[CII] EMISSION AND STAR-FORMATION IN LATE-TYPE GALAXIES

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ABSTRACT

We demonstrate the existence of a linear correlation between the ratio of the [CII($^2P_{3/2} \rightarrow ^2 P_{1/2}$)] ($\lambda$ 158 μm) fine structure cooling line intensity to the [^{12}CO(J : 1 $\rightarrow$ 0)] (λ 2.6 mm) line emission, I_{CII}/I_{CO}, and the Hα (λ 6563 Å) equivalent width (EW), over the range 2-71 Å in Hα EW, for a sample of 21 late-type galaxies. The latter is comprised of an optically selected sample of 12 normal Virgo cluster spiral galaxies with [CII] detections obtained by us with LWS onboard ISO, plus 9 galaxies with higher star-formation rates (SFRs), for which [CII] data and, especially, Hα EW data are available in the literature. As a result we infer I_{CII}/I_{CO} to be a reliable diagnostic of the current normalized global SFR for non-starburst spiral galaxies. Moreover we find that the ratio of the [CII] line to the total far-infrared (FIR) continuum intensity, I_{CII}/I_{FIR}, decreases from $\sim$ 0.5% to $\sim$ 0.1% with decreasing SFR which we propose is due to a "[CII]-quiet" component of I_{FIR} from dust heated by the general interstellar radiation field (ISRF). The more "quiescent" galaxies in the sample have I_{CII}/I_{CO} different from those observed in "compact" Galactic interstellar regions. Therefore their [CII]-emission is interpreted to be dominated by diffuse regions of the Interstellar Medium (ISM). For normal "star forming" galaxies the diffuse component of the [CII]-emission is estimated to account for at least 50% of the total.

Key words: galaxies; interstellar medium; star-formation; infrared.

1. INTRODUCTION

The physical state of the interstellar gas is regulated by several fine structure cooling lines, among which the [CII($^2P_{3/2} \rightarrow ^2 P_{1/2}$)] ($\lambda$ 158 μm) line transition of singly ionized carbon C^+ often dominates (Tielens & Hollenbach 1985). Its luminosity, I_{CII}, typically amounts to a few $\times 10^{-3}$ of the total FIR continuum emission, I_{FIR}, for galaxies; at the same time the [CII] line is up to 6600 times more intense than the [^{12}CO(J : 1 $\rightarrow$ 0)] (λ 2.6 mm) rotational line (Crawford et al. 1985).

For starbursts there is a good correlation between the [CII] line intensity and the emission from the [CO] line, probing the molecular gas component. This correlation holds also for a large sample of Galactic HII regions, OB associations, reflection nebulae, planetary nebulae, i.e. "compact" interstellar regions, and has suggested to earlier observers a physical association of the [CII]-emitting regions with molecular clouds; for non-starburst galaxies and non-OB star-forming molecular clouds the line ratio is typically a factor of 3 lower (e.g., Stacey et al. 1991 - S91). The correlation has been interpreted as evidence that the [CII]-emission from galaxies is being originated from warm dense gas from an ensemble of photodissociation regions (PDRs), forming the boundaries between HII regions and molecular clouds (Crawford et al. 1985; Tielens & Hollenbach 1985; Wolfire et al. 1989; S91; Hollenbach et al. 1991).

Recent studies, on the other hand, have emphasized other phases of the ISM, i.e., an Extended Low-Density Warm Ionized Medium (ELDWIM) (Heiles 1994) and a Cold Neutral Medium (CNM) (Madden et al. 1993; Bennett et al. 1994), as the main sources of the [CII] line.

In view of the difference between starburst and non-starburst galaxies, Stacey et al. (1991) concluded that I_{CII}/I_{CO} was a diagnostic of the global star-formation activity in galaxies.

Here we study the properties of the [CII]-emission of 21 late-type galaxies with a large range in star-formation activities (as probed by the Hα EW - Kennicutt et al. 1994) in order to: i) sample the behaviour of relatively quiescent galaxies; and ii) estimate the contributions of the different ISM phases.

