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LETTER

Letter to the Editor

[C II] 158 and [O I] 63 μm ISO-Observations of L1457*

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Abstract. We report here the results of [C II] 158 and [O I] 63 μm fine-structure line observations along two cuts across a molecular clump of L1457 (MBM 12) carried out with ISO-LWS. [C II] emission was detected at all positions observed. It can be assigned to the cooling of the diffuse atomic interstellar medium. We observed excess [C II] emission from the dense clumpy molecular component. It is likely to originate from molecular gas that is irradiated by an interstellar FUV-radiation field of order $\chi = (1-2)\chi_0$. Using PDR models for a spherical symmetry we find the molecular gas of L1457 consists of clumps with a density $n_{\rm H} \sim 10^5$ cm^{-3}. Their masses range between 10^{-4} and 10^{-3} M$_\odot$ consistent with the clump distribution derived from high resolution CO observations. [O I] 63 μm emission was not detected toward L1457.

Key words: ISM: abundances – ISM: clouds – ISM: individual objects: L1457 (MBM 12) – infrared: ISM: lines and bands

1. Introduction

L1457 (MBM 12) is the nearest known molecular cloud at a distance of 65 pc (Hobbs et al. 1986). It has been studied in different tracers, such as CO, [C I], H I and through optical absorption. ^{13}CO(2–1) line observations at the CSO (Ingalls et al. 1994) and the IRAM 30m-telescope (Zimmermann 1993) provide evidence that L1457 consists of dense molecular clumps down to masses of $\sim 10^{-4}$ M$_\odot$ and sizes $\lesssim$2000 AU.

It is assumed that L1457 is not associated with sources of FUV-radiation. When such radiation impinges onto a molecular clump a PDR is formed on its outer layer. At low FUV-intensities the [C II] 158 μm emission is a strong function of the FUV-field, since it maintains an equilibrium in C + h$\nu \rightarrow$ C$^+$ + e$^-$ and CO + h$\nu \rightarrow$ C + O. Thus, C$^+$ column densities depend strongly on the FUV-radiation field χ in the PDR. Moreover, [C II] cooling is also a function of χ owing to the gas temperature. The emission is, however, expected to be faint at $\chi \sim \chi_0$, where $\chi_0 = 2.0\times10^{-4}$ erg s^{-1}cm^{-2}sr^{-1} (Draine 1978). Therefore, appropriate spectrometers on board the Kuiper Airborne Observatory could not detect such emission easily due to the large thermal background. It has been discovered to date only from the high-latitude molecular clouds in Ursa Major through a rocket-borne observation (Matsuhara et al. 1997).

In order to test the FUV-field in the vicinity of L1457 we performed [C II] 158 μm and [O I] 63 μm observations with the Infrared Space Observatory (ISO). The [C II] together with previous CO and [C I] 492 GHz observations were also utilized as tracers to constrain the mass and density of the molecular clumps.

2. Observations

On 1997 September 2, we observed L1457 (MBM 12) in the LWS02 mode of the LWS (Clegg et al. 1996) on board ISO. The LWS Observer's Manual contains a detailed description of this mode. The data were taken along two cuts with 10 positions each across a molecular clump (see Fig. 1) observed at CO(1–0) (Zimmermann et al. 1990) and in the vicinity of the positions CO03 and 01 (Pound et al. 1990). The spacing between the two cuts and the individual positions on a cut is 3$'$. ISO's beam size is 80$''$ (FWHM). The cuts are oriented at a position angle (measured East of North) of 135°. The two zero positions are at $\alpha = 2^h\ 52^m\ 53\overset{s}{.}9$, δ = +19° 24$'$ 37$''$ and $\alpha = 2^h\ 52^m\ 44\overset{s}{.}8$, δ = +19° 22$'$ 29$''$ (1950). The target dedicated time was 2297 s for every fine-structure line and every spectrum was scanned 7 times. Reduction was carried out using standard Off Line Processing v6.11 routines. We used the ISAP[1] package v1.3 for further data reduction.

3. Origin of the [C II] Line

The results of the [C II] 158 μm observations are presented in Fig. 2. The uncertainty in the observations is dominated by the present flux calibration uncertainty of about 30% for the LWS

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[1] 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.

