AN ANALYSIS OF SPECTROPHOTOMETRIC OBSERVATIONS OF COMETS AUSTIN (1982g) AND BRADFIELD (1980t)

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Abstract. Post-perihelion observed emission fluxes at 388 nm (CN) and 516 nm (C_2) of the coma of comets Austin (1982g) and Bradfield (1980t) are analysed in the framework of the Haser model. Ratios of Haser model CN and C_2 parent production rates with expansion velocity show that each comet behaves normally. For comet Austin (1982g), the Q_{CN}/v and Q_{C_2}/v values decrease with increase of heliocentric distance of comet. For an assumed 20% activity of the total spherical surface area of the nucleus, the water vaporization theory coupled with derived water production rates from the International Ultraviolet Explorer H and OH flux data yields a nuclear diameter of about 6 km for comet Austin (1982g). For comet Bradfield (1980t), the derived nuclear diameter is expected to be of about 1 km. In each comet, the dust mass production rates as well as ratio of dust-to-gas mass production rates decrease with increase of heliocentric distance of comet.

1. Introduction

The heliocentric distance (r_h) of comet Austin (1982g) was about 0.648 AU at the time of perihelion which occurred on 1982 August 24.7215 ET. The parabolic orbital elements of comet Austin (1982g) were $\omega = 33°.8144$, $\Omega = 325°.5651$ and $i = 84°.4970$, referred to equinox 1950.0 (see IAU circular 3721). The evolution of the ultraviolet coma of comet Austin (1982g) before perihelion has been studied by Feldman et al. (1984) with the IUE satellite. The ultraviolet study of comet Austin (Feldman *et al.*, 1984) over a range of heliocentric distance (r_h) from 1.10 to 0.81 AU (pre-perihelion) shows that comet Austin (1982g) was very similar in chemical composition and appearance to comet Bradfield (1979X). Using observed brightness of UV emissions of H, O, and OH (dissociation products of H_2O), Weaver *et al.* (1981) found water production rate to obey $r_h^{-3.7}$ power law for post-perihelion $0.71 < r_h < 1.55$ AU in comet Bradfield (1979X). For comet Austin (1982g), a straight line fit of the OH production rates gives a dependence of $r_h^{-3.6}$ for the H_2O production rate for preperihelion heliocentric distance ranging from 1.10 to 0.81 AU.

At perihelion, the heliocentric distance of the comet Bradfield (1980t) was about 0.26 AU on 1980 December 29.5423 ET and its parabolic orbital elements were $\omega = 358°.2990$, $\Omega = 114°.6596$ and $i = 138°.5893$, referred to equinox 1950.0 (see IAU circular 3562). Near perihelion, the comet Bradfield (1980t) showed enhanced visual brightness (Ney, 1981) due to forward scattering as previously seen in comet (1976VI) and it fragmented on January 15, 1981 (Ney, 1982).

Spectrophotometric observations of comets Austin (1982g) and Bradfield (1980t)

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during post-perihelion period have been performed by Goraya *et al.* (1982; 1984) who have determined CN and C_2 production rates using old g-values and have not taken into account the effects of heliocentric variation of g and Swings effect (see a discussion by Landaberry *et al.*, 1990). In addition, no dust mass production rates have been determined for these comets by them (Goraya *et al.*, 1982, 1984). In this paper, their observed CN (388 nm) and C_2 (516 nm) emission fluxes have been analysed in the framework of Haser model (1957) using new g-values, where, in the case of CN (388 nm), the effects of heliocentric distance and heliocentric velocity of comet on g-values have been taken into account. Haser model CN and C_2 production rates and its dependence on heliocentric distance in comets Austin (1982g) and Bradfield (1980t) are determined (Section 2). Section 3 describes estimation of nuclear radii of comets Austin (1982g) and Bradfield (1980t) on the basis of water vaporization theory. The determination of dust as well as gas mass production rates in these comets are decribed in Section 4. Finally, we present a brief discussion of these findings in the light of other comets.

