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Hydrogen and Hydroxyl Production Rates of Comet Tago-Sato-Kosaka (1969 IX)

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Summary. Comet Tago-Sato-Kosaka (1969 IX) was observed with the ultraviolet photometers on OAO-2 from January 16.41 to January 29.89, 1970, while its heliocentric distance increased from 0.78 to 1.03 a.u. The production rates of hydrogen and hydroxyl are derived from Lyman alpha (1216 Å) and the OH ($A^2\Sigma^+ - X^2\Pi_i$) (0–0) band (3090 Å) emission. The variation of the hydrogen and hydroxyl production ran parallel to one another while their ratio was about 3:1. These results are consistent with the assumption that vaporization of water ice controlled the production rate of gas during this interval. The hydrogen production rates of four non-periodic comets are compared.

Key words: Comets — hydrogen — hydroxyl — dissociation

I. Introduction

The first ultraviolet observations of a comet ($\lambda < 3000$ Å) were obtained at 11:10 UT on January 14, 1970, when the stellar photometers and spectrophotometers of the Wisconsin Experiment Package (WEP) on the Orbiting Astronomical Observatory (OAO-2) were directed toward Comet Tago-Sato-Kosaka (1969 IX) (TSK) (Code et al., 1970). The initial observation, at a point 16′ from the nucleus, was intended to measure the sky background but, instead, detected a strong emission due to hydrogen, λ1216, confirming the prediction of Bierman (1968). Subsequent observations revealed the second strong ultraviolet emission feature at λ3090 is due to the hydroxyl molecule and suggested that water is the most abundant ice in comets. A preliminary discussion of these data has been presented by Code (1970) and Code et al. (1972).

The observations of TSK turned out to be a rehearsal for the more detailed measurements of Comet Bennett (1970 II) for which the production rates of H and OH have been determined by Keller and Lillie (1974). In this paper we present a similar analysis for the OAO-2 observations of TSK.

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II. Observations

The OAO-2 observations of TSK, all post-perihelion, were initiated on January 14, 1970, when the comet's angular distance from the sun first exceeded 45° (a spacecraft pointing constraint) and continued until January 30th, when the spacecraft's regular observing program was resumed. The instrumentation and operation of WEP has been described by Code et al. (1970). The observing routine for TSK was similar to that used for Comet Bennett (Keller and Lillie, 1974).

The characteristics of the photometers used for this study are listed in Table 1. The absolute calibration was taken from Wende (1976). The sensitivities listed in Table 1 are lower than those adopted by Keller and Lillie (1974) by approximately 2% at λ3090, and approximately 30% at λ1216. A complete discussion of the WEP calibration is given by Bless et al. (1976).

The data used for our analysis of the H and OH production rates are listed in Table 2. These data are a subset of the total observations and include only the measurements obtained with the filters sensitive to H λ1216 and OH λ3090 when the 10′ diameter fields-of-view (FOV) of the photometers were centered on the comet's nucleus.

Table 1. OAO-2 photometer characteristics

Photometer/filter	$\lambda_{1/2}$	λ_{eff}	Sensitivity*
ST1 F4	2760–3170 Å	2980 Å	129.9 R/ct
ST2 F2	2740–3170	2940	281.4
ST4 F4	1185–1370	1330	126.9

* At gain indicated in Table 2

Table 2. Photometric data

Orbit	Date	Net Digital Counts			R	Δ
		ST1 E1F4	ST2 E1F2	ST4 E3F4		
5824	Jan 16.41 UT	507	241	531	0.779	0.404
5840	17.52	458	212	440	0.797	0.393
5849	18.22	382	192	328	0.810	0.388
5861	18.98	347	167	267	0.824	0.383
5873	19.82	307	148	202	0.838	0.381
5921	23.16	194	105	160	0.897	0.390
5923	23.37	194	102	149	0.901	0.391
5927	23.58	187	98	144	0.904	0.393
5931	23.86	185	96	145	0.909	0.395
5934	24.14	198	99	168	0.915	0.398
5937	24.35	181	93	143	0.919	0.400
5940	24.56	166	89	140	0.922	0.402
5944	24.83	157	86	138	0.927	0.405
5949	25.05	170	86	136	0.930	0.407
5951	25.32	164	84	136	0.936	0.411
5954	25.53	156	79	131	0.939	0.414
5966	26.30	135	77	127	0.952	0.423
5971	26.64	146	73	113	0.958	0.428
5980	27.27	131	68	120	0.970	0.437
5987	27.76	119	64	118	0.978	0.445
5994	28.24	114	59	95	0.988	0.453
6002	28.73	119	66	106	0.996	0.462
6009	29.36	111	63	108	1.006	0.473
6016	29.85	107	58	83	1.016	0.483
6026	30.47	96	53	78	1.028	0.495