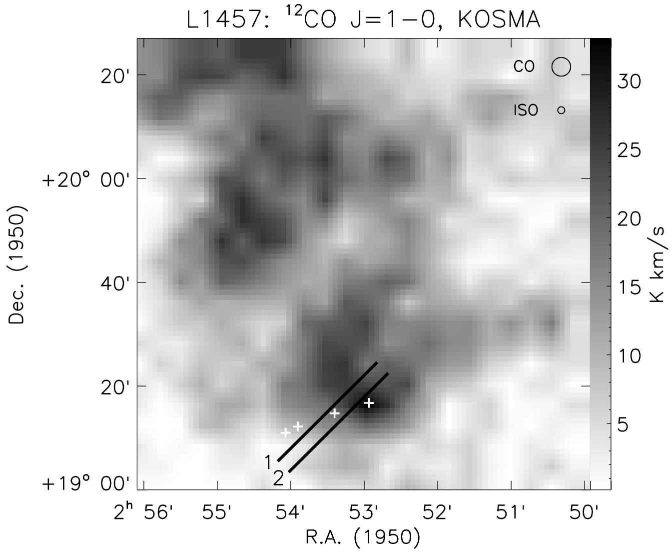

Fig. 1. The positions of the two cuts (labeled 1 and 2) observed at [C II] 158 and [O I] 63 μm overlaid on a CO (1–0) map (Zimmermann & Ungerechts 1990). The HPBW of the CO map is $3\overset{\prime}{.}6$. The CO map is sampled to $1'$. Indicated are the locations (4 crosses) at which the [C I] 492 GHz and ^{13}CO(2–1) lines were observed (Ingalls et al. 1994). They are labeled as CO03, 01, 10, and 11 from right to left (Pound et al. 1990).

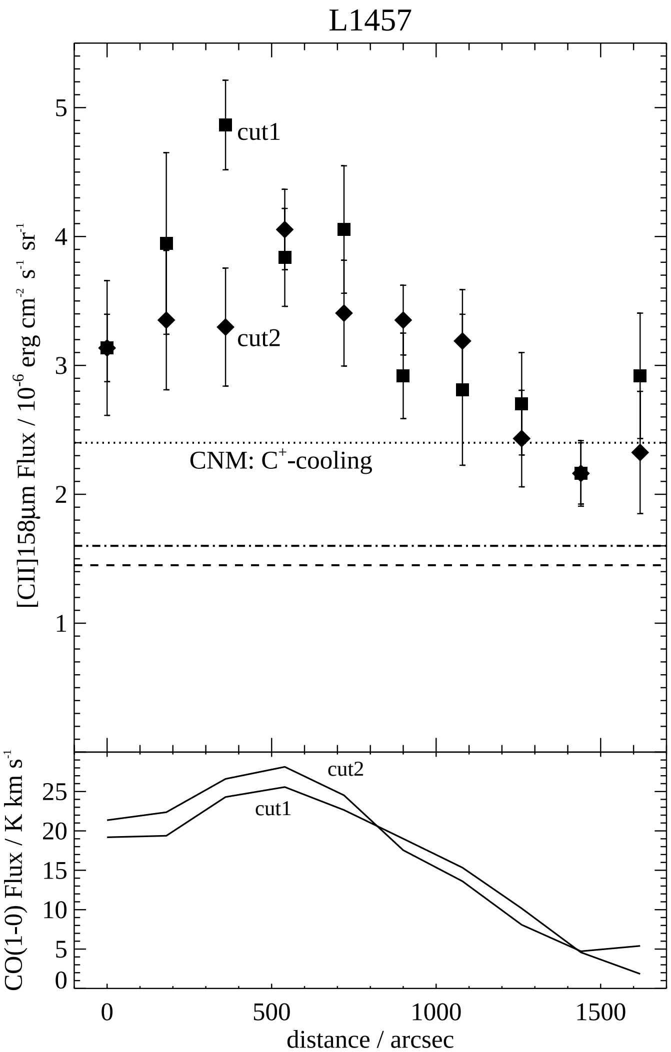

Fig. 2. [C II] 158 μm line fluxes for the positions along cut 1 and 2 (see Fig. 1). The zero positions are given in Sect. 2. The error bars are computed from the noise level on the continuum. The dotted line indicates the [C II] cooling of the CNM deduced from present data, whilst the other two lines (dashed and dash-dot) are from Matsuhara et al. (1997) and Dwek et al. (1997), respectively. The lower plot represents the CO(1–0) line fluxes along cut 1 and 2.

(Swinyard et al. 1996). Statistical uncertainties, computed from the noise level near the line, are generally smaller than this.

