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Global Properties of the Interstellar Medium in Nearby Galaxies*

By

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Abstract: Far-infrared spectra ($45-189\,\mu$m) of 36 nearby galaxies taken by the Long Wavelength Spectrometer (LWS) aboard the Infrared Space Observatory (ISO) were analyzed to investigate the general properties of interstellar matter in galaxies. Far-infrared forbidden lines, such as [CII]158 μm, [OI]63 μm, and [NII]122 μm, were detected in most of the sample galaxies. The line intensities of [CII]158 μm and [NII]122 μm relative to the far-infrared intensity (FIR) decrease as the far-infrared color becomes bluer, while the ratio of the [OI] intensity to FIR does not show a systematic trend with the color. We estimate the contribution from photodissociation regions (PDRs) to the observed [CII]158 μm intensity, assuming that all the [OI]63 μm and far-infrared continuum emission comes from the PDRs. The results indicate that the fraction of [CII]158 μm emission arising from the PDRs ranges from 30% to 80% among the sample galaxies. The rest of the emission is suggested to originate from the extended low-density warm ionized medium (ELDWIM). The derived neutral hydrogen gas density increases as the far-infrared color becomes bluer, being compatible with the idea that active galaxies have dense gas in their interstellar medium. The contribution from ELDWIM to [CII]158 μm/FIR does not show any systematic trend with the far-infrared color. The present results suggest that the relation between [CII]158 μm/FIR and the far-infrared color can be attributed to the decrease in [CII] emission from the PDRs owing to the increase in collisional de-excitation rather than the decrease in the photoelectric heating efficiency.

1. INTRODUCTION

Mechanisms for heating interstellar gas include collisions, radiation from stars, shocks, and cosmic rays. Examination of the spectral lines that cool the gas can help determine the dominant excitation mechanisms and conditions. Studies of particular regions in our Galaxy and observations of external galaxies have suggested that stellar UV radiation can ionize vast volumes of a galaxy and that the far-UV (FUV) radiation impinging on neutral cloud surfaces is responsible for a large fraction of the observed far-infrared (FIR) spectral line emission

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that cools the gas (Stacey et al. 1991; Shibai et al.1991; Crawford et al. 1985). Tielens & Hollenbach (1985) defined *photodissociation regions* (PDRs) as a neutral "region where FUV radiation dominates the heating and/or some important aspect of the chemistry. Thus PDRs include most of the atomic gas in a galaxy, both in diffuse clouds and in the denser regions".

[CII]158 μm and [OI]63 μm lines are important coolants in PDRs, while gas heating in PDRs is thought to be dominated by energetic photoelectrons ejected from dust grains following UV photon absorption (Watson 1972). For galactic nuclei and star-forming regions in the spiral arms, most of the observed [CII] line emission arises from PDRs on molecular cloud surfaces. However, integrated over the disks of spiral galaxies, a substantial fraction may also arise from "standard" atomic clouds, i.e. the cold neutral medium gas regions (CNM) (Madden et al. 1993) or from extended low-density warm ionized gas regions (ELD-WIM) (Heiles 1994). Contributions from various gas phases can be estimated by the observations of several FIR forbidden lines (Carral et al. 1994; Luhman et al. 1997).

With the LWS on the ISO (Clegg et al. 1996) it now becomes possible to measure far-infrared lines not only from very infrared-bright but also from normal galaxies (Lord et al. 1996). Because most parts of an external galaxy are included in the beam of the LWS, the observed line emission includes the contribution from various interstellar regions. This paper reports on an analysis of the LWS spectra of a sample of nearby galaxies and investigates the origin of the observed [CII] emission with the aim of better understanding of the physical conditions in the interstellar medium in galaxies.

