OBSERVATIONS OF ATOMIC GAS IN PHOTODISSOCIATION REGIONS

GLENN J. WHITE
Department of Physics
Queen Mary & Westfield College
University of London
Mile End Road
London E1 4NS

RACHAEL PADMAN
Cavendish Laboratory
University of Cambridge
Madingley Road
Cambridge CB3 OHE

ABSTRACT. At the interface between an HII region and a molecular cloud, lies a neutral gas layer which is subject to both an intense radiation field, and to shocks arising from the expansion of the ionisation front of the HII region. The gas in these regions is highly excited, hot, and may be fairly dense. We present the first high resolution images of atomic carbon towards a sample of ionisation front sources. This study has relevance to our understanding of shock induced star formation, the formation and destruction of molecular species under extreme conditions, shock processes in the ISM, and the energy balance in molecular clouds.

1. Atomic Carbon

Carbon is the fourth most abundant element in the universe, and plays a major role in the chemistry of interstellar molecular clouds. Atomic carbon (CI) is formed when CO molecules are photo-dissociated in the interstellar ultraviolet (UV) field [$CO + h\nu \rightarrow C + O$]. It has an ionisation potential which is similar to the dissociation energy of CO, and thus CI in turn is rapidly photo-ionised. At the outside edges of molecular clouds, carbon should exist mainly in the ionised form (CII), in a narrow transition zone near their edges, be in atomic form (as CII recombines with electrons), and inside them be bound into CO molecules (as molecules form). At submillimetre wavelengths, CI has two fine structure transitions, which are efficiently excited by the conditions encountered in interstellar molecular clouds. We present the first high angular resolution maps of molecular clouds in the CI $^3P_1$ - $^3P_0$ line, towards the high mass star formation region Orion A, the externally illuminated cloud S140, the edge-on ionisation front M17, and the Galactic Centre.

The observations were obtained at the James Clerk Maxwell Telescope in Hawaii. A new dual-polarisation InSb detector (Padman et al *in preparation*) was used at a frequency of 492.1607 GHz ($\lambda \sim 609\ \mu m$). The high altitude site, new receiver and excellent efficiency of the telescope allow observations which have hitherto been impossible. A new mapping technique was used: the local oscillator frequency was held constant, and the telescope raster-scanned in azimuth, whilst simultaneously beam-switching in the scan direction using the nutating sub-reflector. Several such dual-beam maps of each source, with different parallactic angles and chopper throws to give good coverage in 2-D Fourier space, were processed jointly using a maximum entropy algorithm (ref 1) to give the final RA-Dec maps. Single point position-switched spectra were also taken at a number of positions in each source: these were used to verify that the emission was indeed zero near the edges of the maps, and to check the maps.

P. D. Singh (ed.), Astrochemistry of Cosmic Phenomena, 297–302.

From observations of Mars we find that the beam size is 9-arcseconds and the main beam efficiency is 0.39+/-.04: this efficiency is consistent with the effective surface error of ~34-microns (rms) deduced from 450-micron beam mapping of Mars, Jupiter and the moon, by R.Hills and J.Richer (*private communication*). We deduce from these beam maps that the error beam at 492 GHz should contain about 40 percent of the total power, and have a maximum amplitude ~2 percent that of the main beam, with a characteristic radius of ~50 arcseconds.

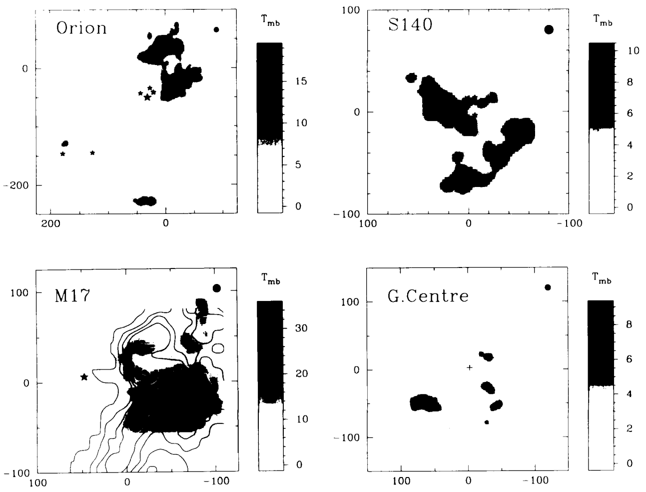
The MEM reconstruction process attempts to deconvolve the dual beam response function from the observed maps. Direct comparison of the dual-beam maps with the position-switched spectra shows that the former underestimate the total flux by up to 30 percent. This appears to be due to self-chopping of the extended error beam: the error beam was neglected in the MEM restoration because of memory constraints in the computer. The image of the northern part of Orion was re-processed to take the full error beam into account, using a much more computationally expensive algorithm: we find that the discrepancies with the single-point fluxes are reduced, but that otherwise the image is not qualitatively different from that presented in Figure 1a.

