OBSERVATIONS OF CII, CI AND CO IN INTERFACE REGIONS

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1. Introduction

UV-radiation longward of the Lyman edge (912 Å) can escape from HII-regions. It photodissociates carbon monoxide ($\lambda < 1118$ Å) and photoionizes neutral atomic carbon ($\lambda < 1101$ Å). The resulting CII/CI/CO transition zone on the edges of molecular clouds (photodissociation region or photodominated region: PDR) has been studied in great detail theoretically (Tielens & Hollenbach, 1985; van Dishoek & Black, 1988; Sternberg & Dalgarno, 1989) and these investigations have recently been extended to cover a wide range of densities and UV-intensities (Burton, Hollenbach & Tielens, 1990; Hollenbach, Takahashi & Tielens, 1991; see also A. Sternberg, this volume).

Observations of the three species CII, CI and CO by means of optical and UV absorption studies are limited to diffuse clouds (E. van Dishoek, this volume). The study of PDR's on dense molecular clouds thus has to rely on the fine structure lines of [CII] (158 μm) and [CI] (371 μm and 609 μm) and the higher rotational transitions of CO in the far-IR and the submm. The energy range above ground state from a few 10 K up to about 150 K, as well as the critical density of the transitions, ranging between a few $\times\ 10^3\ \mathrm{cm}^{-3}$ for the fine structure transitions, up to a few $\times\ 10^6\ \mathrm{cm}^{-3}$ for the higher rotational levels of CO, make the transitions easy to excite in PDR's, and they in fact contribute significantly to the gas cooling.

Interpretation of the observed line intensities relies on the availability of reliable collision rates. The references for these are summarized in Table 1. In addition to the presentation here the observations have been summarized in two recent reviews (Genzel, Harris & Stutzki, 1989; Keene 1990) to which the reader is referred for further information. With the limited amount of space available, this review tries to outline the basic observational results and their astrophysical implication.

2. Instrumentation

The submm and far-IR transitions have only become observable with the rapid technical advance in instrumentation over the last ten years. In ad-

P. D. Singh (ed.), Astrochemistry of Cosmic Phenomena, 303–308.

C^+ - H	Launay & Roueff, 1977, J.Phys.B 10, 879
C^+ - H_2	Flower & Launay, 1977, J.Phys.B 10, 3673
C^+ - e	Haye & Nußbaumer, 1984, A&A 134, 193
C^0 - H	Launay & Roueff, 1977, A&A 56, 289
C^0 - H_2	Staemmler & Flower, 1991, J.Phys.B 24, 2343 [1)]
C^0 - He	Schröder et al. 1991, J.Phys.B 24, 2487
C^0 - e	Johnson et al. 1987, J.Phys.B 20, 2553
C^0 - p	Roueff & Le Bourlot, 1990, A&A 236, 515
CO - He	Green & Chapman, 1978, Ap.J.Suppl. 37, 169
CO - He	McKee, et al. 1982, Ap.J. 259, 647
CO - H_2 $^{para}_{ortho}$	Flower & Launay, 1985, MNRAS 214, 271
CO - H_2 para	Schinke et al. 1985, Ap.J. 299, 839 [2)]

TABLE I

Collision Rate References

1) suggested preferential J=2→O excitation is actually unimportant, in contrast to [OI] (Monteiro & Flower, 1987, MNRAS 228, 101). 2) good agreement with McKee et al. (1982) once detailed balance factors are included properly (in contrast to the conclusion by the authors)

dition to the sophisticated instruments necessary, all these lines require extremely good atmospheric conditions. For ground based observations these are presently only available from the observatories on Mauna Kea, Hawaii. Far-IR observations have to be carried out from the Kuiper Airborne Observatory and from balloon platforms (Okuda 1991). The angular resolution is thus limited typically to the range of a few arcminutes down to 30 arcsecs. With the availability of the new large submm ground based telescopes, the angular resolution has recently been pushed down to the 10 arcsecs regime in the sub-mm spectral lines, thus making possible the first detection of extragalactic CO J=6→5 emission (Harris et al. 1991) and allowing to spatially resolve the clumpy structure of the [CI] emission (G. White, this volume).

The following discussion is still based on a limited number of observations towards typically the brighter sources with favourable geometry (e.g. M17 SW, S140 and Orion A). This is especially true for the submm lines. The situation is better in case of the [CII] observations, where e.g. the high sensitivity multi pixel Fabry-Perot instrument built by the MPE group now allows rapid mapping with adequate spectral resolution in many sources, including external galaxies (e.g. S. Madden et al., this volume).