2. DATA REDUCTION AND OBSERVATIONAL RESULTS

The LWS01 data (full grating scan) of 36 nearby ($z<0.25$) galaxies have been extracted from the ISO archival database. The sample includes various types of galaxies, ranging from normal, starburst, to Seyfert galaxies (see Table 1). The spectra covers $48-189\,\mu$m with a spectral resolution of $\lambda/\Delta\lambda \sim 200$ (Clegg et al. 1996). The Standard Processed Data (SPD) of off-line processing (OLP) version 7 products were used in the present investigation. The dark current and the drift in the detector responsivity were corrected by using the LWS Interactive Analysis software (LIA version 7.3).[1] The ISO Spectral Analysis Package (ISAP version 1.6a) [2] was then used for further data reduction to derive the line intensities and the dust temperature of the continuum emission. Final continuum spectra were obtained by shifting each detector signal with "LWS Dark Offset" method. The final spectra have been scaled to SW3 detector unless the connection led to an unnaturally distorted spectrum.

The observational results are summarized in Table 1. Figures 1a, 1b and 2, plot the ratios of the flux of [CII]158 μm, [NII]122 μm, and [OI]63 μm to FIR against the far-infrared color $R(60/100)$, respectively, where FIR is the total far-infrared intensity obtained by integrating the LWS spectra and $R(60/100)$ is the color of the 60 μm to 100 μm flux density (in Jy) derived from the LWS spectra with the IRAS band filters. The ratios [CII]/FIR and [NII]/FIR decrease as $R(60/100)$ becomes larger, but [OI]/FIR does not show any systematic trend with $R(60/100)$ (Figure 2). Similar trends of [CII]/FIR with the far-infrared color have been reported for other galaxy samples (Malhotra et al. 1997; Leech et al. 1999).

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[1] LIA is a joint development of the ISO-LWS instrument team at RAL, UK, the PI institute and IPAC.

[2] The ISO Spectral Analysis Package (ISAP) is a joint development by the LWS and SWS Instrument Teams and Data Centers. Contributing institutes are CESR, IAS, IPAC, MPE, RAL and SRON.

