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Letter to the Editor

CO and CI observations of shock-excited gas in IC 443C

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Abstract. The blast-wave at the edge of the supernova remnant IC443 is colliding with nearby quiescent gas. In this paper a multi-transition study of CO $J = 1 - 0 \rightarrow J = 4 - 3$ is presented of one of these clouds, IC443C, and the detection of atomic carbon, *CI*, reported. The CO is optically thin with $T_{ex} \sim$ 45K, a *measured* isotopic ratio [CO]/[^{13}CO] = 80, and $N(CO) \sim$ 2 - 4 10^{17} cm^{-2}. Atomic carbon emission was detected *for the first time in shocked gas* only towards the IC443C *C*-shocked region, with an abundance ratio [*CI*]/[CO] $\sim$ 1.3 - 2.9. *CI* is overabundant by $\sim$ one order of magnitude compared with quiescent molecular cloud cores, suggesting that shock(s), or an enhanced cosmic ray flux density, has increased the [*CI*]/[CO] ratio. A narrow CO absorption line towards the shocked region IC443G has $T_{ex} \sim$ 13-18K, and $n_{H_2} \sim$ 2-3 10^3 cm^{-3}, which may be typical of conditions in the pre-shock gas.

Key words: interstellar medium: abundances - clouds - IC443

1. Introduction

The south-eastern edge of the blast-wave of the supernova remnant IC443 is colliding with several nearby molecular clouds, fragmenting, compressing, heating, and accelerating the gas to high velocities (DeNoyer 1979, White *et al.* 1987, Turner & Lubowich 1991, Wang & Scoville 1992 (hereafter WS92) and Tauber *et al.* 1993). This shocked material emits strongly in the near-IR lines of H_2 (Burton *et al.* 1990) and shock excited [*OI*] at 63μm. The H_2 luminosity of > 2000 L$_\odot$, the ratio of the H_2 2-1/1-0 S(1) lines and the lack of strong X-ray or ultraviolet flux point to the importance of a mixture of fast *J*- and slower *C*-type shocks in exciting the gas. One region showing asymmetric molecular line spectra is IC443C (White *et al.* 1987 and WS92), which contains several highly excited regions; (IC443C1) at the leading edge of the clump which is experiencing a *J*-shock from the high velocity flow from the expanding SNR, and (IC443C2) a slower *C*-shocked region on the clump's opposite side resulting from its coalescing with nearby quiescent molecular gas, caused by its ram-pressure driven acceleration. The chemistry of this region is complex, and a good site to test shock chemistry models, although there is little evidence that shocks have affected the abundances significantly (van Dishoeck *et al.* 1993). In this study, IC443C was observed in the CO $J = 2 - 1$, $J = 3 - 2$ and $J = 4 - 3$ lines, and the ^{3}P$_1$ - ^{3}P$_0$ transition of *CI* to examine conditions in the shocked gas.

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2. Instrumentation

The CO and *CI* observations were obtained using the James Clerk Maxwell Telescope (JCMT) in Hawaii, during October 1993. The receivers were SIS mixers used with a 920 MHz digital auto-correlation spectrometer. The tracking and pointing were better than 1 arc second. The temperature scales were calibrated in main-beam brightness temperature, T_{mb} units. The telescope parameters are listed in Table 1.

Table 1. *Telescope Parameters*

Species	Transition	Frequency GHz	η_{fss}	η_{mb}	Beam width ″
C^{18}O	$J = 2 - 1$	219.560	0.80	0.72	22
^{13}CO	$J = 2 - 1$	220.399	0.80	0.72	22
CO	$J = 2 - 1$	230.538	0.80	0.72	22
CO	$J = 3 - 2$	345.796	0.70	0.53	15
CO	$J = 4 - 3$	461.041	0.69	0.51	10.5
CI	^{3}P$_1$ - ^{3}P$_0$	492.161	0.64	0.49	10.2

3. The Data

The CO $J = 4-3$ line was mapped at 91 positions on a 5″ grid, running about 100 ″ along the ridge of IC443C. The distribution of the gas is shown in Figure 1. The CO maps show several peaks; IC443C1 and IC443C2 at offsets (+14,+5) and (0,0) arc seconds respectively (from WS92) dominate the -45 km s^{-1} and -25 km s^{-1} velocity intervals, and lie in a larger ridge with dimensions $\sim$ 40 x 15″ . A third CO clump, IC443C3, seen in the -25 →-5 km s^{-1} maps, lies ~20″ *NE* of IC443C2.

