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THE PRODUCTION RATE AND POSSIBLE ORIGIN OF O (^1D) IN COMET BENNETT 1970 II

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ABSTRACT

From the brightness profiles of the forbidden emission of oxygen [O I] at 6300 Å in comet Bennett 1970 II, the production rate of O (^1D) atoms was found to be $(2.8 \pm 1.4) \times 10^{30}$ atom s^{-1} and the scale length for the decay of the parent of O (^1D), $10^{4.53 \pm .05}$ km. These results were obtained at a heliocentric distance of 0.841 AU. Combined with other data, they strongly suggest that the origin of O (^1D) is the photodissociation of CO_2 into CO ($X\ ^1\Sigma^+$) + O (^1D). This would imply that CO_2 was more abundant than water in comet Bennett. The observed extent of the source of CO_2 also suggests the presence of an icy grain halo controlled by the vaporization of CO_2 ice.

Subject headings: comets — molecular processes

I. INTRODUCTION

Since its discovery in comet Mrkos 1957 V by Swings and Greenstein (1958), the red forbidden line of oxygen has been a puzzle. It is clear that, contrary to most other cometary bands, it cannot be excited by resonance fluorescence. Biermann and Trefftz (1964) have suggested that the oxygen atoms are produced in the ^1D state upon the dissociation of the parent molecules. This parent is as yet unknown. In particular its proposed identification with the OH which comes from the dissociation of water, as discussed by Delsemme (1973*a*), has never been substantiated. Malaise (1976) has suggested that if the forbidden red line were produced by dissociative recombination of some ion like H_2O^+, we could observe its two profiles to be asymmetric in the direction of the H_2O^+ tail.

It is surprising that no brightness profile of the forbidden red line of oxygen has ever been published for any comet. We have established it for comet Bennett with the hope that we could answer some of the previous questions. The technique used was that of Delsemme and Moreau (1973) which still achieves simultaneously the best spectral and spatial resolutions.

II. ANALYSIS AND RESULTS

The sunward and antisunward brightness profiles for [O I] were constructed from a 10 and a 3 minute spectrum of comet Bennett 1970 II taken on 1970 April 18 by Delsemme and Moreau (1973).

The two-parameter coma model developed by Haser (1957) was used to fit the inner portion of the profile where the airglow contribution was too small to be detected ($<10^{4.7}$ km from nucleus). The difference between the profile obtained with the model when extrapolated to distances greater than $10^{4.7}$ km, and the observed profile, accounted for a uniform airglow contribution.

The airglow line provided an absolute calibration of the brightness profile of the comet. For Ritter Observatory (40°40′ N, 5^h30^m2 W) astronomical twilight began at 3:36 LST; the midpoint times of the two spectra were at 3:31 and 3:39 LST (exposure times 10 and 3 minutes, respectively). The average number of air masses on the line of sight of the comet was 2.53 and 2.39. From Truttse's (1972) data for 1970 April, the zenith intensity of the red line had reached 255 rayleighs at 3:35 LST for our latitudes, and was growing steadily at a rate of 2 percent per minute. The brightness of the airglow line at the comet's position went therefore from 560 to 620 rayleighs. The possible fluctuations in the airglow excitation from place to place have been somewhat taken into account by considerably enlarging our error bars. A local *enhancement* near twilight by conjugate photoelectron excitation is always possible, but it is interesting to note that it would *enlarge* the cometary production rate and rather reinforce our interpretation of its origin, whereas it is unlikely to go much below Truttse's values. Figure 1 shows the absolute cometary brightness profiles, both from the model and from observations, as well as the level of the airglow intensity.

Because of the peculiar origin of the cometary O (^1D) atoms, the brightness profile has nothing to do with any fluorescence mechanism and is therefore proportional to the column density of the O (^1D) *parent* only, itself influenced by the extended source coming from the decay of a possible *grandparent*. Hence, the fitting of Haser's two-parameter model gives two scale lengths, which describe the decay of this *parent and grandparent*, respectively. Their sum was found to be $10^{4.83 \pm 0.5}$ km and their ratio 1.0 ± 0.1. This implies that they are almost identical, in the vicinity of $10^{4.53}$ km. The one-parameter model, which implies that the second scale length is zero, is therefore excluded. By integrating the profiles over the observed cross section of the coma, the production rate for O (^1D) was then found to be $(2.8 \pm 1.4) \times 10^{30}$ atoms s^{-1}. The heliocentric distance was 0.841 AU.