The Orion molecular cloud contains many indicators of on-going star-formation[2], including the ~ 50 $M_{\odot}$ pre-main sequence object, IRc2, which is surrounded by a dense rotating ring of gas. This is being eroded by the combined effects of radiation and an energetic molecular outflow which originates close to IRc2. IRc2 lies ~ 1 arc minute north-west of the well-known Trapezium star cluster, responsible for ionisation of surrounding gas to create the prominent optical nebula M42. This cluster also illuminates a dense molecular ridge (the 'Bright Bar') ~ 3 arc minutes south-east of IRc2, where the UV radiation intensity is ~ 10^5 times the average interstellar UV field, G_o ($G_o = 1.7 \times 10^{-3}$ erg s^{-1} cm^{-2}). The CI map obtained towards Orion is shown in Figure 1a.

In the north of the map, the CI appears as part of a clumpy broken cavity. The two most intense regions lie ~ 30 arc seconds (0.06 parsecs) north-east and south-west of IRc2, at the edges of the 'quiescent ridge', which contains several other star forming complexes. The CI intensity is weaker along the direction of the molecular outflow (south-east - north-west). While there is *general* agreement between the CI distribution and other tracers such as ^{13}CO or $C^{18}O$, any formal correlation is poor. CI traces the *edges* of the quiescent molecular ridge instead of following the distribution of other molecular species more closely. South-east of IRc2, the CI forms a narrow bar, containing several clumps embedded in diffuse emission, displaced back by ~ 30 arc seconds from the edge of the Orion HII region [3,4]. The northernmost clumps in the bar lie close to the positions of ionised knots, which resemble HH-objects [5].

Towards IRc2, the main beam brightness temperature, $T_{MB} = 16.6$ K, and the integrated emission is 79 K km s^{-1}. For an excitation temperature of 100K, N(CI) = 1.1×10^{18} cm^{-2}, and τ(CI) ~ 0.2 (see ref. 15 for details of CI abundance derivation). Assuming N(CO) = 1.6×10^{19} cm^{-2}(ref. 6), N(CI) / N(CO) = 0.07. At the strongest point on the Bright Bar, N(CI) / N(CO) = 1.22. The CI spectrum (Figure 2a) towards IRc2 is narrow ($\Delta V = 4.5$ km s^{-1}), showing no evidence of out-flowing molecular gas. Subtracting emission from the ambient cloud, the optically thin upper limit for the outflow gas N(CI) / N(CO) ~ 0.005 (assuming $T_{ex} = 100K$). Thus CI appears less abundant in the outflow gas than at nearby cloud positions, as suggested from previous large beam studies [7].

S140 is an active region containing a cluster of forming B stars, which appear as compact infrared sources in its core. A nearby (~2 parsecs) B0 star photo-dissociates the outer layers of the S140 cloud (UV field ~ 150 G_o), exciting a Hα emission nebula [8]. The CI map is shown in Figure 1b. This shows a