2. CN and C_2 Production Rates

For resonance scattering, the column density N (cm^{-2}) of a cometary species in a circular area of radius s (cm) at a distance Δ projected in the plane of sky when the diaphragm is focused at the nucleus of a comet is given by

$$N = 8.95 \times 10^{16} F \Delta^2 / g\, s^2\ \text{cm}^{-2}\,, \tag{1}$$

where F is the observed cometary species flux (in units of $\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}$), Δ is geocentric distance (in AU) and g is resonance scattering factor (in units of erg s^{-1}). The ratio of parent's production rate of cometary observed species (Q) with its expansion velocity (v), according to Haser model (1957), is given in a modified form by the expression (cf. O'Dell and Osterbrock, 1962; Newburn and Spinrad, 1984)

$$(Q/v) = \frac{T_s(l_p - l_r)}{l_r s}\left[\int_0^{s/l_r} K_0(y)\,\mathrm{d}y - \int_0^{s/l_p} K_0(y)\,\mathrm{d}y + \left(\frac{l_p - l_r}{s}\right) + \right.$$
$$\left. + K_1\left(\frac{s}{l_r}\right) - K_1\left(\frac{s}{l_p}\right)\right]^{-1} \text{mol}\,\text{s}^{-1}\,\text{km}^{-1}\,\text{s} \tag{2}$$

where $T_s(\equiv \pi s^2 N)$ is the number of cometary observed species in a circular area of radius s (cm) centered at the nucleus of the comet; l_p and l_r are parent's and radical's scale lengths; K_0 and K_1 are, respectively, zero-order- and first-order modified Bessel function of the second kind. For estimation of ratio of Haser model CN and C_2 parent's production rates with its expansion velocity from Equation (2) we have utilized recently recommended new scale lengths by Cochran (1985). Note that C_2 parent's scale length varies as $r_h{}^{2.5}$ (Cochran, 1985). In Table

TABLE I

Observational data* and Haser model CN and C_2 production rates in comets Austin (1982g) and Bradfield (1980t)

Comet	Date (U.T.)	r_h (AU)	Δ (AU)	Radius (S) (km)	$\dot{r}_h$ (km s^{-1})	Flux (F)* (erg cm^{-2} s^{-1})	Production rate/velocity (Q/v) (mol s^{-1})/(km s^{-1})
Austin (1982g)	5.6/9/82	0.70	0.94	15339	+13.8	(a) 1.527(−9) (b) 2.133(−9)	(a) 2.34(26) (b) 4.91(26)
	8.6/9/82	0.73	1.02	16644	+16.5	(a) 9.693(−10) (b) 9.240(−10)	(a) 1.97(26) (b) 2.54(26)
	9.6/9/82	0.74	1.05	17134	+17.2	(a) 7.600(−10) (b) 7.150(−10)	(a) 1.75(26) (b) 2.09(26)
	18.6/9/82	0.83	1.27	20724	+21.7	(a) 1.425(−10) (b) 1.375(−10)	(a) 5.33(25) (b) 6.35(25)
	20.6/9/82	0.86	1.32	21540	+22.6	(a) 1.235(−10) (b) 1.034(−10)	(a) 5.04(25) (b) 5.43(25)
	21.6/9/82	0.87	1.34	21866	+22.8	(a) 1.027(−10) (b) 0.825(−10)	(a) 4.31(25) (b) 4.53(25)
Bradfield (1980t)	14.56/1/81	0.55	1.14	35965	+41.3	(a) 1.641(−8) (b) 2.150(−8)	(a) 2.57(25) (b) 5.95(25)
	15.57/1/81	0.58	1.18	37227	+41.1	(a) 5.17(−9) (b) 10.0(−9)	(a) 1.50(25) (b) 6.19(25)

r_h, Δ and $\dot{r}_h$ represent heliocentric distance, geocentric distance and heliocentric velocity, respectively, of comet. Figures in parenthesis represent power of ten.

* Taken from Goraya *et al.* (1982; 1984) – see text. (a) CN data, (b) C_2 data.

I we list in column 7 the post-perihelion CN and C_2 flux data of comets Austin (1982g) and Bradfield (1980t) taken from Goraya *et al.* (1982; 1984). The observed CN (388 nm) fluxes of these comets have been analysed using new g-values of Tatum (1984) and Tatum and Gillespie (1977) where the effects of r_h and $\dot{r}_h$ on g-values have been taken into account. The g-factors are assumed to obey $r_h{}^{-2}$ power law (Tatum, 1984). For C_2 (516 nm) band, we have derived a value of 4.5×10^{-13} erg s^{-1} from Oliverson *et al.* (1985) at $r_h = 1$ AU (Landaberry *et al.* 1990). The ratio of CN and C_2 Haser model parent production rates with its expansion velocity in comets Austin (1982g) and Bradfield (1980t) were computed from Equation (2) and are listed in the last column of Table I.