3. Observational Results: Clumpy, UV-penetrated Clouds

With a few exceptions discussed below, both the spatial distribution and the observed line intensities are in rough agreement with the theoretical expectations from PDR models, i. e. bright emission in [CII], [CI] and warm CO originates from HII-region/molecular cloud interfaces. However, the simple theoretical picture of a semi infinite, plane parallel slab with a stratified layer of CII, CI and CO is not adequate. The observations provide strong support for a picture where the UV-radiation can penetrate substantially deeper into a molecular cloud due to the clumpy or filamentary structure of the molecular material with a high clump/interclump density contrast. While being attenuated and scattered by the dust in the clumps, the UV radiation can create PDR surfaces on clumps rather deep into the molecular cloud, and thus affect a much larger fraction of the cloud material. Evidence for this conclusion comes from basically three facts:

The observed intensity ratios imply rather high densities of the emitting material. In case of the [CII] 158 μm line this is inferred from the intensity ratio relative to the two [OI] lines at 63 μm and 145 μm (Watson 1985), that constrain the density and temperature of the emitting gas to $\sim 10^4$ cm^{-3} and a few 100 K. Optical depth corrections for the [OI] 63 μm line can change these values some. The observed brightness ratio of the two [CI] finestructure transitions $T_B(370\ \mu m)/T_B(609\ \mu m)$ of about unity implies densities above $10^{3.5}$ cm^{-3} at temperatures of $\sim$ 200 K and $> 10^4$ cm^{-3} at the minimum temperature of $\sim$ 60 K (e.g. Zmuidzinas et al. 1988). Similar conclusions are drawn from the comparison of far-IR and submm CO line intensity ratios (Harris et al. 1987), where, dependent on the column density of the warm CO, a minimum pressure $n \times T$ of about $\leq 10^7$ K cm^{-3} has to be present. In all three cases comparison of the line intensities expected under these conditions and the observed intensities implies area filling factors of about 20 - 30 %, and hence small scale structure within the telescope beam.

A second, strong argument comes from the fact that none of the observations so far have succeeded in spatially resolving the CII/CI/CO transition region. The new, high angular resolution [CI] observation with the JCMT (G. White, this volume) show for the first time the [CI] emission peaking at the edge of the molecular clump as traced in $C^{18}O$ 2$\rightarrow$1. At lower angular resolution the emission of CII, CI and warm CO coincides both spatially and in the line shapes (Keene et al. 1985, Genzel et al. 1988, Boreiko et al. 1990, Stutzki et al. 1991, Stacey et al. 1991c). This is naturally explained by the assumption of many spatially unresolved PDR's on individual clumps in the beam, where the observed linewidth is due to the interclump velocity dispersion, whereas the clump intrinsic linewidth is much narrower. An additional component in the [CII] emission from M17 SW overlaps with the clumpy radio-continuum emission at the edge of the HII region.

The third evidence comes from the large spatial extent of the observed [CII] emission, out to an A_v of typically 40-100, estimated from the average density and linear scale. Clearly, no UV photons can travel that far through a homogenous medium. Only clumpiness, with sufficient density contrast so

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that the photons can travel far distances through the interclump medium, can explain the large observed extent. Modelling of the [CII] emission distribution from a clumpy medium along a cut through the M17 SW interface (Stutzki et al. 1988), and more recently for the two dimensional mapping results in W3 and NGC 1977 (Howe et al. 1991) can successfully reproduce the observed emission. A recent large scale [CII] map of the Orion B region (Jaffe et al. 1991) supports this picture by showing that the [CII] emission closely follows the ridge of high density clumps south of NGC 2023 seen in the survey by Lada et al. (1991).

4. CII/CO correlation: PDR's everywhere?

Also on larger scales does the [CII] 158 μm emission follow very closely the CO 1→0 emission tracing the molecular cloud distribution. Latitude cuts across the Galaxy (Shibai et al. 1991) show this correlation in great detail, confirming earlier results by Stacey et al. 1985. Apparently, PDR's due to the average interstellar radiation field significantly influence also the average molecular cloud, not only the material in the immediate neighbourhood of bright HII regions. The observed correlation between the [CII] and CO 1→0 line flux can indeed be reproduced by theoretical modelling (Wolfire et al. 1989). A similar conclusion is suggested by low-J ^{12}CO and ^{13}CO observations. Castets et al. 1990 reported ^{12}CO and ^{13}CO 1→0 and 2→1 line ratios throughout large parts of the extended Orion A cloud that indicate external heating. Similar line ratios are observed in other clouds (Weikard, et al. 1991, Herbertz, priv. comm). Recently, Gierens, Stutzki and Winnewisser (1991) showed that in a simple model of a spherically symmetric clump with an $n \propto r^{-3/2}$ density structure, and the radial temperature and chemical distribution given by a simple PDR model approximation, can reproduce the observed line ratios. This model includes as a necessary ingredient the ^{13}CO enrichment in the deeper PDR layers due to the $^{13}C^+ +^{12} CO \leftrightarrow {}^{12}C^+ +^{13} CO + 35K$ exchange reaction.