A small (ΔRA, ΔDec $\sim$ 120 x 40″ on an $\sim$ 15″ grid) CO $J = 3 - 2$ map, and $J = 2 - 1$ CO and ^{13}CO spectra were obtained. The CO spectra at IC443C1 and IC443C2 are shown in Figure 2. The CO line towards IC443C1 peaks at $\sim$ -45 km s^{-1} , and IC443C2 at $\sim$ -25 km s^{-1} . The $J = 2 - 1$ spectra (and $J = 1 - 0$ spectra - White *et al.* 1987), have lower antenna temperatures than the $J = 3 - 2$ or $J = 4 - 3$ lines; the ratio of peak T_{mb} values ($J = 1 - 0 \rightarrow J = 4 - 3$) are approximately 1:1.8:3.6:3.6 towards IC443C2 (at -25 km s^{-1}), and 1:2.0:3.6:4.6 towards IC443C1 (at -40 km s^{-1}). Thus the

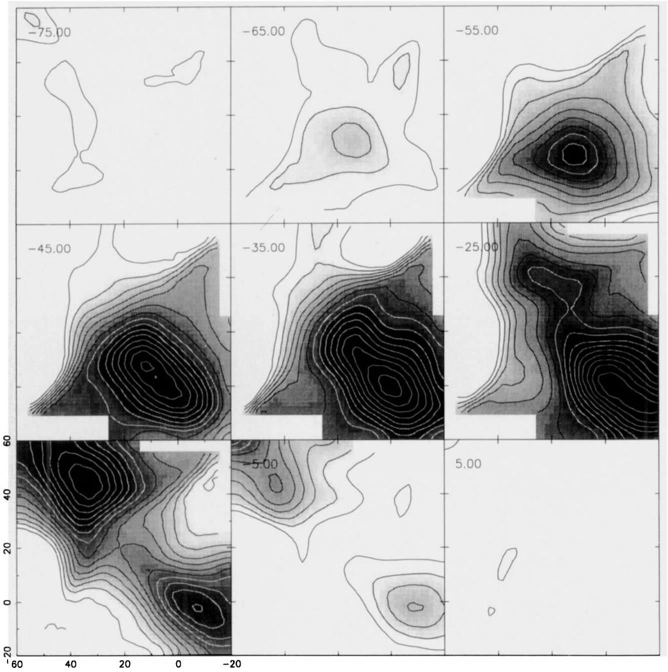

Fig. 1. *Channel maps for the CO $J = 4-3$ line binned in 5 km s^{-1} intervals. The contour levels are in units of 15 K km s^{-1}. The (0,0) point on the maps is at $\alpha = 6^h\ 14^m\ 41.25^s$ $\delta = +22^\circ 22' 42''$ (all positions quoted in this paper are in 1950 coordinates).*

