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Letter to the Editor

CO and C I maps of the starburst galaxy M 82

G.J. White[1], B. Ellison[2], S. Claude[2], W.R.F. Dent[3], and D.N. Matheson[2]

[1] Department of Physics, Queen Mary and Westfield College, University of London,
Mile End Road, London E1 4NS, United Kingdom
[2] Space Science Department, The Rutherford Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom
[3] Joint Astronomy Centre, 660 N.A'Ohoku Place, University Park, Hilo, Hawaii 96720, USA

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Abstract. The first map of an external galaxy in the $^3P_1$ – $^3P_0$ fine-structure line of atomic carbon (*CI*) is presented towards the nucleus of the starburster M82, and compared with the distribution of the CO $J = 4-3$ molecular emission. The *CI* traces features that are seen in lower transition CO maps, and shows that *CI* and the CO are well mixed and have similar spatial distributions. There are small differences between the CO $J = 4-3$ line and lower transition CO data towards the NE part of the molecular ring, where the emission is less prominent. The abundance ratio [*CI*]/[CO] across M82 is very high, with an average value ~ 0.5 across most of the nucleus, a factor at least 5 times that which is typical of dense molecular cloud cores seen in our own Galaxy. This means that on average, *CI* is overabundant towards M82. This result can be explained using models which provide enhancements to the *CI* abundance above normal Interstellar Medium values, a result of a greater cosmic ray flux in M82, or where there is substantial mixing of the gas.

Key words: Galaxies: atomic & molecular abundances - CO and CI - M82

1. Introduction

M82 is a relatively nearby (3.25 Mpc) and well-studied starburst galaxy (see Carlstrom & Kronberg 1991 for a recent review), which has been mapped in a variety of molecular line species by many workers including Nakai *et al.* (1987), Lo *et al.* (1987), Carlstrom (1988), Baan *et al.* (1990), Tilanus *et al.* (1991), Wild *et al.* (1992) Brouillet & Schilke (1993) and Güsten *et al.* (1993). The nucleus is straddled by a rotating molecular ring that extends over $\sim$ 700 x 200 pc, and contains $\geq 6\ 10^7$ $M_\odot$ of molecular gas. The chemical and thermal structure in M82's interstellar medium are strongly influenced by the conditions in the central starburst, which include a high UV field ($\sim 10^4$ times greater than in our Interstellar Medium), and an enhanced cosmic ray flux which are a consequence of prodigious OB star formation and the high supernova rate. Multi-transition molecular line studies have shown that M82 contains a substantial amount of warm, dense, neutral gas (temperatures $\sim$ 50 - 60K and $n_{H_2} \sim 10^5$ cm^{-3}), interspersed with cooler material ($\sim$ 20K and $n_{H_2} \sim 10^3$ cm^{-3}) and hot shocked atomic gas (Wolfire *et al.* 1990, Lester *et al.* 1990). The atomic carbon line has been detected towards M82 at five positions by Schilke *et al.* (1993), who show *CI* is overabundant compared to the emission of our own Galaxy. In the present study, the relative distributions of the molecular and atomic gas in M82 are reported using the CO $J = 4-3$ rotational emission line and the $^3P_1$ – $^3P_0$ *CI* fine structure line, and used to study the implications for the chemistry, ionisation and thermal properties of the gas.

2. Instrumentation

The observations were made with the 15m James Clerk Maxwell Telescope (*JCMT*) during commissioning of a new 450 - 510 GHz receiver in May, August and October 1993. The receiver used a lead alloy SIS junction, with a single-sideband mixer noise temperature of $\sim$ 200K (Ellison *et al.* 1993) and T_{sys} which varied between 930 and 3000K over the frequency range during the observations, depending on the atmospheric transmission. The spectra were calibrated in units of main beam brightness temperature, T_{mb} , correcting for sideband gains, atmospheric emission in both sidebands, and the telescope efficiency. The surface accuracy of the *JCMT* was $\sim$ 30μm rms, with values of the forward scattering and spillover efficiency, $\eta_{fss} = 0.67 \pm 0.05$, and the main beam efficiency, $\eta_{mb} = 0.43 \pm 0.05$ at the CO $J = 4-3$ and *CI* frequencies. The data were processed with a 500 MHz AOS spectrometer, and 920 MHz digital auto correlator. The beamsize at the CO $J = 4-3$ (461.0408 GHz) and *CI* (492.1603 GHz) frequencies was 11.3 and 10.2$''$ respectively, and the absolute pointing of the maps was good to $\sim 3''$ *rms*. The spectra were obtained by beam-switching with a chopping secondary to a reference position 180$''$ north of the adopted map centre (0,0) at $\alpha = 9^h\ 51^m\ 44.0^s$ $\delta = +69°55'\ 03''$.