Data analysis and model fitting were described by Delsemme and Miller (1971) and Delsemme and Moreau (1973).

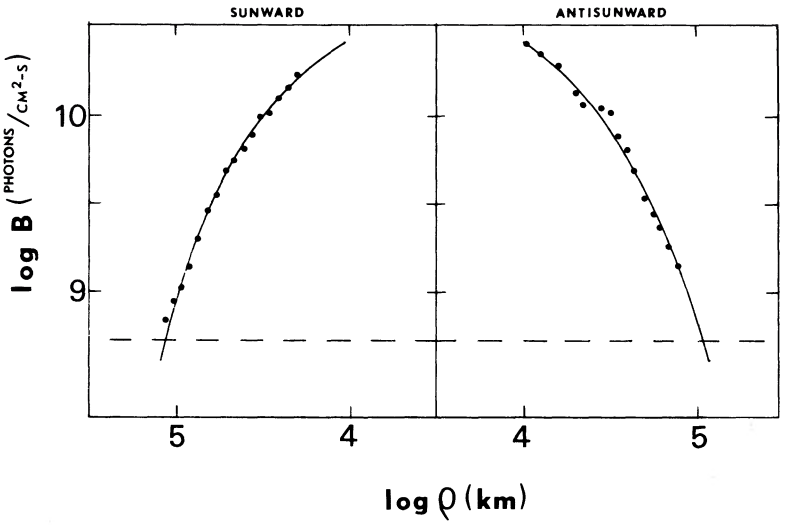

FIG. 1.—The points form the observed brightness profile of the [O I] line plotted as log brightness (photons cm^{-2} s^{-1}) versus log projected distance (km). The solid lines give the best fit of Haser's model. The dashed line shows the level of the airglow emission of [O I].

III. DISCUSSION

The comparison of the O (^1D) results given here with those for H and OH determined for the same comet by Keller and Lillie (1973) seems to rule out the possibility that the principal source of O (^1D) atoms in comet Bennett was H_2O, either directly or indirectly through OH. The O (^1D) production rate is indeed substantially larger (about 7 times). (The scale lengths are also substantially smaller than for either H_2O or OH, but this argument is not strong, as will be explained later.)

From OAO-2 ultraviolet observations of the fourth positive system of CO ($A\ ^1\Pi$–$X\ ^1\Sigma^+$) of the same comet (Lillie 1975), the production rate for CO would be 2.9×10^{30} molecules s^{-1} at a heliocentric distance of 0.825 AU. This is a rather uncertain result because of the very low fluxes observed and the deconvolution needed to decipher the spectra. However, the production rates of O (^1D) and CO, both being about 7 times that of water, are consistent with the brightness variation with heliocentric distance, which rather suggests a large abundance of CO_2 in comet Bennett (Delsemme 1975). It seems possible to rule out CO as the major parent of O (^1D) because its extremely long lifetime against photodissociation seems to be in sharp contradiction with the small scale length observed here for the parent of O (^1D). As mentioned later, predicted lifetimes rarely agree with observational data, but here the discrepancy would be by far the largest. Another strong argument, although for another comet, can be deduced from Feldman and Brune's (1976) data on comet West (1975*n*). Although their C I line at 1657 Å is 30 times as bright as the strongest CO fourth positive band, the dissociation of CO into O (^1D) + C (^1D) is only about 10 percent of that for O (^3P) + C (^3P) (McElroy and McConnell 1971); therefore, CO alone cannot explain the observed production rates. It is unfortunate that our spectra do not cover the CO^+ range, which could have provided another corroborative test. The existence of CO_2 is, however, also qualitatively confirmed by the existence of CO_2^+ in the tail spectra.

The production of O (^1D) and CO by the photodissociation of CO_2 would require at the observed rates that CO_2 be about 7 times more abundant than water (with error bars probably as large as a factor of 2). In this case CO_2 would control the vaporization of the nucleus, and since CO_2 is more volatile than water, would agree rather better, according to Delsemme's (1975) arguments, with the observed pattern of its brightness variation (Jacchia 1974).