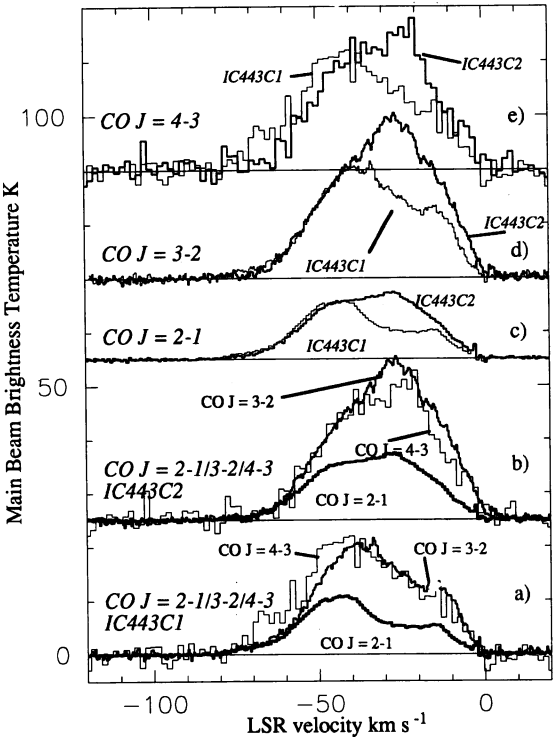

Fig. 2. *Overlay of the CO $J = 2-1$, $J = 3-2$ and $J = 4-3$ spectra. In Figure 2a and b) the CO $J = 2-1$ lines (darker) are super-imposed on the $J = 3-2$ (medium) lines at positions C1 and C2 respectively and the $J = 4-3$ (faint) lines, in c), d) and e) the CO lines for IC443C1 and C2 are superimposed - with C2 being the darker line. The $J = 4-3$ spectra were convolved to the same angular resolution as the $J = 3-2$ beam.*

CO antenna temperature increases with J-transition up to $J = 3-2$ at both positions, and stays roughly constant for the $J = 4-3$ line; this is a signature of optically thin gas, where the expected variation of brightness temperature;

$$\frac{T_{J+1}}{T_J} = \left(\frac{J+1}{J}\right)^2 e^{-\frac{5.54(J+1)}{T_{ex}}}$$

For T_{ex} ~45K, the ratios should be 1:3.1:5:5.5. Therefore the emission from IC443C1 is almost optically thin, but more opaque towards IC443C2. WS92 find similar results; the CO emission from IC443C2 staying ~ constant between the $J = 1-0$ and $J = 2-1$ lines, but from IC443C1 more than doubling. Correcting for coupling of a 15″ gaussian beam onto the IC443C1/C2 ridge (Ulich & Haas 1976), the $J = 3-2$ and $J = 4-3$ radiation temperatures would increase by ~ 50% to ~ 45K, in good agreement with the interferometric estimate of the radiation temperature. The column density towards IC443C2 was estimated using an LVG model with a χ^2 minimisation technique to match the observed antenna temperatures, a best fit being obtained for $N(CO)$ / $\Delta v \sim 2\ 10^{16}$ cm^{-2} km^{-1} s for $T_{ex} = 45$K. Taking a line width, $\Delta v = 30$ km s^{-1} (see Figure 2), $N(CO)$ / $\Delta v \sim 6\ 10^{17}$ cm^{-2}, which is close to the WS92 estimate.

Spectra in the $J = 2-1$ CO and $C^{13}O$ transitions were taken towards both sources to measure the CO opacity, and in $C^{18}O$ at a point between IC443C1 and 2, as shown in Figure 3. The integrated ^{13}CO T_{mb} values are 4.4 and 5.8 K km s^{-1} with peaki T_{mb} values of 0.14 and 0.16 K respectively. The *measured* T_{mb} ratio between the CO and ^{13}CO at both positions is ~80, thus the CO emission is optically thin. Multiplying the ^{13}CO column densities by the isotopic ratios gives $N(CO) = 2.3\ 10^{17}$ cm^{-2} and 3.8 10 ^{17} cm^{-2} for IC443C1 and C2 respectively. $N(CO)$ towards IC443C2 agrees to within 60% either by fitting the optically thin CO line ratios with an LVG model, or by deriving an optically thin velocity integrated ^{13}CO column density and multiplying by the isotopic ratio. The upper limit to the $C^{18}O$ emission in a single spectrum centred between both sources was 0.053 K km s^{-1} integrated between 0 and -70 km s^{-1}. Assuming $T_{ex} = 45$K, [CO]/[$C^{18}O$] = 500 and allowing for coupling to the ridge seen in the $J = 4-3$ maps, the 1-σ upper limit to $N(CO) < 3\ 10^{17}$ cm^{-2} (derived from the $C^{18}O$ spectrum), consistent with the ^{13}CO result above, and ruling out the possibility of any significant selective enhancement of the $C^{18}O$ abundance.