3. The Data

A grid of fifty seven CO $J = 4-3$ and forty five *CI* spectra were observed towards M82, sampled at positions on a 5$''$ grid.

The integrated CO $J = 4-3$ map (Figure 1a) has a single peak located at the offset position (-6$''$, -5$''$), close to the peaks at 2.2, 100 and 450μm (Dietz *et al.* 1989, Joy *et al.* 1987, Smith *et al.* 1990), and those seen in the CO $J = 3-2$ (Tilanus *et al.*

Send offprint requests to: Dr Glenn White

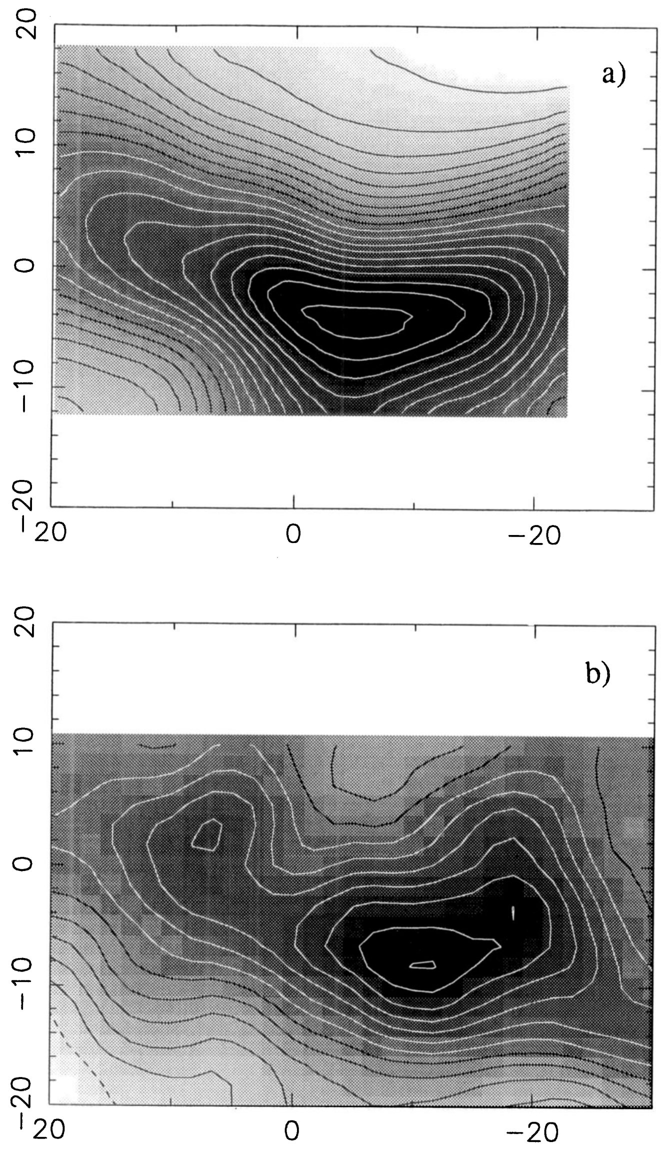


Fig. 1. *a) CO $J = 4 - 3$ map towards M82, integrated over the velocity range 50 - 350 km s^{-1}, with contours at 25 K km s^{-1} intervals, and the first white contour at 250 K km s^{-1}, b) integrated CI $^3P_1$ - $^3P_0$ map for the same velocity range, with contours at 15 K km s^{-1} intervals, and the first white contour at 90 K km s^{-1}.*

1991) and $J = 2 - 1$ CO and ^{13}CO lines (Loiseau *et al.* 1988, 1990). The CO $J = 4 - 3$ map is extended to the NE of the map centre, resembling the 450μm map of Smith *et al.* (1990). A second CO peak is visible in lower transition CO maps (Lo *et al.* 1987), although it is much less prominent in the $J = 4 - 3$ transition. The 450μm maximum has been suggested to lie at a column density peak on the inner edge of the molecular ring (Nakai al 1987, Smith *et al.* 1990), and to have a temperature $\sim$ 45 K. This agrees with the CO excitation temperature, $T_{ex} \sim$ 50K, deduced for the warm component of the gas in the central regions of the nucleus (Güsten *et al.* 1993).

The *CI* map (Figure 1b) is double peaked, showing a similar structure to other tracers of material in the molecular ring; the positions of the maxima agreeing closely with peaks seen in the CS map of Baan *et al.* (1990), and lower transition CO maps.