III. Interpretation

A. Model Description

We assume the brightness of the comet in the photometer's FOV is due to resonant and fluorescent scattering of sunlight and can be described by an equation of the form

$$B(s) = \frac{gQ\gamma}{\pi s^2 v} \cdot f(\gamma, s)$$

where g is the excitation factor (photon molecule^{-1} s^{-1}); s is the FOV radius; Q is the total production rate of the molecules; γ is the characteristic distance to which the molecules expand before destruction; v is their expansion velocity; and $f(\gamma, s)$ is the factor which corrects for the limited FOV of our instrument. As in our previous paper (Keller and Lillie, 1974) we have adopted the parent-daughter molecule model of Haser (1957) to calculate the density distributions of H and OH, and the fraction of the molecules within our instrument's FOV. For our calculations we use the scale lengths (at a heliocentric distance of $R = 1$ a.u.): $\gamma_{H_2O} = 10^5$ km, $\gamma_{OH} = 2 \times 10^5$ km, and $\gamma_H = t_H v_H = (2.2 \times 10^6 \text{ s})(8.2 \text{ km s}^{-1}) = 1.8 \times 10^7$ km (t_H is the lifetime of hydrogen).

B. Q_{OH} Variation

In the lower part of Figure 1 we plot the logarithm of the observed surface brightness of the comet in the λ2940 and λ2980 Å bandpasses versus the logarithm of the heliocentric distance. The points lie close to a straight line with a slope of -5.9 in the log-log diagram. This picture changes, however, when we apply the appropriate filling factors and calculate the production rates of OH, shown in the upper part of Figure 1. During the period of our observations TSK approached the earth until January 21, 1970, and then receded. Since $Q \propto \Delta^2/f(R^2, \Delta)B$ (where R is the heliocentric distance, Δ is the geocentric distance, and B is the apparent brightness), the filling factor, f, roughly compensates for the decrease of Δ during the comet's approach. However, when the comet recedes from the earth, Δ increases while f continues to decrease with R. Thus, the slope of the OH production rate curve changes at closest approach, while the slope of the brightness relation is constant. The comet was not observed during the period from January 20–23, 1970, when this change occurred due to the lack of appropriate guide stars for the OAO-2 spacecraft when pointed to the region of the sky occupied by TSK.

From January 16 to 20, 1970, the production rate of OH decreased approximately as $R^{-3.3}$. After January 23, 1970, Q_{OH} decreased as $R^{-1.5}$. The average slope for the entire observing period, -2.4, is quite close to the value of -2.3 found for Comet Bennett (Keller and Lillie, 1974). At $R = 1$ a.u. $Q_{OH} = 1.3(\pm 0.6) \times 10^{29}$ molecule s^{-1}.

C. Q_H Variation

The variation in the observed brightness of TSK at HI λ1216 and the derived production rates of atomic hydrogen with heliocentric distance are shown in the log-log diagram of Figure 2. The data are influenced by geocoronal absorption of the cometary Lyman alpha emission (Code, 1970) around closest approach of the comet to the earth. No correction has been made for this absorption, and it is reflected in the Q_H curve which must, therefore, be regarded as a lower limit to Q_H for the period of the observations. In general, the production rate of H parallels that of OH, especially in the interval $0.9 < R < 1.0$ a.u. We find $Q_H = 2.5\ (\pm 1.3) \times 10^{29}$ atom s^{-1} at $R = 1$ a.u. Applying an improved density model (see Discussion) yields $Q_H = 4.3(\pm 2.2) \times 10^{29}$ atom s^{-1} at $R = 1$ a.u.