Table 1: Summary of the observational results

Name	$R(60/100)^a$	FIR ^{b} (Wcm^{-2})	T_d ^{c} (K)	[CII](158)^d (Wcm^{-2})	[OI](63)^e (Wcm^{-2})	[NII](122)^f (Wcm^{-2})
Arp220	0.82	6.6E-16	50.4	8.3E-20	-6.7E-20	
Cen A (NGC5128)	0.43	8.6E-16	36.8	2.7E-18	2.0E-18	2.2E-19
Circinus	0.75	1.8E-15	50.7	2.5E-18	2.4E-18	2.0E-19
IC2554	0.40	9.4E-17	32.5	3.6E-19	2.8E-19	
II ZW40	0.56	7.0E-17	41.5	2.0E-19	1.3E-19	
IRAS00506+7248	0.67	1.3E-16	45.7	3.0E-19	2.9E-19	
IRAS13242-5713	0.71	5.1E-16	47.7	5.1E-19	4.2E-19	7.8E-20
MAFFEI2	0.49	6.9E-16	40.3	1.2E-18	5.8E-19	1.3E-19
M51 (NGC5194)	0.37	3.3E-16	34.5	9.5E-19	4.5E-19	2.5E-19
M81	0.48	6.0E-17	39.1	5.8E-20		
M82	0.88	8.0E-15	52.6	1.2E-17	1.8E-17	2.0E-18
M83	0.63	7.6E-16	45.5	1.7E-18	1.2E-18	3.1E-19
NGC253	0.69	6.2E-15	47.4	4.9E-18	4.0E-18	8.7E-19
NGC520	0.67	2.1E-16	48.2	2.6E-19	2.0E-19	4.5E-20
NGC891	0.27	2.3E-16	30.5	7.7E-19	2.2E-19	1.4E-19
NGC1068	0.64	1.3E-15	45.7	2.1E-18	1.7E-18	3.6E-19
NGC1097	0.53	3.6E-16	40.8	6.8E-19	3.1E-19	1.5E-19
NGC1365	0.52	6.1E-16	41.3	1.1E-18	5.3E-19	1.8E-19
NGC2146	0.67	9.2E-16	46.2	2.6E-18	1.9E-18	2.2E-19
NGC3256	0.71	6.4E-16	48.5	1.3E-18	1.3E-18	1.7E-19
NGC3690	1.04	6.2E-16	57.5	8.4E-19	8.5E-19	5.0E-20
NGC4038	0.48	1.7E-16	39.3	5.1E-19	3.8E-19	4.8E-20
NGC4041	0.38	8.1E-17	32.8	3.5E-19	2.0E-19	5.3E-20
NGC4945	0.51	3.6E-15	39.7	3.0E-18	1.9E-18	4.2E-19
NGC5430	0.50	8.3E-17	40.0	1.5E-19	9.9E-20	3.0E-20
NGC5937	0.49	8.8E-17	39.4	4.1E-19	1.6E-19	3.3E-20
NGC6156	0.64	1.3E-16	46.8	3.9E-19	2.0E-19	3.4E-20
NGC6240	0.91	1.3E-16	53.9	2.9E-19	7.4E-19	2.3E-20
NGC6764	0.55	3.9E-17	44.5	1.2E-19	1.2E-19	8.2E-21
NGC6810	0.44	1.2E-16	40.3	3.8E-19	1.5E-19	5.9E-20
NGC6824	0.44	5.3E-17	37.9	1.8E-19	8.4E-20	2.5E-20
NGC6946	0.51	4.3E-16	41.8	9.3E-19	6.0E-19	1.1E-19
NGC7469	0.66	1.3E-16	47.8	2.1E-19	2.4E-19	
NGC7552	0.62	4.7E-16	44.5	6.5E-19	6.6E-19	5.5E-20
NGC7582	0.61	3.3E-16	46.1	4.3E-19	2.9E-19	
NGC7714	0.99	1.0E-16	65.1	2.1E-19	2.3E-19	

[a] Far-infrared color calculated from the 60 μm and 100 μm flux densities (in Jy) derived from the LWS spectra with the IRAS band filters.
[b] Total far-infrared flux integrated over the LWS spectra.
[c] Dust temperature derived from the greybody fit (see text).
[d] [CII]158 μm line flux; [e] [OI]63 μm line flux; [f] [NII]122 μm line flux.