The first measurements of CO towards M82 suggested the CO was optically thin; the CO $J = 2 - 1$ line being stronger than the $J = 1 - 0$ line. Further measurements which included observations of rarer isotopomers and the $J = 6 - 5$ CO line, showed that the gas was in fact opaque in the lower rotational transitions, and could be modelled with a multi-component model with a cool component of the gas having $T_{kin} \sim$ 20-30 K and $n_{H_2} \sim 10^3$ cm^{-3} , and warmer material with $T_{kin} \sim$ 50 K and $n_{H_2} \sim 10^5$ cm^{-3} (Wild *et al.* 1992, Güsten *et al.* 1993), with beam averaged column densities $N(CO) \sim 5\ 10^{18}$ cm^{-2} . Due to the finite opacity of the CO lines, the lower rotational levels are therefore not good tracers of the mass distribution in M82. In Figure 2, a composite diagram showing the integrated CO intensity variation along the major axis of M82 in the various CO rotational transitions, *CI* and other tracers of the material in M82.

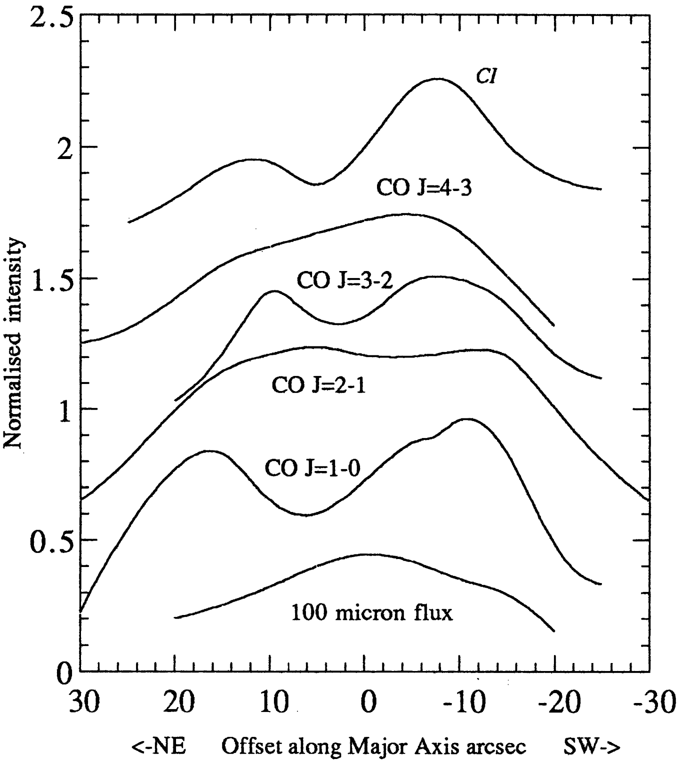


Fig. 2. *Relative variation of the integrated CO line strength along the major axis of M82 for the CO $J = 1 - 0$ (Carlstrom 1989), $J = 2 - 1$ (Loiseau et al. 1990), $J = 3 - 2$ (Tilanus et al. 1991) and $J = 4 - 3$ (this work) data. Intensities are normalised to a peak intensity of 1.0, and offset by successive values of 0.25 units, with the exceptions of the 100μm strip (Joy et al. 1987) - which is normalised to a peak value of 0.5 with a base value of 0.0 , and the CI line normalised to a peak intensity of 1.0 and offset by 1.25 units.*

From Figure 2, the *CI* emission is similar to the double peaked structure seen in the CO $J = 1 - 0$ and $J = 3 - 2$ lines. The CO $J = 2 - 1$ and $J = 4 - 3$ lines do not show this double-lobed structure as clearly as the other CO transitions or the *CI*. The $J = 4 - 3$ line peaks between the SW lobe and the nucleus (see also the integrated CO map in Figure 1). It is not immediately clear why there are these differences between the CO strips. The similarity of the CO $J = 4 - 3$ distribution to the 100μm emission does however suggest that this transition traces denser and / or warmer material in the nucleus.

In Figure 3, channel maps for CO and *CI* integrated into 30 km s^{-1} intervals are shown.