We have not attempted to derive the cometary Lyman alpha emission line profile or its equivalent width by assuming selective geocoronal absorption as a function of geocentric radial velocity (Code, 1970). The production rates do not vary smoothly enough, and the Q_H:Q_{OH} ratio shows too much scatter. This is to be expected if the evaporation rate of H_2O is not uniform, since the scale lengths (lifetimes expansion velocities) of H and OH

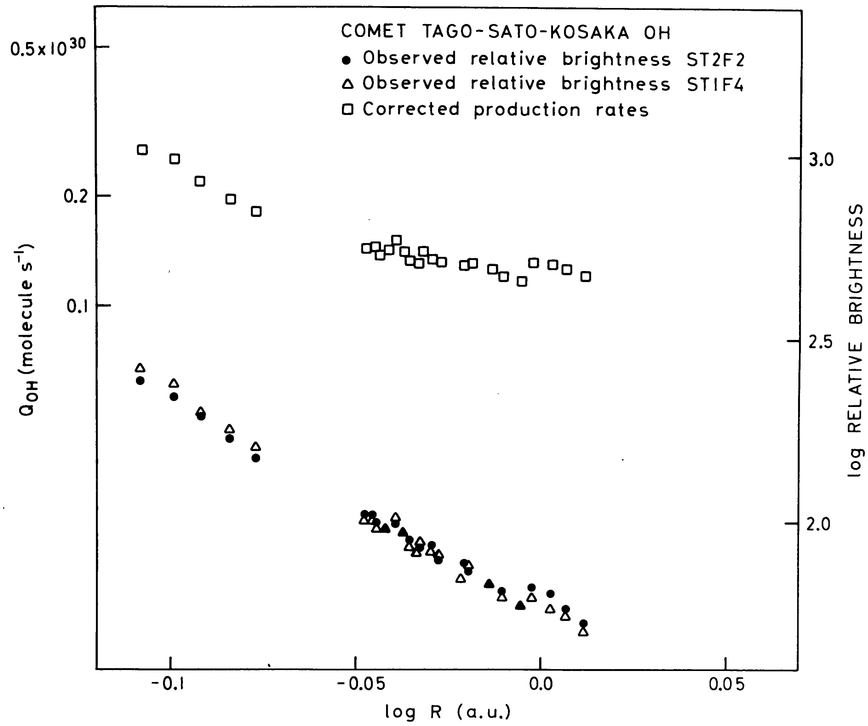

Fig. 1. The OH λ3090 photometer observations of Comet TSK from January 16 to 30, 1970. The lower points show the logarithm of the observed brightness (right ordinate) from ST1F4 (△) and ST2 F2 (●) versus the logarithm of the heliocentric distance, *R*. The upper points (□) show the production rate of OH (left ordinate) versus log *R* which were computed from these data

are quite different. The cometary Lyman alpha emission line profile is not constant across the photometer's FOV, and optical thickness effects make such an analysis rather difficult.

IV. Discussion

In the preceding work we approximated the two-step dissociation process of water ($H_2O \rightarrow H + OH$ and $OH \rightarrow O + H$) for the hydrogen atoms by a single dissociation with a scale length of the parent molecule of 2×10^5 km. Recently, Haser's (1957) model has been generalized to take two consecutive dissociations into account (Drake et al., 1976). We have also calculated the filling factor for the Lyman alpha observations on the basis of this model. The filling factor remains unchanged if $\gamma_{H_2O} = 10^5$ km and $\gamma_{OH} = 2 \times 10^5$ km are taken