2. THE SAMPLE

The galaxies observed by us with the Long Wavelength Spectrometer (LWS) (Clegg et al. 1996) are a subsample of targets of the ISO Guaranteed Time program VIRGO, an ISOPHOT (Lemke et al. 1996) 40 - 220 μm study of a deep optically complete sample of spiral, irregular and BCD galaxies, selected from the Virgo Cluster Catalogue (VCC) of Binggeli et al. (1985) (Völk et al. in preparation).

Nineteen normal spiral galaxies were selected from the parent ISOPHOT sample by Leech et al. (these proceedings - L98) within a limiting magnitude of $B_T \leq 12.5$ and observed with LWS (80$''$ HPBW),

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onboard ESA's Infrared Space Observatory (ISO) (Kessler et al. 1996), in the spectral region around the [CII] line. Here we consider only those 12 of the 15 detected galaxies, which have Hα EWs from Kennicutt & Kent (1983) and from Gavazzi (private communications), [^{12}CO(J : 1 → 0)] line emission from Kenney & Young (1988) (at the 45″ resolution of the 14 m FCRAO telescope) and IRAS FIR fluxes (Thuan & Sauvage 1992).
In order to investigate the [CII]-emission properties over a large dynamic range in SFRs, we extend the L98 sample of "quiescent" (as defined in Section 3) Virgo spirals to late-type galaxies more active in star-forming, which have [CII], [CO], FIR and, in particular, Hα measurements as well. Therefore we add 3 low-mass VCC spiral galaxies (Smith & Madden 1997 - SM97), with LWS [CII] line intensities and [CO] line observations taken at the 12 m NRAO telescope, with a resolution (beamsize FWHM = 55″) similar to FCRAO. The sources of the FIR and Hα data are the same as for the L98 sample.
We consider, without introducing any morphological or luminosity bias, in addition 3 gas-rich galaxies and 3 starbursts, taken from S91 (see S91 for the sources of the data).

3. RESULTS

We explore the dependence of I_{CII}/I_{CO} on the Hα EW. We divide non-starburst galaxies into "quiescent" and normal "star-forming" galaxies according to their values of Hα EW < 10 Å and ≥ 10 Å, respectively, which have consistently a stellar birthrate parameter b of Scalo (1986) < 0.1 and ≥ 0.1 (see Kennicutt et al. 1994), where b is defined as the ratio of the SFR at the current time to the past SFR averaged over the age of the disk.
Moreover, we study the dependence of I_{CII}/I_{FIR} on the Hα EW. For the Virgo cluster galaxies IRAS integrated fluxes are used, as a definitive calibration of the ISOPHOT data is not yet available. Given the low resolution of IRAS, we assume that the bulk of the FIR (Helou et al. 1985) emission originates within the LWS beam in order to determine I_{CII}/I_{FIR}.
Finally we compare the parameter ranges occupied by entire galaxies with those occupied by compact Galactic sources.

3.1. I_{CII}/I_{CO} and the current SFR

Figure 1a shows the existence of a reasonably tight linear relation between I_{CII}/I_{CO} and the Hα EW. The [CII]-to-[CO] line intensity ratio increases from 1.6×10^2 to $\sim 6.3 \times 10^3$, varying by more than a factor of 35, with Hα EW increasing from 2 to 71 Å (see SM97 for the case of NGC 4299).
Therefore I_{CII}/I_{CO} is indeed a reliable diagnostic of the global SFR, at least in normal late-type galaxies.

3.2. I_{CII}/I_{FIR} and the current SFR

Figure 1b shows that I_{CII}/I_{FIR} roughly ranges between 1.1×10^{-3} and a mean "plateau" value of $\simeq 4 \times 10^{-3}$ (defined by the normal star-forming galaxies), which is between the average values $(I_{CII}/I_{FIR})_{Gc} \simeq$ 0.2% and $(I_{CII}/I_{FIR})_{Gd} \simeq 0.6\%$ for compact and diffuse regions of the Galactic ISM, respectively (Nakagawa et al. 1998 - N98).

