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ABSTRACT
The origin of the strong CO Cameron band emission in the Red Rectangle is investigated. From a comparison of laboratory spectroscopic data and astronomical observations in combination with chemical modelling, it is concluded that the Cameron band emission of CO originates from the dissociative recombination of HCO^+, and its intensity provides a measure of the product of the density of HCO^+ ions and the electron density, integrated along the line of sight.

Key words: molecular processes – ISM: individual: Red Rectangle – ultraviolet: ISM.

1 INTRODUCTION

The Red Rectangle is unique amongst astrophysical objects in the nature of its spectrum. Sitko (1983) and Glinski et al. (1996) have identified in it the fourth positive band system and the Cameron band system of carbon monoxide. The fourth positive system is an allowed transition and is almost certainly due to fluorescence (Glinski et al. 1996), but the upper level of the Cameron system is the $a^3\Pi$ state of CO and the transition is forbidden. The Cameron system is present in the dayglow of Mars (Barth et al. 1972), where it has been attributed to the dissociative recombination of CO_2^+, photodissociation of CO_2 and impact excitation of CO by solar-induced photoelectrons (Dalgarno, Degges & Stewart 1970). Glinski et al. (1996) have suggested that charged particles of energies 7–15 eV, assumed to be the high-energy component of a broad distribution of energetic particles, are responsible. We argue here that the upper state of the Cameron band emission is produced by dissociative recombination of HCO^+:

$$HCO^+ + e^- \rightarrow H + CO(a^3\Pi, v'). \quad (1)$$

2 SPECTROSCOPY

Analysis of the observed spectra indicates that the relative efficiencies with which the vibrational levels v' of the $a^3\Pi$ state are populated have the approximate values listed in column (1) of Table 1. They diminish rapidly with increasing v'. The relative efficiencies produced by ion impact are unknown but are likely to be more uniform. The relative efficiencies produced by the impact of electrons with energies between 12 and 14 eV have been measured in a collision-free environment by Wicke, Field & Klemperer (1972). They are reproduced in column (2) of Table 1. They fall off slowly with increasing v', much as do the $X^1\Sigma^+ - a^3\Pi$ Frank–Condon factors. The electron impact hypothesis can be ruled out also because the existence of an abundance of fast electrons would have other observable consequences. The presence of CO implies the presence of a much higher amount of H_2. The electron impact excitation cross-sections for the electronically excited states of H_2 (Liu et al. 1995; Dalgarno, Yan & Liu 1999) are similar to those for the $a^3\Pi$ state of CO (Zobel et al. 1996; Zetner, Kanik & Trajmar 1998), so that significant emission from H_2, much more intense than from CO, would be anticipated. The spectrum of H_2 resulting from electron impact has been calculated by Liu & Dalgarno (1996). It has peaks near 120 and 160 nm of which there is no indication in the spectrum of the Red Rectangle.

The spectrum resulting from the dissociative recombination of HCO^+ has been examined by Butler, Babcock & Adams (1997). It is included in column (3) of Table 1. The distribution with v' is much more like that observed by Glinski et al. (1996).

The spectrum resulting from the dissociative recombination of CO_2^+,

$$CO_2^+ + e^- \rightarrow CO(a^3\Pi, v') + O, \quad (2)$$

has also been measured in the laboratory (Skrzypkowski et al. 1998). The resulting distribution is given in column (4) of Table 1. It also agrees reasonably with the observations. However, a chemical model of the object shows definitively that HCO^+ is much more abundant than CO_2^+.

3 CHEMICAL MODEL

We have constructed a simple model of the Red Rectangle and applied it to a calculation of molecular abundances and the intensity of the Cameron band emission. We assume that the envelope is composed of a thin dense shell of constant density and an outer wind region with an inverse square law density profile. It is irradiated by a central source with an intensity that is a factor of 2×10^5 times that of the standard interstellar field. The intensity is consistent with that expected from the measurements of the far-ultraviolet flux (Sitko 1983).

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Table 1. Observed relative vibrational populations of CO $a^3\Pi$ in four production schemes.

v'	(1)[a]	(2)[b]	(3)[c]	(4)[d]
0	1	1	1	1
1	0.5	1.3	0.3	0.5
2	0.1	1	0.2	0.3
3	0.15	0.6	0.2	0.2
4	0.2	0.4	0.2	
5	0.2	0.3	0.3	

[a] From Glinski et al. (1996) (observations of HD 44179).
[b] From Wicke et al. (1972), CO + e (electron energy is 13 eV).
[c] From Butler et al. (1997), HCO^+ + e.
[d] From Skrzypkowski et al. (1998), CO_2^+ + e.

The chemistry is that appropriate to a photon-dominated or photodissociation region (Sternberg & Dalgarno 1995). The calculations are similar to those carried out for a similar model of the planetary nebula NGC 7027 (Yan et al. 1999).

The model yields a column density of CO of $10^{18}\,\mathrm{cm}^{-2}$ and of HCO^+ of $10^{13}\,\mathrm{cm}^{-2}$. The column density of CO_2^+ is negligible. The emission intensity is determined by the product of the electron density and the density of HCO^+ integrated along the line of sight. If we assume that dissociative recombination of HCO^+ leads with unit efficiency to the $a^3\Pi$ state of CO, we obtain a total intrinsic emissivity of 6.5×10^{41} photon s^{-1}. Correcting for a distance of 330 pc (Cohen et al. 1975) and the effects of extinction, we predict an intensity at Earth of $1 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, in agreement with the observed value of $0.8 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (Glinski et al. 1996).

Additional support for the identification of dissociative recombination as the source of the Cameron band emission is obtained by a comparison of the Cameron and fourth positive intensities. The model yields 0.19, in agreement with observations which yield a ratio of 0.19, accurate to 30 per cent (Glinski et al. 1996).

The Cameron band emission in the Red Rectangle may be a unique example of a chemical reaction beyond the Solar system serving as a source of ultraviolet emission.

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REFERENCES

Barth C. A., Stewart A. I., Hord C. W., Lane A. L., 1972, Icarus, 17, 457
Butler J. M., Babcock L. M., Adams N. G., 1997, Mol. Phys., 91, 81
Cohen M. et al., 1975, ApJ, 196, 179
Dalgarno A., Degges T. C., Stewart A. I., 1970, Sci, 167, 1490
Dalgarno A., Yan M., Liu W., 1999, ApJS, 125, 237
Glinski R. J., Nuth J. A., Reese M. D., Sitko M. L., 1996, ApJ, 467, L109
Liu W., Dalgarno A., 1996, ApJ, 467, 446
Liu X., Ahmed S. M., Multari R. A., James G. K., Ajello J. M., 1995, ApJS, 101, 375
Sitko M. L., 1983, ApJ, 265, 848
Skrzypkowski M. P., Gougousi T., Johnsen R., Golde M. F., 1998, J. Chem. Phys., 108, 8400
Sternberg A., Dalgarno A., 1995, ApJS, 99, 565
Wicke B. G., Field R. W., Klemperer W., 1972, J. Chem. Phys., 56, 5758
Yan M., Federman S. R., Dalgarno A., Bjorkman J. E., 1999, ApJ, 515, 640
Zetner P. W., Kanik I., Trajmar S., 1998, J. Phys. B, 31, 2395
Zobel J., Mayer U., Jung K., Ehrhardt H., 1996, J. Phys. B, 29, 813

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