3. The Size of Nucleus

The determination of shape and size of the nucleus of a comet is not a simple problem. An estimate of the size of the nucleus of a comet can be made from water vaporization theory (Cowan and A'Hearn, 1979; Delsemme, 1982) under the assumption that the nucleus is spherically symmetric. For parameters: cos $\theta = 0.5$ (assumed value), $A_0 = 0.04$ (Delamere *et al.*, 1986) and $A_1 = 0.03$ (Cochran, 1982), the water vaporization theory, under 50% activity of total spherical surface area yields nuclear radius ranging from 2.3 to 2.7 km corresponding to extrapolated observed H_2O production rates of Feldman *et al.* (1984) in comet Austin (1982g) for $0.70 < r_h < 0.87$ AU. We have supposed the same $r_h^{-3.6}$ power law for H_2O production rate for post-perihelion heliocentric distance range: $0.70 < r_h < 0.87$ AU for comet Austin. For 20% of total spherical surface activity, the nuclear radius of comet Austin (1982g) would range from 3.6 to 4.3 km. In view of uncertainty of nuclear surface activity we adopt a value of 3 km as the radius of nucleus of comet Austin (1982g).

For comet Bradfield (1980t) no water production rate data are available and estimation of nuclear radius is highly uncertain. A crude estimation of nuclear diameter of comet Bradfield (1980t) can be made as follows: the CN and C_2 Haser model production rates (Table I) ratio of January 14, 1981 (see below) shows that the comet Bradfield (1980t) belongs to the family of a normal comet (Cochran, 1987). In addition, the comet Bradfield (1980t) was very similar to comet Kohoutek (1973XII) at the same r_h and Δ except that comet (1973XII) at post-perihelion was about one magnitude brighter (Ney, 1981). In a normal comet, H_2O production rate ($Q_{H_2O} \equiv H_2O$) can be estimated from $^1D_2$ data by the expression (Newburn and Spinrad, 1985, 1989; Spinrad, 1987):

$$Q_{H_2O} = (H_2O/O^1D_2)(O^1D_2/CN)Q_{CN}\ \mathrm{mol\ s^{-1}}\,. \tag{3}$$

At solar maximum, $(H_2O/O^1D_2) = 10$ and $(O^1D_2/CN) = 100$ (Spinrad, 1987; Newburn and Spinrad, 1989). Hence Equation (3) can be written as:

$$(Q_{CN}/Q_{H_2O}) = 10^{-3}\,. \tag{4}$$

With Equation (4), under the assumption: $Q_{H_2O} \propto r_h^{-2}$, the CN Haser model production rates of January 14 and 15, 1981 having expansion velocity $v = 0.58\ r_h^{-0.5}$ (Delsemme, 1982) yield extrapolated water production rates 6.1×10^{27} mol s^{-1} and 3.8×10^{27} mol s^{-1}, respectively, at $r_h = 1$ AU for comet Bradfield (1980t). Since on January 15, 1981 the comet Bradfield (1980t) fragmented (Ney, 1982) we adopt a water production rate of about 10^{28} mol s^{-1} at $r_h = 1$ AU for comet Bradfield (1980t). The water vaporization theory (Cowan and A'Hearn, 1979; Delsemme, 1982), with the parameters listed above, in conjunction with the derived H_2O production rate yields an effective nuclear radius of about 400 m if the surface activity of the assumed spherical nucleus is 50%. For 20% of the total spherical surface activity, the corresponding effective nuclear radius would be of about 600 m. We adopt a nuclear radius of about 500 m for comet Bradfield (1980t).

4. Dust Mass Production Rates

It is believed that the continuum emission at optical wavelengths is due to scattering by dust grains present in the coma which come out from the nucleus by the action of sunlight during an apparition of a comet. The continuum fluxes for comets Austin (1982g) and Bradfield (1980t) were measured at wavelengths 530 nm and 479 nm, respectively, by Goraya *et al.* (1982, 1984) and, at the dates of their observations, these are listed in column 5 of Table II. The solar fluxes at wavelengths 530 and 479 nm are 1.993×10^2 erg cm^{-2} s^{-1} A^{-1} and 2.108×10^2 erg cm^{-2} s^{-1} A^{-1}, respectively (Arvesen *et al.*, 1969). Assuming dust grains roughly spherical we have a dust mass-production rate

$$m_d = \int_{a_0}^{a_m} (4\pi/3)a^3\rho(a)n(a)\,\mathrm{d}a \ \text{gm s}^{-1}\,, \tag{5}$$

where a is the radius of grain that lies between $a_0 = 0.1 \times 10^{-4}$ cm (Hanner, 1983) and maximum a_m which can be lifted from the nucleus against drag forces (see Equation (19) of Newburn and Spinrad, 1985), $\rho(a)$ is grain's density (Newburn and Spinrad, 1985) and $n(a)$ is a distribution function defined by Hanner (1983) and Newburn and Spinrad (1985) as

$$n(a) = K(1 - a_0/a)^M(a_0/a)^N \quad \text{cm}^{-1}\,\text{s}^{-1}\,. \tag{6}$$