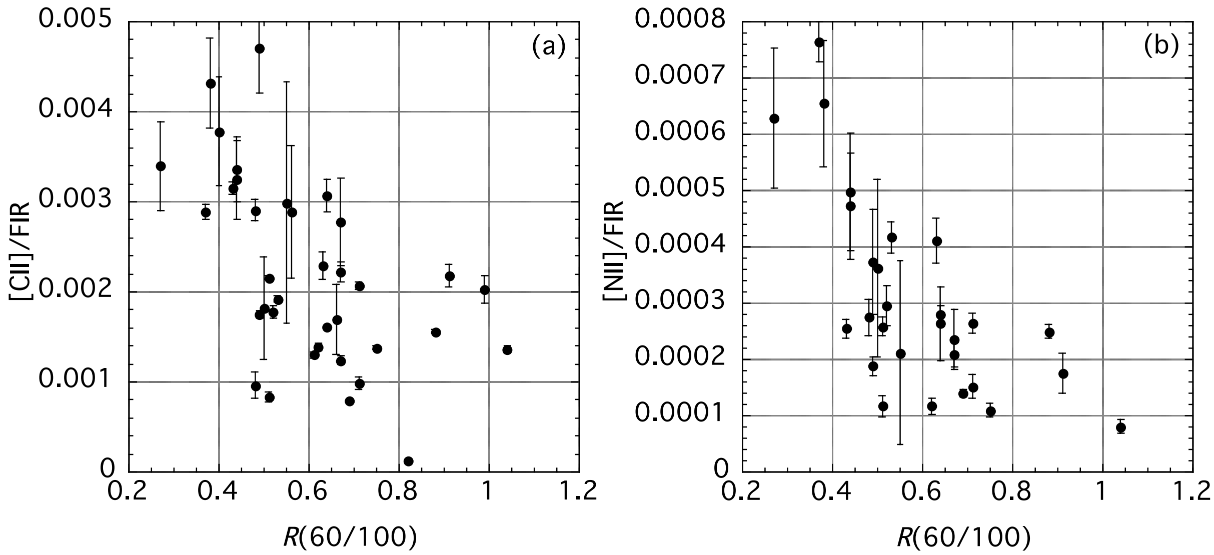

Fig. 1: (a) The ratio of the [CII]158 μm intensity to the total far-infrared flux FIR against the far-infrared color $R(60/100)$. (b) The ratio of the [NII]122 μm intensity to FIR against $R(60/100)$.

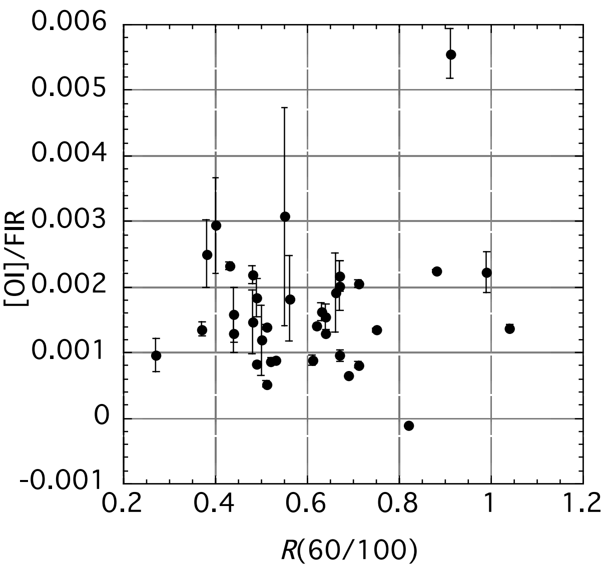

Fig. 2: The ratio of the [OI]63 μm intensity to FIR against $R(60/100)$.

3. ANALYSIS AND DISCUSSION

The [CII]158 μm line has been considered as one of the most important lines in the diagnosis of PDRs because of its large strength. Together with other lines, such as [OI]63 μm and 145 μm lines, the physical conditions of the region can be derived based on PDR models (e.g. Tielens & Hollenbach 1985; Wolfire, Tielens, & Hollenbach 1990; Kaufman et al. 1999), in which the major model parameters are the strength of the incident radiation field in units of the solar neighborhood value G_0 and the neutral hydrogen gas density n. However, the [CII] line could also originate from ionized regions (Heiles 1994) and the fraction of the contribution cannot be estimated *a priori*. In this paper we first estimate G_0 from the dust temperature $T_{\rm d}$ derived from the LWS continuum spectra (see below) and then use the ratio of the [OI]63 μm intensity to FIR and the derived G_0, to estimate n based on the model provided by Kaufman et al. (1999), assuming that the observed [OI]63 μm and the far-infrared emissions come mostly from the PDRs. Because in the LWS spectral range thermal emission from warm grains should be dominant in the continuum, the emission from cold cirrus clouds is supposed not to make significant effects in the derivation on G_0. With the derived G_0 and n the contribution from the PDRs to the observed [CII]158 μm line intensity is estimated and that from other regions (non-PDR component) is derived.

From the energy balance equation, the radiation strength G_0 can be shown to be proportional to $T_{\rm d}^{\alpha+4}$, if the dust emissivity is proportional to $\lambda^{-\alpha}$ (e.g. Klein, Wielebinski, & Morsi 1988). In this paper we assume $\alpha = 0.7$ and G_0 is scaled to that for M82 ($G_0 = 10^{3.5}$) given by Kaufman et al. (1999). The absolute values of the derived G_0 may have uncertainties owing to this scaling. Any weak trends which may be seen in the following figures should be taken with care and will not be discussed in this paper. However, the major conclusions of this paper are not affected by the scaling of G_0.