At least for luminous galaxies, the observed [CII] emission also seems to be dominated by PDR's (Stacey et al. 1991a). In fact, the PDR modelling results can be used to infer from the observed line flux the typical density and UV intensity in the emitting gas (Wolfire et al. 1989, Stacey et al. 1991a).

5. Discussion

Despite of the remarkable success of the UV penetrated, clumpy cloud model in explaining the CII, CI and CO observations, two major problems should be noted: 1) The recent ^{13}CO 6—5 detection (Graf et al. 1990) and subsequent observations in many sources (Graf et al. 1991) indicate the presence

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of very large column densities of medium warm ($\geq$ 100 K molecular material, much more than can be explained by the UV-heating within PDR models. It may thus well be that our models still miss an important heating mechanism in molecular cloud cores. 2) At the moment it is unclear what mechanism might stabilize the clump/interclump gas, considering the large density contrast required for sufficient UV-penetration.

The basic observational results outlined above may be, at least to some extent, affected by optical depth effects or self absorption. The reported tentative detection of a rather strong [^{13}CII] fine structure line from Orion A (Boreiko et al. 1988), implying a [CII] 158 μm optical depth much too large to be consistent with PDR models, was not confirmed by more recent observations (Stacey et al. 1991b). The new observations detect [^{13}CII] emission on a much lower level, consistent with τ of around unity. Also, observed self reversed profiles as reported for [CII] by Boreiko et al. (1990) and tentatively reported for [CI] 609 μm by Keene (1990), may be the result of chopping onto an extended emission component, rather than originating from absorption in a low excitation foreground gas component. On the other hand, an extended low density and low temperature component, if present, could easily acquire an optical depth of close to unity in the fine structure transitions, and up to now most observations would easily miss its rather weak emission.

We should keep in mind that the present observations are limited to a few selected galactic regions and luminous external galaxies. Observations of lower luminosity regions and larger-scale surveys, which will become feasible with some of the planned space borne observatories and new ground based facilities, may significantly alter the picture outlined here. In fact, the recent spectral line results obtained by COBE (B. Wright, this volume) may be the first challenge towards this direction.

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QUESTIONS AND ANSWERS

M.Guelin: Wouldn't carbon recombination lines provide same additional valuable information? They can be observed with a fair/good angular resolution and their intensities scales like n_e^2.

J.Stutski: The first observations of what we now call PDR's where actually the carbon recombination lines are in Orion, NGC 2024 and a few other sources. At the low radiofrequencies where the recombination lines are bright, the angular resolution is, however, rather poor. In addition, due to the high S/N required to sort out the C recombination line on the shoulder of the hydrogen line, makes the observations rather difficult also.

V.Burdyusha: 1)After off shock waves it takes place very good conditions for thermal instability and a medium must fragmentate. Your results confirm this or not? 2)Why do you think that clouds rotate?

J.Stutski: The picture of a clumpy, UV penetrated cloud implies that the clumpiness exists already before the UV radiation from one or several newly formed stars is turned on. The increased pressure due to the UV radiation, and possibly also the ionisation shock propagating into the clump cloud could then indeed trigger the collapse of at least some of the clumps and thus induce the formation of the next generation of stars.

L.F.Rodrigues: You showed the remarkable agreement between CO and C^+ in the galactic center. Can you say how much of the carbon is in CO and in C^+ for this region?

J.Stutski: The galactic latitude cut I showed from the work by Shibai et al. is actually at a galactic longitude of 31°. The remarkable agreement between the [CII] and CO emission is, however, very typical and supports the picture of most of the [CII] emission coming from molecular cloud surfaces. The relative amount of [CII] and CO is thus determined by the amount of molecular material behind the interface, whereas the column density of CII is limited to an A_V of a few. I do not recall the precise numbers for the galactic center region, but I think it is not very different from other luminous regions, and is probably of the order of about 10%.