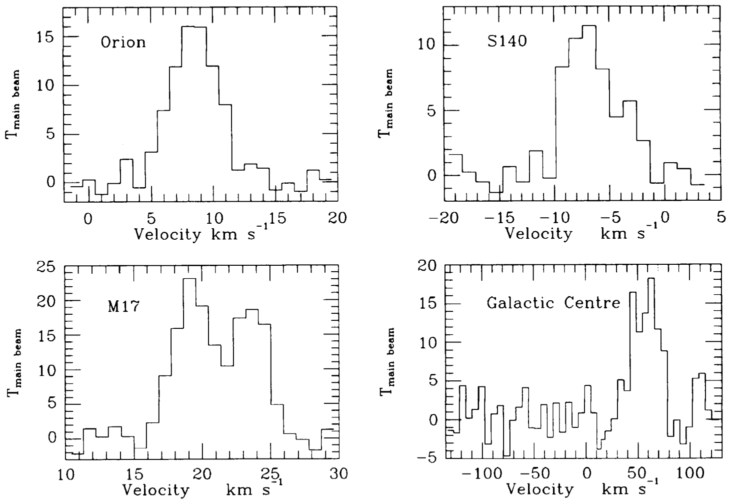


Figure 1

Figure 2

Figure 1 CI distribution towards the sources, obtained with a 1.3 km s^{-1} channel (half power width). The positions of infrared and some visible objects are indicated by stars. The centre positions and velocities of the maps are ; Orion:- R A (1950) 05^h 32^m 46.9^s Dec (1950) -05^0 24' 26" (+9 km s^{-1}) [the square and dot right of centre are IRc2 and BN respectively, the central four stars are the Trapezium Cluster, and the two at bottom are Θ^2 Orionis A and B], S140:- R A (1950) 22^h 17^m 42.0^s Dec +63^0 3' 45" (-8 km s^{-1}) [the stars show the positions of embedded B stars], M17:- R A (1950) 18^h 17^m 31.2^s Dec -16^0 13' 30" (+20 km s^{-1}) [contours of $C^{18}O$ temperature for the same velocity interval as the CI data are overlaid; the star is the position of a bright SAO star], Galactic Centre:- R A (1950) 17^h 42^m 29.5^s Dec -28^0 59' 20" (+50 km s^{-1}) [the Centre is marked with a cross]. The beam size is shown as a filled circle in the top left corner. The grey scale is in units of T_{mb}.

Figure 2 Position switched CI spectra towards the sources, at the positions; Orion:- R A (1950) 05^h 32^m 47.0^s -Dec (1950) -05^0 24' 23", S140:- R A (1950) 22^h 17^m 42.0^s Dec 63^0 3' 45", M17:- R A (1950) 18^h 17^m 29.9^s Dec -16^0 13' 00", Galactic Centre:- R A (1950) 17^h 42^m 27.2^s Dec -28^0 59' 53".

clumpy bar-like distribution at the front edge of the molecular cloud, adjacent to the ionisation front. There is good correlation between this CI bar, running from offsets (+20,-70) to (-60,-10), and a ridge of hot CO[8]. The star-forming core and density peak lie ~ 50" north-east of the CI bar. As shown in Figure 1b, the infrared sources are adjacent to a clumpy CI ridge deeper inside the cloud. The tendency for CI to avoid the regions of highest column density resembles behaviour seen in Orion. The spectrum towards this core is shown in Figure 2b. N(CI) / N(CO) = 0.19 at this position, and N(CI) / N(CO) = 2.8 at 30 arcseconds west and 45 arc seconds south, on the ionisation front.

The M17 complex is the archetypal edge-on ionisation front, lying next to an O-B star cluster, which heats and provides UV illumination (~ 2 x 10^5 G_o) of the cloud edge. In Figure 1c, contours of the J=2-1 $C^{18}O$ line for a velocity interval which matches the CI data (Stutzki - *private communication*) are overlaid on the CI distribution. The CI appears clumpy and fragmented, dropping off sharply (< 1 beamwidth) at the eastern edge, next to the ionisation front. The CI peaks show significant position offsets from the $C^{18}O$ peaks; CI emission is ***not*** enhanced in the regions of highest column density, or on the ionisation front of M17 (see also ref. 9). No significant velocity variation is seen across the edge of the cloud. A spectrum is shown in Figure 2c.

The inner 10 parsecs of our Galaxy contains a rotating neutral molecular ring, surrounding a 2 parsec radius ionised cavity. The inner-edge of this ring is excited by a strong UV field (~ 7 x 10^4 G_o), and hot, dense gas has been reported [10]. The CI distribution is shown in Figure 1d, and a spectrum in Figure 2d. The CI is concentrated into several clumpy groups lying ~ 2 - 4 parsecs from the Centre. As in the other sources, the CI peaks lie close, but not co-incident, to those of other molecular tracers [11]. The ring has a rotation velocity of ~ 100 km s^{-1} , so the CI map velocity was chosen to match a dominant velocity seen in the optically thin $C^{18}O$ line.