The parameters M and N are the maximum in the distribution function and the slope of the function at large value of a, respectively. Following Hanner (1983) and Newburn and Spinrad (1985, 1989), we have taken $N = 4.2$ for both comets and the values of M, which depend upon r_h, have been calculated from de Freitas Pacheco *et al.*, (1988) and are listed in column 8 of Table II. K is a normalization constant and is related to the 'observed' area-geometric albedo product: $Ap(\lambda)$ (described below) to the nucleus centered circular area of radius s (cm) by the relation (Newburn and Spinrad, 1985; Newburn and Spinrad, 1989)

$$K = \frac{2Ap(\lambda)}{\pi^2 s p_g(\lambda)}\left[\int_{a_0}^{a_m} \frac{a^2}{V(a)}\left(1 - \frac{a_0}{a}\right)^M \left(\frac{a_0}{a}\right)^N \mathrm{d}a\right]^{-1} \quad \text{cm}^{-1}\,\text{s}^{-1}\,, \tag{7}$$

where $p_g(\lambda)$ is the geometric albedo of grains (following Newburn and Spinrad (1989) a value of $p_g = 0.04$ has been assumed in the present investigation) and $Ap(\lambda)$ is given (cf. Newburn, 1981) by

$$Ap(\lambda) = \frac{r_h^2 \pi \Delta^2 f_{\text{cont.}}(\lambda)}{\phi(\theta) f_\odot(\lambda)} \quad \text{cm}^2\,, \tag{8}$$

where $f_{\text{cont.}}(\lambda)$, $f_\odot(\lambda)$ and $\phi(\theta)$ are, respectively, cometary continuum flux at wavelength λ, solar flux at wavelength λ and scattering function at phase angle θ. For $\phi(\theta)$, we have used the curve of Divine (1981) based on Ney and Merrill's observations (1976) for comet West. in Table II, $f_{\text{cont.}}(\lambda)$, $\phi(\theta)$ and $Ap(\lambda)$ are listed in columns 5, 7 and 9, respectively. The determination of grain's velocity $V(a)$ for whole range of radii (Equation (7)) is a difficult problem. As dust-to-gas mass production rates ratio (defined as mass loading ψ) is less than unity in both

TABLE II

Dust-mass production rates in comets Austin (1982g) and Bradfield (1980t)

Comet	Date (U.T.)	r_h (AU)	Δ (AU)	$f_{\text{cont.}}(\lambda)$ erg cm^{-2} s^{-1} Å^{-1}	Phase angle (θ)	$\phi(\theta)$	M	$Ap(\lambda)$ (cm^{-2})	m_g (gm s^{-1})	m_d (gm s^{-1})	Mass loading (ψ)
Austin (1982g)	5.6/9/82	0.70	0.94	5.19(−14)	74°	0.464	11	1.708(11)	2.46(7)	9.36(4)	3.8(−3)
	8.6/9/82	0.73	1.02	2.08(−14)	68°	0.464	11	8.750(10)	2.12(7)	4.32(4)	2.0(−3)
	9.6/9/82	0.74	1.05	1.46(−14)	66°	0.464	11	6.687(10)	2.02(7)	3.18(4)	1.6(−4)
	18.6/9/82	0.84	1.27	2.70(−15)	52°	0.478	12	2.267(10)	1.27(7)	8.57(3)	6.7(−4)
	20.6/9/82	0.86	1.32	2.49(−15)	50°	0.493	12	2.297(10)	1.16(7)	8.19(3)	7.1(−4)
	21.6/9/82	0.87	1.34	2.08(−15)	49°	0.493	12	2.019(10)	1.13(7)	7.04(3)	6.2(−4)
Bradfield (1980t)	14.56/1/81	0.55	1.14	1.43(−12)	60°	0.464	9	4.045(12)	6.84(5)	5.28(5)	0.772
	15.57/1/81	0.58	1.18	7.20(−13)	56°	0.478	10	2.353(12)	6.50(5)	3.18(5)	0.489

The cometary continuum fluxes ($f_{\text{cont.}}(\lambda)$) are at wavelengths 530 and 479 nm for comets Austin (1982g) and Bradfield (1980t), respectively (see text) and are taken from Goraya *et al.* (1982, 1984).