The *CI* line was detected towards IC443C2 but not towards IC443C1. *This is the first detection of CI in shock-excited gas.* The spectrum towards IC443C2 is shown in Figure 3, and the line parameters are listed in Table 2. To estimate the *CI* column densities, IC443C2 and IC443C1 were assumed to have the same sizes as the compact CO clumps detected by WS92, and the integrated line strengths (or upper limits) have been divided by the coupling factors using coupling efficiencies (from the relationship given by Ulich & Haas 1976) of 0.45 and 0.39 respectively.

The CO column density towards IC443C1 is estimated to

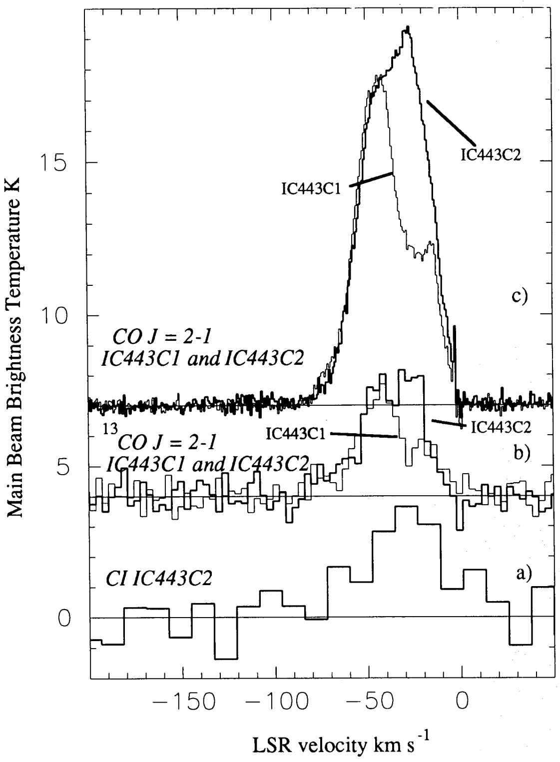

Fig. 3. *a) CI, b) ^{13}CO and c) CO $J = 2-1$ spectra towards IC443C1 (feint lines) at $\alpha = 6^h\ 14^m\ 41.25^s$ $\delta = +22°\ 22'\ 42''$ and IC443C2 (bolder lines) at $\alpha = 6^h\ 14^m\ 42.4^s$ $\delta = +22°\ 22'\ 47''$*

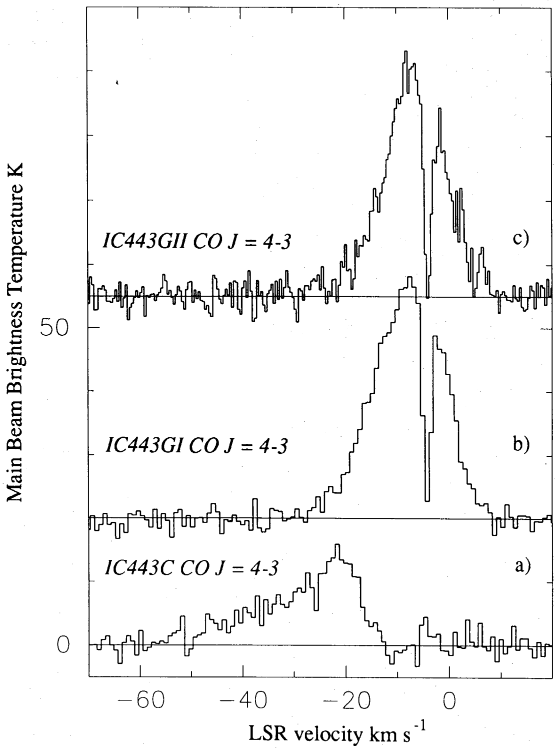

Fig. 4. *CO $J = 4-3$ spectra towards IC443C, GI and GII at van Dishoeck et al's (1993) positions a) $\alpha = 6^h\ 14^m\ 43.0^s$ $\delta = +22°\ 23'\ 25''$, b) $\alpha = 6^h\ 13^m\ 42.0^s$ $\delta = +22°\ 33'\ 40''$ and c) $\alpha = 6^h\ 13^m\ 40.4^s$ $\delta = +22°\ 32'\ 50''$*