The proposed photodissociation CO_2 ($^1\Sigma_g^+$) + $h\nu \rightarrow$ CO ($X\ ^1\Sigma^+$) + O (^1D) is consistent with all known data on the CO_2 ultraviolet absorption band between 1700 and 1400 Å (Loucks and Cvetanovic 1972). In particular, it is an allowed singlet-singlet dissociation, whereas the production of oxygen in its ground state (^3P) would imply a singlet-triplet transition in order to get an excited state of CO_2 yielding O (^3P), which is much less likely to have a high transition probability. This absorption band shows some fuzzy structure, suggesting predissociation, and its wavelength threshold is in the vicinity of $\lambda = 1673$ Å, yielding an excitation energy ≥ 7.41 eV. Since the dissociation energy of CO_2 into CO + O (^3P) is $D_0 = 5.45$ eV (Herzberg 1966), the minimum excess energy of the band is 1.96 eV, exactly yielding the energy of the [O I] transition ^1D–$3P$ = 1.96 eV; there is therefore a strong suggestion that the photodissociation of CO_2 into CO + O *always* yields the O atoms, not in the ground state ^3P but in the ^1D state, from which they radiate the observed forbidden line before reaching ^3P. Because of the same energy threshold argument, there is no reason to believe that CO could rather be produced in any excited state. This confirms the fluorescence mechanism for the emission of the fourth positive system of CO, and hence the appropriateness of Lillie's model to deduce the production rate of CO.

The decay scale lengths of the O (^1D) parent (CO_2)

would imply a lifetime at 1 AU of $10^{4.9\pm.2}$ s, contrasted with a predicted lifetime for photodissociation of $\sim 10^{5.6}$ s (Feldman *et al.* 1974). However, many lifetimes of suspected parent molecules are also longer than those inferred from scale length measurements (Potter and Del Duca 1964), therefore the production of O (^1D) from CO_2 is not precluded by the discrepancy in lifetimes. It may only confirm either the poor quality of the present data of the solar ultraviolet or—more likely—the poor understanding of the interaction of the solar wind with the cometary head.

The best fit obtained with Haser's two-parameter model requires that a physical meaning be attached to the extended source of CO_2 whose scale length is deduced from the O (^1D) brightness profile. Since no molecular grandparent of O (^1D) is suggested by the proposed mechanism, the only other possibility is that the extended source of CO_2 is an icy-grain halo, as required for comet Burnham by Delsemme and Miller (1971) in order to explain the brightness profiles of its C_2 and of its continuum. Here, the icy-grain halo would be about $10^{4.5}$ km, somewhat larger than theoretical estimates for *water* grains, and therefore consistent with a propellant more volatile than water. Delsemme (1976) mentions that brightness profiles of the icy-grain model and of Haser's two-parameter models, although different, are observationally undistinguishable.

If we extend the premise that O (^1D) atoms are produced by CO_2 to the observations of O (^1D) in comet Kohoutek 1973 XII (Huppler *et al.* 1975), we find a production rate of O (^1D) (and CO_2 likewise) = 2×10^{28} s^{-1} which is $\sim$20 percent of the production rate for water ($\sim 10^{29}$ molecules s^{-1}) as inferred from the observations of H and OH by Wyckoff and Wehinger (1976). This means that an excess of CO_2, over the 15 percent which could be trapped in solid hydrates, could have been present. This could rather well explain the sharp ascent of the light curve of comet Kohoutek beyond 4.0 AU before its passage, whereas any stuff more volatile (like CO or CH_4) or less volatile (like H_2O) implies extreme values of the nuclear albedo that are much less plausible (Delsemme 1975).

Contrary to most short-period comets, where the behavior of the nongravitational forces (Delsemme 1972; Marsden, Sekanina, and Yeomans 1973) convincingly shows that water sublimation *only* controls the vaporization of the nucleus, we conclude that long-period comets that probably are "young" like Bennett (no more than a couple of hundred passages) or even "new" like Kohoutek (possibly first passage) in Oort's (1950) sense, as shown by photometry (Jacchia 1974) even better than by orbital energy, show definite patterns of a slightly more volatile major constituent much too abundant to be emprisonned in solid hydrates. The present results strongly suggest that it is CO_2.[1]

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[1] *Note added in proof.* In particular, the excellent symmetry of the two profiles seems to rule out a large contribution of fast electrons for the excitation of oxygen into the ^1D state.

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