The [C II] 158 μm emission along the two cuts varies by a factor of $\sim$2 and peaks on or close to the densest CO(1–0) clump (see Figs. 1 and 2). The appropriate peak values are $I_{158} = (3.9 - 4.9) \times 10^{-6}\,\mathrm{erg\,s^{-1}cm^{-2}sr^{-1}}$ for cut 2 and cut 1, respectively, whilst the minimum value is $I_{158}^{\mathrm{min}} \sim 2.4 \times 10^{-6}\,\mathrm{erg\,s^{-1}cm^{-2}sr^{-1}}$ at the eastermost ends of the cuts. At these positions the CO(1–0) emission has dropped to almost zero which implies the absence of molecular material. Since the [C II] 158 μm line flux is not zero, the emission originates from non-molecular gas. We argue it is due to the cooling of the diffuse atomic neutral hydrogen gas in the line of sight toward L1457.

3.1. C^+-cooling of the Cold Neutral Medium

Emission from the [C II] 158 μm line is thought to be the dominant cooling process for the cold neutral medium (CNM). The C^+-cooling of the diffuse ISM has been inferred from two observations. Dwek et al. (1997) and Matsuhara et al. (1997) deduced cooling rates of $\Lambda_{158} = 4\pi I_{158}/N(\mathrm{H I})$ of 1.45×10^{-26} and $1.32 \times 10^{-26}\,\mathrm{erg\,s^{-1}}$ H-atom^{-1} at high galactic latitude using COBE and rocket-borne observations, respectively. The latter authors detected also excess [C II] emission that originates from molecular MBM clouds.

H I observations indicate the L1457 complex is associated with about 50 $M_\odot$ of atomic hydrogen (Moriarty-Schieven et al. 1997). The column densities derived for the positions on the two cuts are $N(\mathrm{H I}) \sim 1.1 \times 10^{21}\,\mathrm{cm^{-2}}$ (Moriarty-Schieven, priv. comm. 1998), where the variation ($\sim$5%) along the two cuts was found to be negligible. Their beam size ($2'$) is roughly comparable with ISO's beam (see also Fig. 1). If we assume the [C II] emission from the easternmost parts of the cuts ($I_{158}^{\mathrm{min}} = 2.4 \times 10^{-6}\,\mathrm{erg\,s^{-1}cm^{-2}sr^{-1}}$) originates exclusively from non-molecular gas, we deduce a cooling efficiency of $\Lambda_{158} = 2.7 \times 10^{-26}\,\mathrm{erg\,s^{-1}}$ H-atom^{-1} (dotted line in Fig. 2) for the CNM. Its uncertainty is $\sim$40%. The cooling rates of Matsuhara et al. (1997) and Dwek et al. (1997) are smaller than ours by a factor of 2.

Utilizing the present value for the [C II] emission from the CNM, we can derive the atomic hydrogen density and temperature of the CNM (Table 1). We assumed a [C^+]/[H] ratio of 10^{-4} (Dwek et al. 1997) and a fractional ionization $x_e = 6 \times 10^{-4}$ (Kulkarni & Heiles 1987). The collision rates for C^+-H and

Table 1. Physical parameters of the CNM

$n_{\rm H}$ (cm^{-3})	$T_{\rm kin}$ (K)	N(O I) (10^{19} cm^{-2})
20	360	<0.022
30	145	<0.070
50	83	<0.20
100	54	<0.58
300	36	<2.1

C^+-e were adopted from Launay & Roueff (1977) and Hayes & Nussbaumer (1984), respectively, and the Einstein coefficient is from Nussbaumer & Storey (1981). Moriarty-Schieven et al. (1997) derive a density $n_{\rm H} \sim 300\,{\rm cm}^{-3}$ for the atomic hydrogen in the line of sight toward L1457 from the H I column density and the extent of the H I 21 cm emission. This infers a kinetic temperature $T_{\rm kin} = 36\,{\rm K}$ for the atomic hydrogen (Table 1) which is lower than that commonly adopted ($T_{\rm kin} \sim 100\,{\rm K}$) (Moriarty-Schieven et al. 1997).

No [O I] 63 μm emission was detected at any position and we infer an upper limit of $I_{63} < 8.1 \times 10^{-7}$ erg s^{-1}cm^{-2}sr^{-1}(3σ). The third column of Table 1 is the calculated O I column density deduced from this limit. The atomic data for [O I], Einstein coefficients and collision rates, were employed from Baluja & Zeippen (1988) and Launay & Roueff (1977), respectively. We emphasize that N(O I)$\lesssim 4.4 \times 10^{17}$ cm^{-2} if we assume [O]/[H]$\sim 4 \times 10^{-4}$. Hence, our [O I] observation puts a limit to $n_{\rm H} \gtrsim 30\,{\rm cm}^{-3}$. This observational limit is not good enough to constrain the density/temperature any further, since $n_{\rm H} \gtrsim 50\,{\rm cm}^{-3}$ (Moriarty-Schieven et al. 1997).