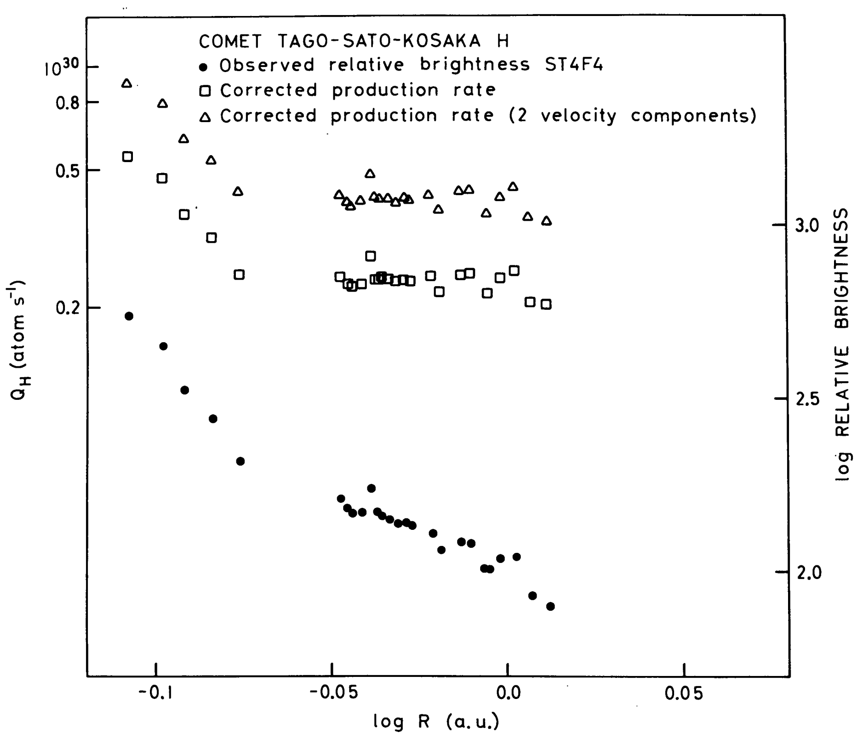

Fig. 2. The hydrogen Lα photometer observations of Comet TSK from January 16 to 30, 1970. The lower points show the logarithm of the observed brightness (right ordinate) versus the logarithm of the heliocentric distance, *R*, by filled circles (●). The production rate of hydrogen (left ordinate) derived from the observations, corrected for field-of-view effects with the two models discussed in the text, versus log *R*, is shown by the open squares (□) and triangles (△)

instead of the hypothetical one parent scalelength of $2\,10^5$ km. For these calculations, it has been assumed that the scalelength of the hydrogen atoms of the first (H_2O) and second (OH) dissociation are equal:

$\gamma_H = v_H \cdot t_H = 1.8 \times 10^7$ km with $v_H = 8.2$ km s^{-1}
and $t_H = 2.2 \times 10^6$ s

(Keller, 1973). However, recent investigations of the cometary Lyman alpha emission of comets Bennett (Keller and Thomas, 1975) and Kohoutek (1973 XII) (Meier et al., 1976) required an additional hydrogen velocity component of about 20 km s^{-1} for an optimal fit of the calculated models to the data. If this high velocity component is attributed to the dissociation of water (Keller, 1971) the hydrogen scalelength would increase to 4.4×10^7 km. This combination of two hydrogen scalelengths changes the density distribution and, hence, the filling factor. The hydrogen production rate of comet TSK would then increase by about 70% to 4.3×10^{29} s^{-1} at 1 a.u. This figure is about a factor of 2 smaller than the production rate quoted by Keller (1976a, 1976b) based on a preliminary analysis. The slope in the log-log diagram (Fig. 2, uppermost points) is hardly changed. A similar calculation for the OAO-2 data of comet Bennett would increase its hydrogen production by about 22% over the figures given by Keller and Lillie (1974), after applying the most recent calibration data at Lyman alpha.

Test calculations showed that the spectrometer profiles of the OH emission of comet TSK could be fitted with the scalelength determined from the Bennett data (Keller and Lillie, 1974). In contrast to our result for comet Bennett, the production rates of H and OH in TSK do not decrease with a constant exponent of the heliocentric distance during the observational period. In general, this is to be expected, especially if the comet is rather active. Indeed, the visual brightness of TSK showed a standstill after January 21, 1970, ($R = 0.859$ a.u.) for about 10 days according to a compilation of selected brightness observations by Sekanina (1970). The comet seemed to show a deficiency of its brightness performance coinciding by chance with its closest approach to the earth (Beyer, 1972). The variation of the production rates of H and OH agrees remarkably well with the visual brightness performance of the cometary coma. The ratio $Q_H/Q_{OH} = 3.3$ may indicate some hydrogen in excess of the production by water which would yield a ratio around two. The uncertainty of this figure is too large to pursue this difference further.