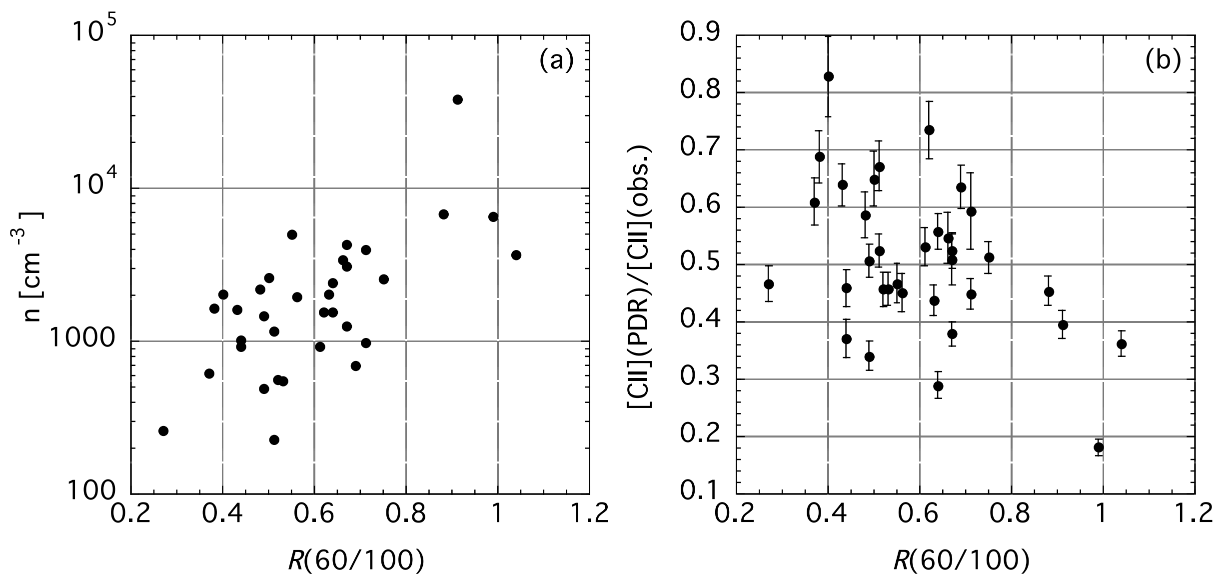

Fig. 3: (a) Derived neutral hydrogen gas density n against the far-infrared color $R(60/100)$. (b) The fraction of the contribution from the PDRs to the observed [CII]158 μm emission against $R(60/100)$.

Figure 3a plots the derived gas density n against the color $R(60/100)$. The derived density increases with the color. The tendency results mainly from the constancy of [OI]/FIR against the color because the ratio should be roughly proportional to G_0/n in PDR models (e.g. Tielens & Hollenbach 1985), while the color is correlated with G_0. This trend is compatible with the general view that active galaxies have dense gas in their interstellar medium. Figure 3b shows the ratio of the estimated contribution from the PDRs to the observed total intensity for the [CII]158 μm emission. The fraction of the [CII] emission arising from PDRs ranges from 30% to 80% among the sample galaxies. In the following we investigate whether the non-PDR component can be attributed to the emission from low-density ionized regions.