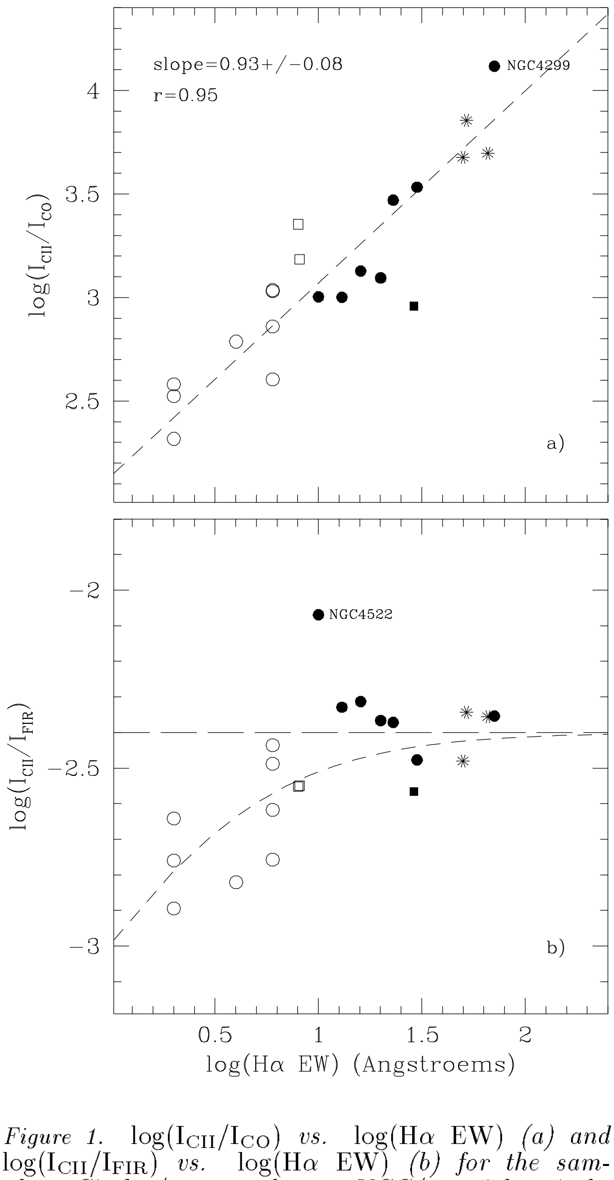

Figure 1. log(I_{CII}/I_{CO}) *vs.* log(Hα EW) *(a) and* log(I_{CII}/I_{FIR}) *vs.* log(Hα EW) *(b) for the sample. Circles/squares denote VCC/gas-rich spirals. Filled/open symbols denote objects with* Hα EW ≥ 10 Å/< 10 Å. *Asterisks denote starbursts. The short-dashed line in (a) shows the least-squares fit of* I_{CII}/I_{CO} *vs.* Hα EW, *while the long-dashed line in (b) represents the mean "plateau" value of* I_{CII}/I_{FIR} *for the normal star-forming galaxies (NGC 4522 excluded - see Pierini et al. 1999).*

We find in addition a positive trend of the value of I_{CII}/I_{FIR} with increasing Hα EW for the quiescent galaxies, reproduced by the model-curves of Völk et al. (in preparation), one of which is shown as the short-dashed line in Figure 1b.