Table 2. *CI detections*

Quantity	units	IC443C1	IC443C2
Velocity	km s^{-1}	0	-70→0
Linewidth	km s^{-1}	-	58
$\int$ T$_{mb}$ $(CI)dv$	K km s^{-1}	< 6.4	34.9
Flux	erg s^{-1} cm^{-2} sr^{-1}	<7.7 10^{-7}	4.2 10^{-6}
$N(CI)$ T=45K	cm^{-2}	<1.9 10^{17}	1.1 10^{18}
$N(CI)$ T=200K	cm^{-2}	<2.3 10^{17}	1.5 10^{18}

be ~ 2.3 10^{17} cm^{-2} (this work), and 4.4 10^{17} cm^{-2} by WS92; and ~ 3.8 10^{17} cm^{-2} towards IC443C2 compared with 8 10^{17} cm^{-2} by WS92. Taking the *CI* column densities from Table 2, the relative abundance ratio [*CI*]/[CO] has values of < 0.4 - 0.8 and ~ 1.3 - 2.9 towards IC443C1 and IC443C2 respectively; assuming $T_{kin} = 45$K - these values only increase by ~ 25 percent if $T_{kin} = 200$K. Thus the [*CI*]/[CO] abundance ratio towards IC443C2 is overabundant by $\geq$ 3.3 relative to IC443C1, and up to ten times greater than typical of dense molecular cloud cores (White & Padman 1991, Minchin *et al.* 1993).

CO $J = 4-3$ spectra towards other shocked regions; IC443C, G*I* and G*II* studied by van Dishoeck *et al.* (1993), are shown in Figure 4. These have similar lineshapes to the $J = 3-2$ data of van Dishoeck *et al.* (1993), although the $J = 2-1$ line is less intense than $J = 3-2$ and $J = 4-3$ lines towards IC443C. The $J = 4-3$ absorption feature (Figure 4) towards clump G at -4 km s^{-1} traces cooler foreground material, and is deeper than in the lower transition spectra, almost totally self-absorbing the background emission. An *LTE* model, modified to calculate the absorption of a background source by a foreground cloud (Greaves *et al.* 1992) was run to fit the increasing depth of the self-absorption feature with increasing *J*-transition. This model allows the excitation temperature, T_{ex} , of a linear molecule to be estimated from observations of two adjacent rotational transitions, with the relationship;

$$\frac{\int T_{r_1} dv}{\int T_{r_2} dv} = \frac{v_1}{v_2} \frac{J}{J+1} \frac{\left(e^{\frac{h\nu_1}{kT_{ex}}} - 1\right)}{\left(1 - e^{-\frac{h\nu_2}{kT_{ex}}}\right)} \frac{T_{back_1}}{T_{back_2}}$$

where $\int T_{r_1} dv$ and $\int T_{r_2} dv$ are the integrated absorption line intensities for adjacent transitions denoted by (1) ($J \rightarrow J$-1) and 2) (J+1 $\rightarrow J$), at frequencies ν_1 and ν_2 against a background source of temperature T_{back}, assuming both transitions have the same T_{ex} .

Using this relationship, the CO multi-transition data for the absorption line constrain T_{ex} of the absorbing material to the range 13-18K, and its density to be ~ 2-3 10^3 cm^{-3} , in agreement with the estimates of van Dishoeck *et al.* (1993); this is typical of gas in a quiescent dark cloud and probably represents pre-shock material lying along the line of sight and close to IC443.

4. Discussion

Burton *et al.* (1990) suggest that neither the photoelectric- or x-ray heating can explain the observed [*OI*] emission from IC443, leaving shocks and/or cosmic rays as the most likely source of excitation for the gas. The data can be explained if the gas is excited by several superposed shocks; slow shocks ($\sim$ 10 km s^{-1}) generating the [*OI*] emission, and faster ones ($\sim$ 40 km s^{-1}) the H_2 emission. These models predict *CI* line intensities $\sim 1\ 10^{-5}$ erg s^{-1} cm^{-2} sr^{-1} for fast or slow *C*-shocks, or $\sim 7\ 10^{-7}$ erg s^{-1} cm^{-2} sr^{-1} for a fast *J*-shock. The *CI* flux detected from IC443C2 lies between these two models, and is $\sim$ 5 times greater than the prediction for a fast *J*-shock. The detection of *CI* towards IC443C2, favors its excitation in a *C*-shocked region. The observed *CI* abundance can be best explained if the gas is excited by a slow *C*-shock.