3.2. Excess C^+-emission from molecular gas

In addition to [C II] emission from the CNM we detected excess emission that shows a maximum on or close to the brightest CO(1–0) peak (see Figs. 1 and 2). In order to deduce the [C II] line flux that originates from the molecular gas the value for the [C II] cooling of the CNM (see Sect. 3.1) was subtracted from the observed emission. Hence, [C II] emission peaks at $I_{158} = (1.5 - 2.5) \times 10^{-6}$ erg s^{-1}cm^{-2}sr^{-1} for cut 2 and cut 1, respectively. We argue that this emission emanates from dense molecular clumps that are irradiated by the mean interstellar FUV-field.

In order to determine the physical parameters of the dense clumps we employed PDR models for spherical symmetric clumps (Störzer et al. 1996) with different densities, clump masses, and FUV-radiation fields and compared the computed line fluxes with those observed at [C II] 158 μm, [C I] 492 GHz, CO(1–0), ^{13}CO(1–0) and (2–1). The cosmic ray flux was set to $5 \times 10^{-17}\,{\rm s}^{-1}$. Table 2 summerizes the results for the best fit models. We ran models with $\chi = 0.5$, 1.0 and $2.0\chi_0$ to evalutate the sensitivity of the [C II] emission on the FUV-radiation and found the [C II] line flux to vary strongly upon χ. For $\chi = 0.5\chi_0$ the line flux turned out to be lower by more than a factor of 10 compared to that at $\chi = \chi_0$ and fails to explain the observations. The area filling factor of clumps in the beam Ω needed to match the [C II] observations is so large that the total mass required exceeds that deduced from ^{13}CO(1–0) observations. The PDR models also rule out clumps with average densities $<n_{\rm H}>$ in excess of 10^5 cm^{-3} because the ^{13}CO line fluxes are much higher than those observed, whilst the calculated [C II] emission is lower than observed. For $\chi \gtrsim 5\chi_0$ [C II] emission exceeds that observed by far.

As seen in Table 2 one layer of clumps is not sufficient to explain the observations. We need Ω $\sim$4 and 1.5 for the best fit models M=10^{-4} M$_\odot$ (χ=χ_0) and M=10^{-3} M$_\odot$ (χ=2χ_0) at $<n_{\rm H}>$=10^5 cm^{-3}, which implies a total mass of $\sim$ 0.6 and 0.48 M$_\odot$, respectively, within a diameter of 0.17 pc (9$'$.0). This is a factor of $\sim$3 lower than that deduced from ^{13}CO(1–0) observations (Pounds et al. 1990). We note that models with clump densities $<n_{\rm H}>$=10^5 cm^{-3} generally find a better match to the CO observations, whilst models with $<n_{\rm H}>$=10^4 cm^{-3} require usually smaller filling factors and seem to be more consistent with the [C I] 492 GHz observations. However, larger clump masses are required in order to match the CO observations.

We caution against multiplying the computed line fluxes by filling factors $\Omega > 1$ for cases in which the optical depth of a line for an individual clump is $\tau \gg 1$, e.g. for ^{12}CO. We should mention, however, that the observed line ^{13}CO(2–1) width for the clump CO03 is v(FWHM)$\sim$ 2.7 km s^{-1} (Ingalls et al. 1994), whilst our computations assumed 1.2 km s^{-1} for indivudual clumps. The observed line width may therefore be caused by a superposition of individual clumps lying at slightly different velocities and the line fluxes from a single clump may be simply multiplied by Ω.

The calculated [O I] 63 μm emission turned out $I_{63} \lesssim 5 \times 10^{-9}$ erg s^{-1}cm^{-2}sr^{-1} for all models owing to the low temperature of the molecular gas. This is about 2 orders of magnitude lower than our upper limit. [O I] 63 μm emission would have been detected in our spectra if the FUV-radiation field $\chi \gtrsim 15\chi_0$ for clumps with M=10^{-4} M$_\odot$ and $<n_{\rm H}>$=10^5 cm^{-3}, according to our PDR models.