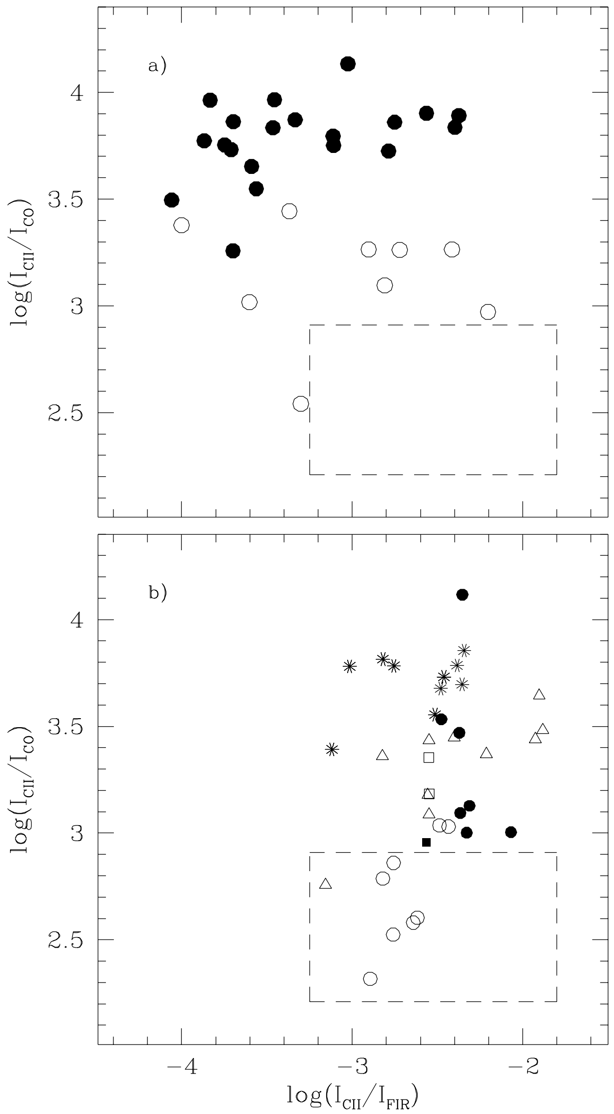

Figure 2. *log(I_{CII}/I_{CO}) vs. log(I_{CII}/I_{FIR}) (a) for Galactic sources (S91), with big filled/open circles denoting star-forming regions/molecular clouds; (b) for the galaxies shown in Figure 1 (with the same symbols) plus all other galaxies in S91 as in the text (gas-rich systems without Hα EWs are represented by empty triangles). Boxes denote a range in parameter space for galaxies without compact Galactic counterparts.*

3.3. The [CII] line emission from compact Galactic sources and from the global ISM of external galaxies

Galactic molecular clouds and HII regions/OB associations (Figure 2a) span a much wider (2 decades cf. S91) range in I_{CII}/I_{FIR} than galaxies and cluster at two definite values of I_{CII}/I_{CO} ($\sim$ 3.3 and $\sim$ 3.8 in log respectively), while galaxies go from 2.3 to $\sim$ 3.8 in log. This is seen by comparison with Figure 2b, where our galaxy sample is plotted, together with all the other galaxies in S91 that lack Hα EW. The compact Galactic regions leave the rectangular box empty (within 1σ) which is filled by our low-Hα EW-galaxies.

4. DISCUSSION

For moderate values of I_{CII}/I_{CO}, its correlation with the Hα EW is interpreted as the global, *mass-normalized* [CII]-emission from a galaxy, increasing about linearly with the *mass-normalized* present SFR. Mass-normalization is for [CII] in terms of I_{CO}, and for Hα in terms of the stellar continuum I_R in the red (see Pierini et al. 1999). The [CO]-normalization however, while very interesting in itself, has the great advantage that we can make use of existing I_{CII}/I_{CO} data for compact Galactic regions in a comparison with those for our galaxy sample.

The linear correlation implies that all the non-ionizing UV-flux from intermediate-mass stars ($5 \leq$ M ≤ 20 $M_\odot$), that is not primarily absorbed in dense HII regions, is used for the production of [CII], independent of how large the SFR per unit mass is. Since most of the non-ionizing UV-flux is from B stars, whereas Hα is due to massive stars in OB associations producing mainly Lyman continuum radiation, the correlation implies in addition a rather tight coupling of the stellar initial mass function between these two stellar populations (e.g., Güsten & Mezger 1983; Larson 1986). For a low normalized SFR this is a significant result, and is equally consistent with the [CII]-emission coming from PDRs or from low-density diffuse galactic regions.

For high SFRs the [CII]-emission might be dominated by (high-density) PDRs. At very high UV-fluxes the [CII]-emission from PDRs becomes saturated due to grain charging and dust absorption, and I_{CII}/I_{CO} takes the value of $\sim$ 6300 found for starburst galaxies (cf. S91).

I_{CII}/I_{FIR} is fairly constant within $10 \leq$ Hα EW $\leq$ 50 Å. It should decrease for larger Hα EWs or, equivalently, higher values of I_{FIR}, as demonstrated observationally by, e.g., S91, Malhotra et al. (1997; and these proceedings) and N98, and theoretically by e.g. Tielens & Hollenbach (1985) in the PDR picture.