The observations reported here represent a major advance on earlier observations of CI [12,13] which showed that N(CI) / N(CO) varied from >10 in clouds having low extinction (A_v), to ~ 0.1 in cores where A_V ~ 100 magnitudes. This contrasted with chemical models[14,15] where carbon at molecular cloud edges is almost all in the form of CII, with a layer of CI between A_V ~ 3-8, and the transition between C and CO at A_v ~ 5 [16,17], the CII/CI/CO interface existing in a narrow range of hydrogen column densities between 4 x 10^{21} and 10^{22} cm^{-2}. However CI would rapidly (< 10^6 years) convert back to CO, and multi-component models [18,19], in which dense clumps are interspersed with a more tenuous inter-clump medium, were developed. The CI abundances produced are relatively insensitive to the external UV field, the CI forming narrow shells around clump cores. In S140, we may be seeing evidence of both processes - direct photo-dissociation of the cloud edge giving the bright CI rim, and then deeper into the cloud penetration of UV photons through the interclump medium.The present observations show that;

2. Conclusions

a) Molecular clouds adjacent to ionization fronts often show strong CI emission from a thin surface layer. In S140 and the Orion bright bar photodissociation of CO leads to peak values of N(CI)/N(CO) greater than 1, even though this CI layer is only marginally resolved in our 9-arcsecond beam. Our observations also confirm previous conclusions based on lower-resolution data that CI is widely distributed (with less intensity) throughout molecular clouds, remaining abundant (N(CI)/N(CO) typically ~ 0.1) up to several parsecs away from the UV-illuminated edges. CI is not detected in the IRc2 outflow, where we find that N(CI)/N(CO) < .005, appearing to indicate that shock dissociation of CO in the vicinity of outflows is *not* a major source of CI.

b) In non-uniform molecular clouds such as M17, the CI peaks on the edges of the clumps revealed by column density tracers such as $C^{18}O$, and apparently avoids the densest regions, presumably because the UV radiation is too highly attenuated. Since the CI emission is distributed throughout the molecular cloud core, this is *direct* evidence for low filling-factor, high density-contrast clumping, as previously deduced from molecular line and lower resolution CI observations.

Acknowledgements

We acknowledge the work of many people at Cambridge University, Queen Mary College, London and the JACH, Hawaii who contibuted towards the instrumentation used in this work. The JCMT is operated by the Royal Observatory Edinburgh, on behalf of the SERC, the Netherlands Organisation for Pure Research, and the National Research Council of Canada.

References

1.Richer, J. *MNRAS in press* (1991)
2.Genzel, R and Stutzki, J, *Annual Rev. of Astronomy & Astrophysics*, **27**, 41 (1989)
3.Martin, A.H.M. and Gull, S.F., *M.Not.R.Astr.Soc.* **175**, 235 (1976).
4.Yusef-Zadeh, F., 1990, *Astrophys. J.* **361**, L19.
5.Taylor, K. and Münch, G. *Astr. Astrophys.* **70**,359 (1978).
6.Wilson, T.L., Serabyn, E., Henkel, C. and Walmsley, C.M. *Astr. Astrophys.* **158**, L1 (1986).
7.Hayashi, M., Omodaka, T., Hasegawa, T. and Suzuki, S. *Astrophys. J.* **288**, 170 (1985).
8.Beichman, C., Phillips, T.G., Wootten, H.A & Frerking, M.A. *Regions of Recent Star Formation, edited by R.Roger and P Dewdney*, D. Reidel Press (1982)
9.Stutzki, J. & Gusten, R. *Astrophys.J.* **356**, 513 (1990).
10.Harris, A.I., Jaffe, D.T., Silber, M. and Genzel, R. *Astrophys. J. Lett.* **294**, L93 (1985).
11.Mezger, P.G., Wink, J.E. and Zylka, R. Astr.Astrophys. **228**, 95 (1990).
12.Phillips, T.G., Huggins, P.J., Kuiper, T.B. and Miller, R.E. *Astrophys.J.* **238**, L103 (1980).
13.Phillips, T.G. & Huggins, P.J. *Astrophys. J.* **251**, 533 (1981).
14.Tielens, A. H. M. and Hollenbach, D. *Astrophys.J.* **291**,747, (1985b).
15.van Dishoeck, E.F. and Black, J.H. *Astrophys.J.* **334**, 771 (1988).
16.Tielens, A. H. M. and Hollenbach, D. *Astrophys.J.* **291**,722, (1985a).
17.Keene, J., Blake, G., Phillips, T.G., Huggins, P. & Beichman, C. *Astrophys.J.* **299**, 967 (1986).
18.Monteiro, T.S. *Astr.Astrophys.* **241**, L5 (1991).
19.Stutzki, J., Stacey, G.J., Genzel, R., Harris, A., Jaffe, D.T. & Lugten, J.B. *Astrphys. J.* **332**, 379 (1988)

QUESTIONS AND ANSWERS

D.A.Williams: Can you say what evidence there is of dynamics in these interfaces?