The [NII]122 μm line emission stems from the extended low-density warm ionized medium (ELDWIM) (Heiles 1994; Wright et al. 1991; Bennett et al. 1994), from which [CII]158 μm is also supposed to arise. The line ratio of [NII]/[CII] in the ELDWIM depends on the electron density, but is insensitive to the temperature of the ionized gas. The electron density of the ELDWIN has been estimated as 50 cm^{-3} for our Galaxy and 200 cm^{-3} for M82 based on the observed line ratio of [NII]205 μm to 122 μm (Petuchowski et al. 1994). In Figure 4a, the ratio of the observed [NII]122 μm intensity to the non-PDR component of [CII]158 μm is plotted. The [NII]/[CII] ratio does not show a systematic trend with color. The hatched area shown in the figure is the expected range of the ratio for an electron density of $50 - 300\,\mathrm{cm}^{-3}$, assuming the solar abundance ratio for C^+ and N^+. The observed ratio is mostly in the range expected for the ELDWIM, indicating that the ionized gas which emits [NII]122 μm can produce the [CII]158 μm line emission which is not attributed to the PDR origin.

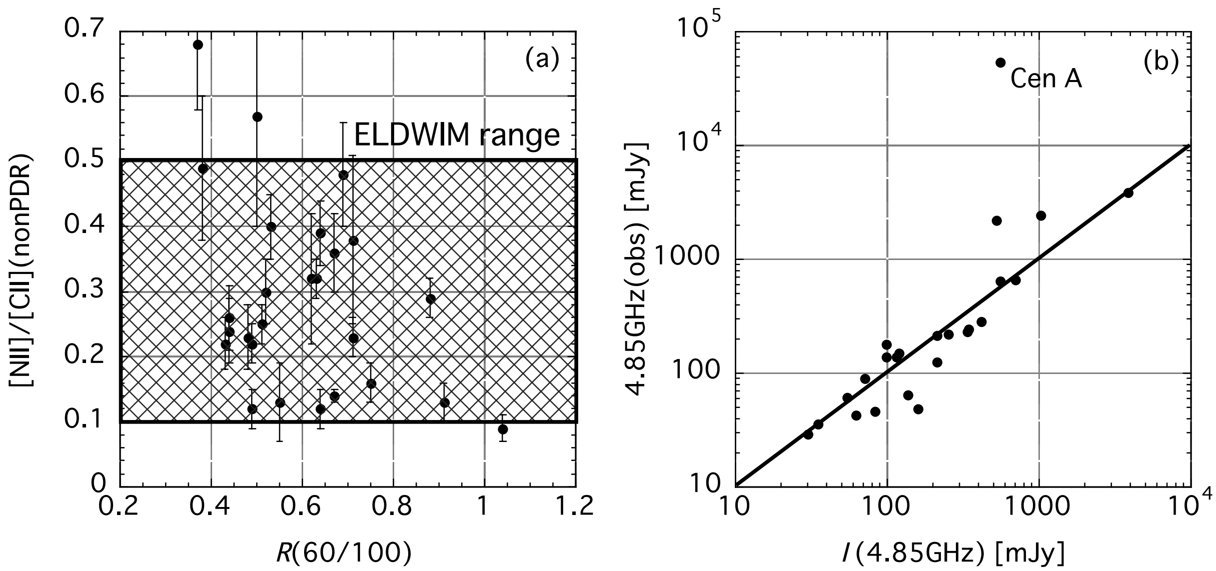

Fig. 4: (a) The ratio of [NII]122 μm intensity to the non-PDR component of [CII]158 μm against the far-infrared color $R(60/100)$. (b) The observed 4.85GHz radio continuum flux density plotted against the 4.85GHz radio continuum flux density predicted from the non-PDR component of [CII]158 μm emission (see text). The observed radio flux densities are taken from Gregory et al. (1991, 1994), Becker, White, & Edwards (1991), and Griffith et al. (1994).