The destruction of a cometary water molecule finally yields two hydrogen atoms since the ionization rate of H_2O and OH are about two orders of magnitude smaller than the corresponding dissociation rates. Therefore, the water production of comet TSK can be calculated from $Q_{H_2O} = 1/3(Q_H/2 + 2Q_{OH}) = 1/3(4.3/2 + 2 \cdot 1.3)10^{29} = 1.6\,10^{29}$. (The OH production was given double weight corresponding to the number of observations.) This rate was less than a factor of 2 smaller than that of comet Bennett ($Q_{H_2O} = 2.9 \times 10^{29}$ s^{-1}), although comet Bennett's reduced brightness was 3 magnitudes brighter. This difference is probably due to the different dust production rates in the two comets (Keller, 1976a). Combining visual brightness observations at larger heliocentric distances with the water production rate at 0.78 a.u., then according to Delsemme and Rud (1973) the albedo, A, and the radius of the nucleus can be determined separately. With the Q_{H_2O} given above this method yields $A = 0.44$ and $r = 2.9$ km for TSK. This albedo is appreciably smaller than that determined by Delsemme and Rud using the preliminary Q_{OH} value reported by Code (1970). It is also smaller than the albedo of Bennett (0.63). This is rather surprising because of the much higher dust production of Bennett. One would expect the nuclear surface to be dirtier and hence to have a lower albedo. The uncertainties of the observations entering into the determination of the two cometary parameters and/or of the simple approach (no optical thickness effects, etc.) makes this method unsuitable for more than a general description of the cometary nucleus. A comparison of similar determinations for comet Kohoutek pre- and post-perihelion (O'Dell, 1976) yields another example that this simple approach does not give reliable information on the individual cometary nucleus.

A compilation of the hydrogen production rates of the four non-periodic comets observed to date reveals an

Table 3

Comet	Q_H at 1 a.u. post-perihelion [atom s^{-1}]	References	Vis. brightness reduced to $R = \Delta = 1$ a.u. [magnitudes]
TSK (1969 IX)	4.3×10^{29}	This paper	6.4
Bennett (1970 II)	5.4×10^{29}	Keller and Lillie (1974)	3.5
Kohoutek (1973 XII)	3.3×10^{29}	Drake et al. (1976)	6.0
West (1975n)	4.6×10^{29}*	Opal and Carruthers (1977)	5.0

* Comet West was observed at $R = 0.38$ post-perihelion. The production rate is scaled down $\propto R^{-2}$

astonishing uniformity (Table 3). The production rate of comet West (1975n) was $Q_H = 3 \cdot 2\ 10^{30}$ atom s^{-1} determined by a single observation at $R = 0.38$ a.u. post-perihelion (Opal and Carruthers, 1977). For the comparison in Table 3 it is scaled down using $Q_H \propto R^{-2}$. At the same heliocentric distance the production rate of comet Kohoutek was about a factor 5 smaller. The pre-perihelion observation at $R = 1$ a.u. from Skylab (Meier et al., 1976), however, yielded almost the same value as that given in Table 3. There are problems associated with the comparison of these comets, since they were observed under rather different circumstances. In spite of these limitations it is found that the production rates of all four comets at 1 a.u. (post-perihelion) differ by less than a factor of 2, i.e., are equal within the error limits. Whether this uniformity is coincidental or due to the fact that non-periodic comets are of about the same nuclear size (for $A =$ const. $r \propto \sqrt{Q}$), will have to be decided in the future on the basis of a larger sample of objects. A different explanation may be that the production rate only weakly depends on the size of the nucleus (at least for a certain range of radii and at $R \cong$ 1 a.u.), e.g., that the production of hydrogen is mainly determined by the solar flux.

V. Conclusions

An analysis of OAO-2 ultraviolet observations of comet TSK, similar to that of comet Bennett by Keller and Lillie (1974), confirms the parallel variation of the hydrogen and hydroxyl production rates during the interval $0.78 \leqq R \leqq 1.05$ a.u. We find $Q_H = 4.3\,(\pm 2.2) \times 10^{29}$ s^{-1} and $Q_{OH} = 1.3\,(\pm 0.6) \times 10^{29}\ s^{-1}$ at $R = 1$ a.u., yielding the ratio $Q_H{:}Q_{OH} \cong 3$, a slightly higher value than found for comet Bennett. This suggests water ice is a major constituent of the nucleus of comet TSK. The hydrogen production rates of all four non-periodic comets observed to date are all close to 4×10^{29} H atom s^{-1} at $R = 1$ a.u., post-perihelion.

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