There are other mechanisms that could explain the enhanced [*CI*]/[CO] abundance ratio. The common picture that has emerged to explain the *CI* emission of molecular clouds is of UV-photodissociation of the surfaces of dense clumps of gas. There is however insufficient UV radiation for photoionisation to be the dominant producer of the *CI* detected towards IC443C2. Recent chemical models (Pineau des Forêts *et al.* 1992, Flower *et al.* 1993, Schilke *et al.* 1993) using a revised H_3^+ recombination rate (Canosa *et al.* 1991) show that the C/CO ratio depends on the fractional ionisation of the gas. This suggests an alternative way of producing *CI* in an environment where there are cosmic rays, as is almost certainly the case in IC443.

Although the *CI* line intensities depend on CO photodissociation in PDRs, high [*CI*]/[CO] abundances can occur in the transition zone between high density gas, where the ion-neutral chemistry is driven by proton transfer with H_3^+ and lower density material where charge transfer with H^+ dominates. In the Pineau des Forêts *et al.* (1992) example, this transition occurs at gas densities, $n_{H_2} \sim 5500$ cm^{-3} assuming a cosmic ray ionisation rate $\zeta = 10^{-17}$ s^{-1}; higher values of ζ resulting in the transition zone occurring at higher densities. It is likely that cosmic rays produced in the original supernova explosion are confined within the boundaries of IC443's expanding shell, and lead to higher ionisation rates (than in our ISM). Models of the chemistry in a cloud where $\zeta \sim 300$ times that of the interstellar medium, predict [*CI*]/[CO] ratios as large as 0.4 (Schilke *et al.* 1993). Since the transition zone occurs at higher densities for large ζ, more of the material in a cloud is able to emit *CI* radiation - increasing the observed [*CI*]/[CO] ratio. In the absence of a strong UV field (see earlier discussion), a mechanism such as this would seem a plausible explanation for the *CI* abundance estimated towards IC443C1. Other potential mechanisms including the erosion of grains or PAH's in shocks, and chemical mixing between the different phases of shielded / unshielded and shocked / unshocked material, offer ways of enhancing the ration, but are much less well theoretically understood.

5. Conclusions

a) The CO emission from IC443C is optically thin, with a ratio [CO]/[^{13}CO] = 80; close to the terrestrial isotope ratio. The column densities towards IC443C1 and C2 agree within a factor of two using either the optically thin integrated emission of LVG modelling of the $J = 1-0 \rightarrow J = 4-3$ CO line ratios. There is no selective enhancement of the C^{18}O abundance $\geq$ 50 percent. The value of the CO excitation temperature is $\sim$ 45K, and the column densities towards IC443C1 and IC443C2 are = 2.3 10^{17} cm^{-2} and 3.8 10^{17} cm^{-2} respectively.

b) Atomic carbon emission is detected in the *C*-shocked gas of IC443C2, but not in the *J*-shocked region IC443C1. The abundance ratio [*CI*]/[CO] is < 0.4 - 0.8 and $\sim$ 1.3 - 2.9 towards IC443C1 and IC443C2 respectively, hence *CI* emission is overabundant by an order of magnitude in IC443C2 relative to that of quiescent cloud cores, suggesting that shock(s), or an enhanced cosmic ray flux density has been important in increasing the [*CI*]/[CO] ratio.

c) A narrow line seen in absorption against the shocked region IC443G is found to be typical of gas in a quiescent molecular cloud, with $T_{ex} \sim$ 13-18K, and a gas density $\sim$ 2-3 10^3 cm^{-3}, and is probably illustrative of conditions in the pre-shock material surrounding IC443.

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