G.White: Sensitive spectra taken in strips running perpendicular to the interface zones are able to measure the expansion velocity of the HII region into the surrounding neutral gas, and hence estimate the incident shock speed. M 17 is a good example where the ionized gas impacting the M17 molecular cloud at $\sim 11\, km/s$, forcing gas to stream outwards along the line of sight. Close to interfaces, the material is observed to be highly fragmented, both spatially and in velocity space. One would hope to be able to examine whether turbulent mixing, systematic streaming of clump/interclump gas and clump/clump collisions are occuring. However we are really at the limit of what single dish telescopes can achieve in angular resolution, and the interferometers are for better suited to trying to examine these processes. One recent experiment which has set out to search for a dynamical signature of ambipolar diffusion - where ions and neutrals can achieve a relative drift velocity of a few km/s has provided a tentative suggestion that some small effect was detected - however the authors again remark that it is only when good higher resolution maps (specifically 2" resolution at M 17) that this can be unambiguously resolved.

E.vanDishoeck: There appears to be a lack of CI in M 17 close to the ionisation front. Could you comment on this?

G.White: Rachel Padman and I were extremely surprised when we were at the JCMT making these observations not to see limb brightening across M 17. We spent a lot os time obtaining sensitive CI spectra across the interface region to really confirm this, and there is clearly no intensity enhancement, no any significant velocity shift across the interface. These results are not off the telescope, and we need to model this further. The two differences between M 17 and S 140 (where a strong CI enhancement is seen) is that the external UV illumination is 2 orders of magnitude greater, and that the neutral density and clumpy structure is much greater. Maybe the transition in M 17 is so abrupt that any CI transition zone is severely beam diluted by our 9 arc second beam.

A.E.Glassgold: In addition to the beautiful observation, I was pleased to hear your critical comments about the difficulty of measuring abundances in these regions. I wonder if you could comment on your thermometry and particularly how the temperature is determined at relatively low temperatures ~100 K.

G.White: We have been fairly successful in using multi-transition CO data to thermometrically probe these interface zones. However the molecular ionised zone interfaces are usually spatially unresolved with 10 arc second beams, so we shall don't have the ability to probe the interesting regions at the neutral/HII boundaries where the gas temperature decouples from the dust. The molecule CH_3C_2H has an easy to observe k-split series across several of the ionisation fronts we have measured and can provide an alternative estimate of the rotational temperature to go with the CO estimates (the more commonly used temperature estimator CH_3CN which has similar k-splitting has been unsuccessful searched for across several interface regions). However these more complex molecular species are less robust than CO, and may give a misleading comparison under some circumstances. On your comments about the CI observations, I must thank my collaborators R.Padman and M.Griffin and others workers at Queen Mary College, Cambridge University and the Joint Astronomy Centre, Hilo, without whom these data would not have been obtained.

R.Rubin: With spatial resolutions achievable how (better than $\sim 9''$), it may be necessary to consider models of the PDR that are not plane parallel when comparing with observations. This may be important for example for properly looking for species stratification. The boundary of HII region/PDR interface will vary with location along the line of sight. The boundary will be curved toward the exciting star(s).

G.White: All of the high angular resolution studies of interface regions have shown that reality lies far away from idealised plane parallel homogeneous models which have been developed so far. It will also be important to include in future modelling a) the possibility that not all the UV illumination comes from a single direction, b) the probability that dynamical effects such as clump rotation or clump obscuration as they move about on time scales less than that required to allow the chemistry to relax after UV stimulation (as proposed by Monteiro A&A 241,L5,1991), and c) that much of the chemistry will occur on the outer layers of dense clumps, may all modify both the chemistry, and also the spectroscopic signature of the region to a telescope. There are currently several groups working with interferometric data, PDR interfaces which may already have detected evidence for chemical stratification. It is clear that "archetypical" sources such as M17 may not be the best places to test more sophisticated chemical models, the S140 ionisation front looks far more suitable as the source of choice due to its relative simplicity compared with M17 or the Orion Bright Bar regions.

R.Opher: Shocks are associated with first order Fermi acceleration of particles, with an appreciable energy of the shock going into these particles. I thus doubt the possibility of treating the clouds near the shock by a single temperature without taking into account the details of the ionization caused by the accelerated particles in the clouds.

G.White: Yes, this is undoubtedly a complex and important issue. Temperature stratification is of course already well known across a region such as M17 (Gatley et al.,Ap.J. 233,575,1979), but little is known observationally about the detailed ionisation profiles. Innovative observational diagnostics of the ionisation state and the small scale magnetic fields would be very helpful in resolving this issue.