In columns 5, 9, 10, 11, and 12 figures in parenthesis are power of ten.

$\Phi(\theta)$, $Ap(\lambda)$, m_g, and m_d represent, respectively, scattering function at phase angle θ, 'observed' area-geometric albedo product, gas mass production rate and dust mass production rate for comet (see text).

comets, we have utilized Sekanina's approximation (1981) to Probstein theory (1969) for estimation of $V(a)$. The Equation (5) was solved numerically and derived dust mass production rates are listed in column 11 of Table II. For gas mass production rate, we have considered the gas of the coma as a mixture of 90% H_2O and 10% other molecules of mean molecular weight 44 amu. Thus, the gas mass production rate

$$m_g = 3.4 \times 10^{-23} (Q_{H_2O}/Q_{CN}) Q_{CN} \quad \text{gm s}^{-1} \tag{9}$$

and the values m_g are listed in column 10 of Table II. For a coma gas mixture of 80% water and 20% other molecules of mean molecular weight 44 amu (see a special issue of *Astron. & Astrophys.*, **187**, No. 1/2, November (II) 1987), Equation (9) will differ in gas mass production rate estimation by 13% which is within the limit of errors (about ±20%) involved in the determination of gas mass production rate for both comets. The mass loadings ψ are listed in column 12 of Table II.

5. Discussion

For comet Austin (1982g), the analysis of post perihelion CN and C_2 observed fluxes in the framework of the Haser model (1957) shows that Q_{CN}/v and Q_{C_2}/v decrease with increase of heliocentric distance for $0.70 < r_h < 0.87$ AU. From Table I it is evident that the ratio of C_2 to CN production rates ranges from 1.1 to 2.1 having an average value at about 1.4. This shows that the comet Austin (1982g) belongs to the family of a normal comet (Cochran, 1987). For September 18.6, 1982 Haser model CN and C_2 parent production rates (Table I) are 3.4×10^{25} mol s^{-1} and 4.0×10^{25} mol s^{-1} for an expansion velocity of about 0.64 km s^{-1} (Delsemme, 1982). If CN and C_2 parent's production rates vary as $r_h{}^{-2}$, September 18.6, 1982 extrapolated CN and C_2 parent production rates would be 2.3×10^{25} mol s^{-1} and 2.8×10^{25} mol s^{-1}, respectively, for $r_h = 1$ AU. These values are consistent with September 14, 1982 observation of comet Austin (1982g) made by Cochran (Table I of Cochran, 1987). Table II shows that the dust mass production rates decrease with increase of heliocentric distance for post-perihelion distance range $0.70 < r_h < 0.87$ AU in comet Austin (1982g). The determination of dust mass production rates from continuum fluxes observed at wavelength 530 nm in comet Austin is based on the assumption that the nucleus is spherical having a diameter of about 6 km and its 20% of the total spherical surface area is active. For 50% activity, the dust mass production rates listed in column 11 of Table II of the comet Austin (1982g) would go down by a factor of about 1.2. The mass loading factors (listed in column 12 of Table II) decrease with increase of heliocentric distance in both comets.

For comet Bradfield (1980t), the CN and C_2 emission fluxes show that the ratio of Haser model C_2 to CN production rates was ~2.3 for January 14.56, 1981. The corresponding ratio went up to a value 4.1 for January 15.57, 1981 – thus supporting enhanced visual brightness observed by Ney (1981) at its fragmentation (Ney, 1982). For January 14.56, 1981, the C_2 to CN production rates ratio of comet Bradfield (1980t) is close to the upper limit ~2.14 found in several normal comets (Cochran, 1987). The comet Bradfield (1980t) appears to be a normal comet and both Haser model Q_{CN}/v and Q_{C_2}/v decrease with increase of heliocentric distance of comet. The dust mass production rate determination (Table II) in comet Bradfield (1980t) is based on the assumption that the nucleus is spherical in shape having diameter of about 1 km and 20% of its total spherical surface area is active. For 50% activity, the dust mass production rates listed in Table II will be lower by a factor of ~1.4 for the comet Bradfield (1980t). It is evident from Table II that the comet Bradfield (1980t) was more dusty than the comet Austin (1982g).

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