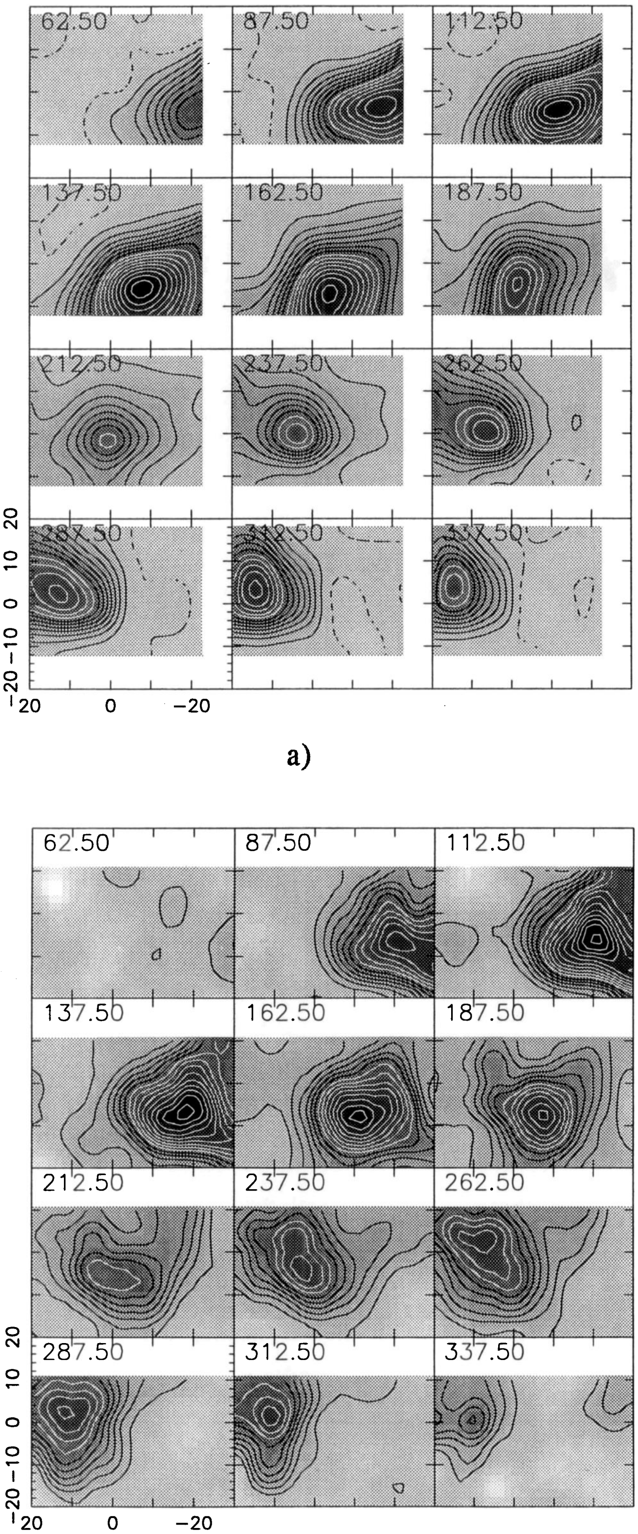
The distribution of the atomic and molecular gas in the *CI* and CO channel maps is very similar, showing the same structural variations with velocity. The main differences between the CO and *CI* maps occurring between ~ 100 and 200 km s^{-1} , where the *CI* peaks 5 - 10″ west of the CO peak, close to the centre of the HCN clump, *P3*, mapped by Brouillet & Schilke (1993). This is a complex region where the molecular clouds and star-formation indicators are clustered, and consequently the high UV-field may have increased the local photoionisation rate. The velocity distribution seen in both maps is also observed in high density tracers such as HCO$^+$, HCN and CS (Carlstrom 1988, Baan *et al.* 1990), suggesting that low and high density gas are co-spatial in their distributions. The relatively close agreement of the CO and *CI* in the two maps implies that the two species are well mixed, as seen towards Galactic molecular clouds.

The beam averaged abundance ratio [*CI*]/[CO] can be calculated for positions where there are CO column density estimates using the optically thin $J = 2-1$ C^{18}O line. Comparing the eight positions where *CI* spectra were obtained in common with the $J = 2-1$ C^{18}O spectra from Wild *et al.* (1992), the average value of [*CI*] / [CO] = 0.48 ±0.15, assuming an abundance ratio [CO]/[C^{18}O] = 500 and $T_{ex} = 45$K. At these positions the [*CI*]/[CO] ratio exceeds that typical of molecular clouds in our Galaxy (Keene *et al.* 1985, White & Padman 1991, Minchin *et al.* 1993) by a factor of at least 3 - 5. This agrees with the high values of this ratio reported by Schilke *et al.* (1993). If [CO]/[C^{18}O] is smaller than 500, as is the case towards the centre of our Galaxy, [*CI*]/[CO] will be even larger. Integrating over M82, the *average* value of *N(CI)* is 1.2 10^{18} cm^{-2} corresponding to an intensity *I(CI(609μm))* = 1 10^{-5} erg cm^{-2} s^{-1} sr^{-1}. By comparison, Wright *et al.* (1991) estimate *I(CI)* = 1.8 10^{-7} erg cm^{-2} s^{-1} sr^{-1}for the sum of the 609 and 370μm *CI* fine structure lines emitted by our own Galaxy, with ~ 65 percent of this in the shorter wavelength line.