The ionized gas also emits the radio continuum. The intensity of free-free transition can be written for $T_\mathrm{e} = 5000\mathrm{K}$ by

$$I(4.85\mathrm{GHz})[\mathrm{mJy\ sr}^{-1}] = 3.55 \times 10^{-14} n_\mathrm{e}^2 l, \tag{1}$$

where n_e is the electron density in cm^{-3} and l is the path length in cm. On the other hand, an upper limit of the intensity of [CII] line from the ELDWIM of the solar abundance gas can be given by

$$I_{[\mathrm{CII}]}(ELDWIM)[\mathrm{W\ cm^{-2}sr^{-1}}] = \frac{1}{4\pi}L(T_\mathrm{e})n(C^+)n_\mathrm{e}l = 2.6 \times 10^{-12}L(T_\mathrm{e})n_\mathrm{e}^2 l, \qquad (2)$$

where $L(T_\mathrm{e})$ is the cooling function of [CII]158 μm (Hayes & Nussbaumer 1984). From equation (2) we can predict the radio continuum emission from the gas which emits the non-PDR component of [CII] line emission. Figure 4b plots the comparison between the predicted and observed flux densities. The predicted values show a positive correlation and is in good agreement with the observations except for Cen A. Cen A is a very strong radio source (e.g. Sreekumar et al. 1999) and the contribution from the regions other than the ELDWIM should be significant. The comparison with the [NII]122 μm emission and the radio continuum thus suggests that the non-PDR component of the [CII]158 μm emission could arise mainly from the ELDWIM for the present sample of galaxies.

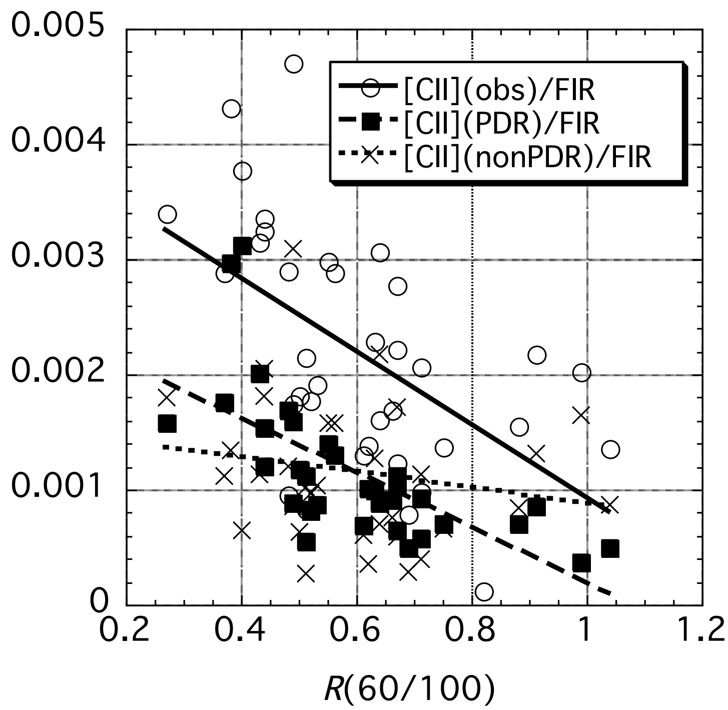

Fig. 5: The decomposition of [CII]158 μm emission into the PDR and non-PDR components plotted against $R(60/100)$.

Figure 5 shows the PDR and non-PDR components of [CII]158 μm emission against the far-infrared color $R(60/100)$. The observed constancy of [OI]/FIR indicates that the photoelectric yield does not decrease with the color in contrast to the suggestion given by Malhotra et al. (1997). The increase in G_0 is compensated by the increase in n and the yield, which is roughly proportional to G_0/n, does not change appreciably with the color. The predicted PDR component of [CII]/FIR shows a clear decrease with the color. This trend can be understood in terms of the increase in the collisional de-excitation (thermalization) of the transition owing to the increase in the density rather than the decrease in the photoelectric heating efficiency. The [OI] transition has a much larger critical density than the [CII] transition and is not affected by the increase in the density. The non-PDR component does not show any clear trend with the color among the sample galaxies. The decrease in the observed total [CII] emission with the color, therefore, can be attributed mostly to the decrease in the PDR component owing to the thermalization of the transition.

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