis for [CII] deficiency listed in the last section.

(a) Since [OI] is present in the interiors of clouds ($A_v < 10$) whereas C^+ is confined to surface layers ($A_v < 4$), [OI] is more likely to go optically thick. Towards the Galactic center a deeper absorption profile is seen in the [OI] (63 μm) line (Keene et al. and Cox et al. in these proceedings) than the [CII] line (Cox et al. these proceedings).

(b) At a shorter wavelength [OI] 63 μm should be more sensitive to dust extinction than [CII] at 158 μm, contrary to the trends seen.

(c) It seems counterintuitive that the warmest and the more actively star-forming galaxies should have softer radiation fields and older stellar populations. However, no connection between the hardness of the radiation field and the far-infrared colors have been drawn. We think that softer radiation fields are responsible for the slight deficiency seen in the three early type galaxies NGC 6958, NGC 1052 and NGC 5866 with the lowest ratios of L_{FIR}/L_B in Figure 2. While optical light is absorbed by the dust grains and heats the dust, dust photoelectric heating of the gas is only possible when UV photons with energy greater than work function of the grain (E > 6eV) are available.

(d) The AGN hypothesis may explain the deficiency of [CII] but does not easily explain the trends in the $L_{[CII]}/L_{FIR}$ with L_{FIR}/L_B and $F_\nu(60\mu m)/F_\nu(100\mu m)$ ratios unless a significant fraction of galaxies have obscured active nuclei.

(e) An increase in [OI]/[CII] ratio is expected when radiation density G_0 increases, gas temperatures go up and more of the cooling is done via the [OI] (63 μm) line. As G_0/n increases further, grains get positively charged and there is less photoelectric heating of the gas, hence there is less total cooling relative to the FIR continuum emitted by grains.

5. CONCLUSIONS

In a study of 60 normal star-forming galaxies it is seen that the [CII] line gets increasingly weaker with respect to FIR continuum for galaxies with warmer dust and more active star formation. At the extreme end of that sequence we find two galaxies with no [CII] detected, and $L_{[CII]}/L_{FIR} < 10^{-4}$, roughly a factor of a 30-100 smaller than expected. The oxygen line at (63 μm) [OI]/FIR is constant to a factor of 7 where it is detected but [OI] is not detected for the [CII] deficient galaxies. The most favored explanation for [CII] variation and deficiency is positively charged grains at high UV radiation densities found in warm and active galaxies. This hypothesis explains the decreasing trend in $L_{[CII]}/L_{FIR}$ with increasing F60/F100 and L_B/L_{FIR}, the non-detection of [CII] and the increase in [OI]/[CII] ratio.

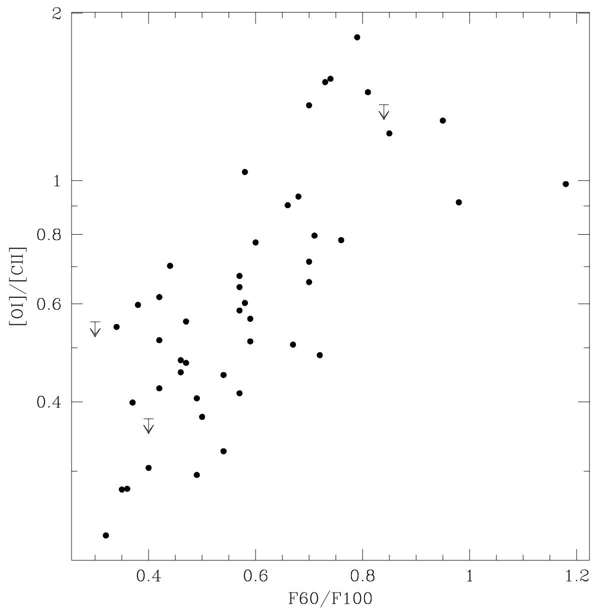

Figure 4. The ratio of [OI](63μm)/[CII] correlates very well with the IRAS colors F60/F100. This figure shows only the galaxies for which [CII] was observed, and the upper limits are 3-sigma non-detections of [OI]. The two [CII] deficient galaxies have no detections of [OI] and are not shown in this figure.

[CII] deficiency is also expected in galaxies with lower ratios of UV to optical radiation due to older or less massive stars. We see this effect in early type galaxies at the lowest end of the FIR/Blue ratio in this sample (Malhotra et al. these proceedings).

The [CII] and [OI] are among the brightest lines emitted by star-forming galaxies. About 0.2-0.7 % of the total FIR luminosity of a galaxy emerges in these lines. Normally, they are not affected by extinction, and are less affected by low metallicity than the CO lines. So, these lines have all that one might wish for in tracers of star-formation, except that we now have evidence that they are suppressed for some galaxies. The [CII]/FIR ratio does not depend on galaxy luminosity or morphology. This implies that high redshift searches for [CII] emitters will be most efficient at finding cool but luminous galaxies. Since [OI] is brighter for more active systems, [OI] searches for starbursts at high redshift may be more efficient.

ACKNOWLEDGEMENTS

This work was supported by ISO data analysis funding from NASA, and carried out at the IPAC and JPL (Caltech).

REFERENCES

Clegg, P.E., et al. 1996, A&A, 315, L38.

Crawford, M.K. et al. 1985, ApJ, 291, 755.

Heiles, C, 1994, ApJ, 720.

Helou, G., Malhotra, S., et al. 1996, A&A, 315, 157.

Kessler, M.F. et al., 1996, A&A, 315, L27.

Kaufman, M. et al., 1999 in preparation.

Lord, S., Malhotra, S. et al. 1996. A&A, 315, 117.

Luhman, M. et al. 1998, ApJ, 504, L11.

Madden, S.C., et al. 1993, ApJ, 407, 579.

Malhotra, S. et al. 1997, ApJ, 491, L27.

Malhotra, S., et al. 1999, in preparation.

Stacey, G. et al. 1991, ApJ, 373, 423.

Tielens, A.G.G.M., & Hollenbach, D., 1985, ApJ, 291, 722

Watson, W.D., 1972, ApJ, 176, 103.

Wolfire, M., Tielens, A.G.G.M., Hollenbach, D., 1990, ApJ, 358, 116.

Wright, E.L., et al. 1991, 381, 200.