Towards the centre of the nucleus (defined by position of the 2.2μm peak of Dietz et al 1989), the integrated emission in the CO $J = 4-3$ and *CI* lines, $\int T_{mb}\,dv = 202.5$ K km s^{-1} and 135.7 K km s^{-1} respectively. The observed peak and integrated intensities are similar to those observed in *CI* by Schilke *et al.* (1993). For $T_{ex} = 45$K, *N(CI)* = 1.9 10^{18} cm^{-2}. This can be compared with the CO column density of *N*(CO) = 5 10^{18} cm^{-2} (Güsten *et al.* 1993) to give [*CI*]/[CO] = 0.4. This agrees well the average ratio over the *whole* of M82. Therefore [*CI*]/[CO] is *not* enhanced in the centre *relative* to values at the positions furthest from the centre of the nucleus.

4. Discussion

The high value of [*CI*]/[CO] occurring over a large fraction of M82 implies a much higher relative abundance than in our Galaxy, confirming the general conclusions reached by Schilke *et al.* (1993). The *CI* intensities exceed the predicted fluxes in photodissociation region models such as those of Hollenbach *et al.* (1991) by up to an order of magnitude, but could be matched if there were several PDR's along any given line of sight. There are several other mechanisms which could explain the *CI* abundances. The common picture that has emerged



a)

b)

Fig. 3. *Channel maps for a) CO and b) CI towards M82. The integrated main beam brightness temperatures of the first white contours and the contour intervals are respectively a) 52.5 and 7.5 K km s^{-1} and b) 21.0 and 3.0 K km s^{-1}.*

to explain the *CI* emission observed towards Galactic molecular clouds is of UV photodissociation of the surfaces of dense clumps of gas. The apparently ubiquitous distribution of *CI* can be understood a consequence of time dependent chemistry on the surfaces of rotating molecular clumps (Monteiro 1991); the transfer of UV radiation scattered through a two-phase clumpy medium (Hobson & Padman 1993); or by multi-phase clumpy clouds (Meixner & Tielens 1993). The conditions in M82 would certainly be capable of sustaining the environment within which any of these models could operate.

Recent chemical models (Pineau des Forêts *et al.* 1992, Flower *et al.* 1993, Le Bourlot *et al.* 1993, Schilke *et al.* 1993) using a revised $H_3{}^+$ recombination rate (Canosa *et al.* 1991) show [*CI*]/[CO] also depends on the fractional ionisation of the gas. These models allow *CI* production in the presence of a strong cosmic ray flux or where shocks interact with the gas. 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^+ becomes more important. The largest *CI* column densities occur in gas with $n_{H_2} \sim 5500$ cm^{-3} , for a cosmic ray ionisation rate $\zeta = 10^{-17}$ s^{-1} (Pineau des Forêts *et al.* 1992); higher values of ζ resulting in the transition zone occurring at higher densities. It is possible to get high [*CI*]/[CO] ratios anywhere outside this transition zone, however the CO column densities may be lower as more of the carbon is driven into *CII*. Models of the chemistry in a cloud where $\zeta \sim 300$ times that of the interstellar medium, (similar to those believed to be present in M82 - Suchkov *et al.* 1993) predict [*CI*]/[CO] ratios as large as 0.4 (Schilke et al 1993). Since the transition zone occurs at higher densities for large ζ, a larger volume of the gas of a cloud is able to emit *CI* radiation - increasing the observed [*CI*]/[CO] ratio. The recent detection of *CI* towards the shocked material in a molecular cloud which is colliding with the blast-wave of the Galactic supernova remnant IC443 lends support to models where high abundances of *CI* could result from another mechanism than photo-ionisation (White 1993). Since both the UV field and the cosmic ray flux are stronger in M82 than our own Galaxy (Suchkov *et al.* 1993), the environment appears favorable for production of carbon by non-photo ionisation models.

An alternative route to produce the high [*CI*]/[CO] ratios is if there is significant turbulence in the molecular cloud ensemble, which would result in frequent clump collisions, allowing more of a clump's surface to be photo-ionised if it rotates on a timescale similar to the *CI* - CO reformation time (10^4 – 10^5 years (Monteiro 1991)). Another possibility is if a substantial amount of the observed *CI* column density is produced in the translucent gas surrounding clouds, where less of the C will be locked in CO (van Dishoeck & Black 1988).

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