Thus the interesting *new* phenomenon in our data is the *opposite* range $2 \leq$ Hα EW ≤ 10 Å, where I_{CII}/I_{FIR} tends to rapidly decrease with Hα EW. It can be shown quantitatively (cf. Xu et al. 1994) that this range corresponds to galaxies which are close to becoming, or are in fact already "radio-quiet" (Condon et al. 1991) in the sense that their dust heating is increasingly dominated by the general ISRF due to stars which are not Supernova progenitors due to their low mass and which therefore cannot produce Cosmic Ray electrons and nonthermal radio emission (Xu et al. 1994). It is physically clear that these stars cannot produce any substantial photoelectric grain heating either, increasingly rendering such galaxies also "[CII]-quiet"! Within this framework, in Figure 1b we plot a characteristic curve, selected from the model curves of Völk et al. (in preparation), which gives a synthetic interpretation of the data.

Compact interstellar [CII] sources do not appear to represent the galaxies with a low normalized SFR in our sample. We interpret this as a tentative indication that such relatively quiescent galaxies are *dominated* in their [CII]-emission by diffuse regions of the ISM (i.e., an ELDWIM or a CNM), whose integrated emission might be considerable indeed (Heiles 1994; Madden et al. 1994; Bennett et al. 1994; SM97). A crucial test of such an interpretation would be a successful search for low I_{CII}/I_{CO} Galactic compact regions which fill the empty rectangular region in Fig-

ure 2a. If such compact objects were to exist, then the PDR mechanism could partially also hold for quiescent galaxies. If not, then a diffuse origin is indicated.
For normal "star-forming" galaxies the mean value of I_{CII}/I_{FIR} is about 4×10^{-3} (cf. Figure 1b and Figure 2b). If we assume this result to be due to a linear combination of compact and diffuse regions as they exist in our Galaxy, then the diffuse component is given by $x \cdot (I_{CII}/I_{FIR})_{Gd}$, where $x = I_{FIRd}/I_{FIR}$ and $1 - x$ define a diffuse and a corresponding compact fraction of I_{FIR}, respectively. With our above mean value, and using the abovementioned results of N98, we obtain for the "plateau galaxies" $x \simeq 0.5$ and $x \cdot (I_{CII}/I_{FIR})_{Gd} \simeq 3 \times 10^{-3}$, with $(1-x) \cdot (I_{CII}/I_{FIR})_{Gc} \simeq 1 \times 10^{-3}$ for the remaining compact component. This corresponds to a 75% diffuse and 25% compact I_{CII}/I_{FIR} fraction, respectively. Thus, for normal galaxies, i.e. non-starburst galaxies, the diffuse [CII]-emission is on average *at least as strong as the compact one.*
For starburst galaxies (e.g. S91), on the other hand, I_{CII}/I_{FIR} decreases with I_{FIR} below the plateau value. The above simple model then implies a corresponding decrease of the diffuse fraction consistent with an increasing dominance of an ensemble of bright compact PDRs. However it remains to be investigated whether the model and its numerical parameters are applicable to such extreme cases.

5. SUMMARY

We use LWS detections of the [CII] (λ 158 μm) fine structure cooling line in 12 VCC normal spiral galaxies to define a sample of 21 late-type galaxies, having [CII], Hα, [CO] and far-IR measurements, with the largest range in star-formation activity available at present in the literature. We find that:
1) The ratio between the [CII] and [CO] line intensities has a reasonably tight positive correlation with the Hα EW. Therefore, we demonstrate that I_{CII}/I_{CO} is a reliable tracer of the global current normalized SFR below the saturation level of I_{CII}/I_{CO}, i.e. up to Hα EW ~ 50 Å.
2) The ratio of the [CII] line to total FIR intensity has a narrow range of $(1.1\text{–} \sim 5) \times 10^{-3}$. Its decrease toward H$\alpha$ EW $\simeq 10$ Å can be readily explained by a "[CII]-quiet" component of the FIR continuum emission at lower SFRs.
3) The lack of compact Galactic [CII]-emission regions as counterparts to the low-SFR galaxies is tentatively interpreted in terms of a dominant [CII]-emission from the diffuse components of the ISM of such galaxies.
4) For starburst galaxies a simple theoretical model gives further indications that the compact fraction dominates the [CII]-emission.
5) The same model demonstrates that for *normal galaxies* the diffuse fraction of the [CII]-emission is *at least as strong as the compact fraction.*

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