3.3. Dust temperature and FIR Intensity

The dust temperatures deduced from 60 and 100 μm IRAS observations of L1457 were found to be $T_{60/100} = 26$ K and 30–35 K for the cloud core and the outer regions, respectively (Clemens & Leach 1989). The 100 μm maps (Corneliussen 1991) show the dust emssion is well correlated with that of CO(1–0). The 100 μm intensity is $\sim$31 MJy/sr on the CO(1–0) peak and $\sim$5 MJy/sr at the easternmost edges of the cuts. Combining the results we infer an energy density of the far-IR radiation field $\chi_{FIR} \sim 5\chi_0$ for the cloud core and $\chi_{FIR} \sim \chi_0$ for the edges if we assume the black body temperature $T_{60/100}$ and a λ^{-2} emissivity law for the dust. This is on the same order of the computed FUV-radiation field.

Table 2. Line fluxes predicted for a single clump using a PDR model of spherical symmetry

$\frac{\chi}{\chi_0}$	$<n_H>$ (cm^{-3})	clump mass $M_\odot$	[C II] 158 μm ($erg/cm^2/s/sr$)	CO(1–0) (K km/s)	^{13}CO(1–0) (K Km/s)	^{13}CO(2–1) (K km/s)	[C I]492 GHz (K km/s)	mass ⌀ 0.17 pc $M_\odot$
1	10^4	10^{-1}	9.8×10^{-7}	7.2	2.5	1.6	4.2	0.32
1	10^5	10^{-4}	5.1×10^{-7}	12.0	2.2	2.8	3.5	0.15
2	10^4	10^0	2.5×10^{-6}	12.0	5.2	3.7	5.8	0.72
2	10^5	10^{-3}	1.3×10^{-6}	17.3	4.4	5.5	5.3	0.32
	observed		$(1.5 - 2.5) \times 10^{-6}$	28[a]	7.7[b]	6.3[c] – 15[d]	4.7[c]	1.46[b]

[a] Zimmermann & Ungerechts (1990);
[b] Pound et al. (1990);
[c] Ingalls et al. (1994);
[d] Zimmermann (1993)

4. Discussion

We have observed the [C II] 158 μm fine-structure line along two cuts across a dense molecular clump of L1457. [C II] emission is detected at all positions. A fraction can be assigned to the cooling of the CNM. We deduced a cooling efficiency $\Lambda_{158} = 2.7 \times 10^{-26}$ erg s^{-1} H-atom^{-1}, consistent with previous measurements. Moreover, we find excess [C II] emission that arises from clumpy molecular gas with $<n_H>$=10^5 cm^{-3}. This is actually larger than that determined by Pound et al. (1990) by a factor of ∼10. Utilizing PDR models for spherical symmetric clumps we deduce an interstellar FUV-radiation field $\chi = (1-2)\chi_0$.

The PDR models that fit the observations best are clumps with masses M=10^{-4} $M_\odot$ (χ=χ_0) and 10^{-3} $M_\odot$ (χ=2χ_0). Their sizes are about 0.0044 and 0.0095 pc, corresponding to 14″ and 30″. The average molecular column densities of such clumps are $N(H_2) = 4.4 \times 10^{20}$ and 9.7×10^{20} cm^{-2}, respectively, somewhat smaller than those deduced from observations of clump CO03 (Pound et al. 1990, Ingalls et al. 1994).

Ingalls et al. (1994) revealed a clumpiness in their ^{13}CO(2–1) maps that continues down to scales of 30″, whilst Zimmermann (1993; see also Kramer et al. 1998) reached a spatial resolution of 12″ and found substructures down to masses $\sim 6 \times 10^{-5}$ $M_\odot$ (0.0086 pc). If clumps are indeed this small ^{13}CO observations favor the evidence of high density clumps n_H∼10^5 cm^{-3} owing to the smaller clump sizes required in our PDR model computations. We have further evidence that the molecular gas of L1457 consists mainly of clumps of small masses. Kramer et al. (1998) exhibited that the clump mass spectrum for L1457 is compatible with a power law, $dN/dM \propto M^{-1.77}$, in the mass range $2 \times 10^{-4} - 0.2$ $M_\odot$ when a Gaussian clump decomposition algorithm is employed on CO maps.

It turns out that PDR model computations at lower densities $<n_H>$=10^4 cm^{-3} do not fit the CO observations very well, whereas the computed [C I] 492 GHz emission generally matches better at this density. Models with $<n_H>$=10^4 cm^{-3}, however, require larger clump masses and their sizes are 0.095 (5.′0) and 0.20 pc (10.′6) for M=10^{-1} $M_\odot$ (χ=χ_0) and 10^0 $M_\odot$ (χ=2χ_0), even much larger than ISO's beam size. This is also not consistent with high resolution CO observations (see above).

No [O I] 63 μm emission was detected in the molecular gas of L1457. This may demonstrate the absence of warm gas that would be present in the vicinity of commencing star-formation.

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