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Coma Expansion and Photometry of Comet Bowell (1980b)

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Optical and infrared observations of comet Bowell are presented. The optical observations indicate that the solid grain coma is expanding at only 0.9 ± 0.2 m sec^{-1}. This is two orders of magnitude slower than the local gas sound speed and may suggest that gas drag is not responsible for stripping the grains from the nucleus. The hypothesis of "electrostatic snap-off" is tentatively advanced to account for the ejection of the grains. Alternatively, the grains may have an unusual size distribution. The extrapolated motion of the grains suggests that the bulk of the coma was formed when the comet was at a heliocentric distance $R \simeq 10$ AU. Any water ice in the nucleus would be too cold to give rise to the observed grain coma by equilibrium sublimation at this R. Further evidence against the production of the grain coma by equilibrium sublimation of the nucleus is provided by broadband (J) photometric observations. Almost all of the observed photometric variations of comet Bowell can be ascribed to geometric effects. Simple models indicate that the total grain cross section has been nearly constant since the time of the earliest observations. The present observations, which suggest that water ice sublimation does not control either the optical morphology or the near infrared photometric behavior of comet Bowell, are contrasted with reported high OH production rates. It is concluded that the grain coma may be largely a relic of activity occurring on the nucleus at $R \simeq 10$ AU while the OH may indicate sublimation from the nucleus near perihelion and from coma grains near $R \simeq 4.6$ AU.

I. INTRODUCTION

Comet Bowell was discovered at the unusually large heliocentric distance $R = 7.3$ AU (Bowell, 1980) and was found to be moving on an orbit that is close to parabolic (Hasegawa *et al.*, 1981). According to Everhart and Marsden (1983) the original reciprocal semimajor axis was about 6×10^{-5} AU^{-1}. Comet Bowell appears "new" in the Oort (1950) sense: it has probably not made many previous journeys through the inner solar system. Consequently, it is of interest to determine whether this object has any properties which might physically distinguish it from the more commonly studied short-period comets of the inner solar system.

Several physical observations have been published in the recent literature. Optical spectra taken by Cochran and McCall (1980) showed the coma to consist of solid grains when the comet was at $R = 7.2$ AU. Subsequent infrared observations, obtained at $R = 4.80$ AU, confirmed the solid grain nature of the coma and showed the grains to be dark, with a visual geometric albedo of about 7% (Veeder and Hanner, 1981). The near infrared geometric albedo was estimated to be $14 \pm 5\%$ by Jewitt *et al.* (1982, hereafter referred to as Paper 1). The latter workers combined near infrared and thermal infrared measurements to estimate the total grain cross section in the coma at $R = 4.5$ AU. Within a diaphragm of projected radius 6×10^6 m, the solid grain cross section was found to be $C(6 \times 10^6) = (3 \pm 1) \times 10^8$ m^2. Combined with their published CCD surface brightness profiles this leads to an estimate of the cross section within the whole coma, $C(\infty) = (3 \pm 1) \times 10^9$ m^2. An additional property of the grains was suggested by the absence of strong "super-

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heat" (Paper 1; Ney, 1982). The thermally dominant grains were inferred to be large (radius $a \gtrsim 5$ μm), in stark contrast to the smaller grains which usually dominate cometary thermal emission ($a \sim 1$ μm).

Peculiar spectral features were discovered in the wavelength range 1.4 to 2.4-μm, when the comet was at $R = 3.38$ AU (Paper 1). The features did not resemble those present in the spectrum of water ice but were instead similar to those of solid ammonia. Identical absorption features were present in the spectrum of comet Panther (1980u) but were absent in comet P/Stephan–Oterma (1980g) (Paper 1). Campins *et al.* (1982) also made spectral observations in the near infrared at $R = 4.5$ AU, but did not detect the spectral features described above.

An optical surface brightness profile of the grain coma revealed a very sharp outer boundary. The profile could not be matched by simple grain coma models, despite the fact that these models were successful in reproducing the profiles of other comets.

Besides the solid grains, which dominate the optical and infrared appearances of the comet, there are published observations pertaining to gaseous emission. Weak emission from CN was reported at $R = 3.39$ AU by Larson (1982). The IUE satellite was used by Feldman *et al.* (1982) to infer a comet Bowell CN production rate $Q_{CN} \approx 7 \times 10^{25}$ sec^{-1} and an OH production rate $Q_{OH} \approx 3 \times 10^{28}$ sec^{-1}, both at $R = 3.39$ AU. Recently, A'Hearn *et al.* (1982, 1983) revised the OH production rates (as reported by Feldman *et al.*) downwards by a factor of about 3. The same authors noted that the peak $Q_{OH} \approx 10^{29}$ sec^{-1} occurred at $R \simeq 4.6$ AU, long before perihelion at $R = 3.34$ AU (see their Table 2). The rapid Q_{OH} fluctuations reported by A'Hearn *et al.* are puzzling since some of them occur on timescales shorter than the diaphragm crossing times for OH gas. The large gas production rates and the peculiar dependence on the heliocentric distance were unexpected features of comet Bowell.

Three photographs of comet Bowell were analyzed by Sekanina (1982). He concluded that the brightness of the comet changed very little with R, and that the radius of the coma increased at about 0.8 m sec^{-1}. Sekanina also noted that the comet had no tail in the first photograph (taken at $R = 6.90$ AU) and that the width of the tail in the other two photographs ($R = 5.20$ AU, 4.52 AU) did not increase with distance from the nucleus. From the former observation he inferred that coma production began at $R \lesssim 14$ AU. From the apparent length of the tail he found an upper limit to the radiation pressure induced acceleration of the grains and used it to estimate their radii as $a \sim 300$ μm. Sekanina supposed that the grain coma of comet Bowell was originally *in orbit* about the nucleus. He did not exclude the possibility of a small amount of nucleus outgassing near perihelion.

In the following sections we will present observations which substantially confirm several of the deductions of Sekanina (1982). We will also attempt to reconcile the apparently inert grain coma with the unusual activity suggested by the large gas production rates measured near perihelion.

II. OPTICAL OBSERVATIONS

The optical observations were taken at the Cassegrainian focus of the Palomar 1.5-m telescope. Images were obtained through broadband filters centered in the wave-

TABLE I

RADIUS OF THE COMA

JD 244+ (days)	R (AU)	Δ (AU)	P (arcsec)	$P\Delta$ (arcsec)	$r \times 10^{-8}$ (m)
4656	4.92	4.10	23 ± 3	94 ± 12	0.69 ± 0.09
4728	4.47	3.66	29 ± 3	106 ± 11	0.77 ± 0.08
5052	3.37	3.16	48 ± 4	152 ± 13	1.10 ± 0.09
5140	3.50	2.48	58 ± 5	144 ± 12	1.05 ± 0.09
5228	3.47	3.47	45 ± 4	156 ± 14	1.14 ± 0.10

Note. The columns list, respectively, the last four digits of the Julian Day Number at the time of observation, the heliocentric and geocentric distances of the comet (R, Δ, in astronomical units), the apparent radius of the coma (p, arcsec), the radius corrected to unit viewing distance ($p\Delta$, arcsec), and the linear radius of the coma ($r \times 10^{-8}$ m).

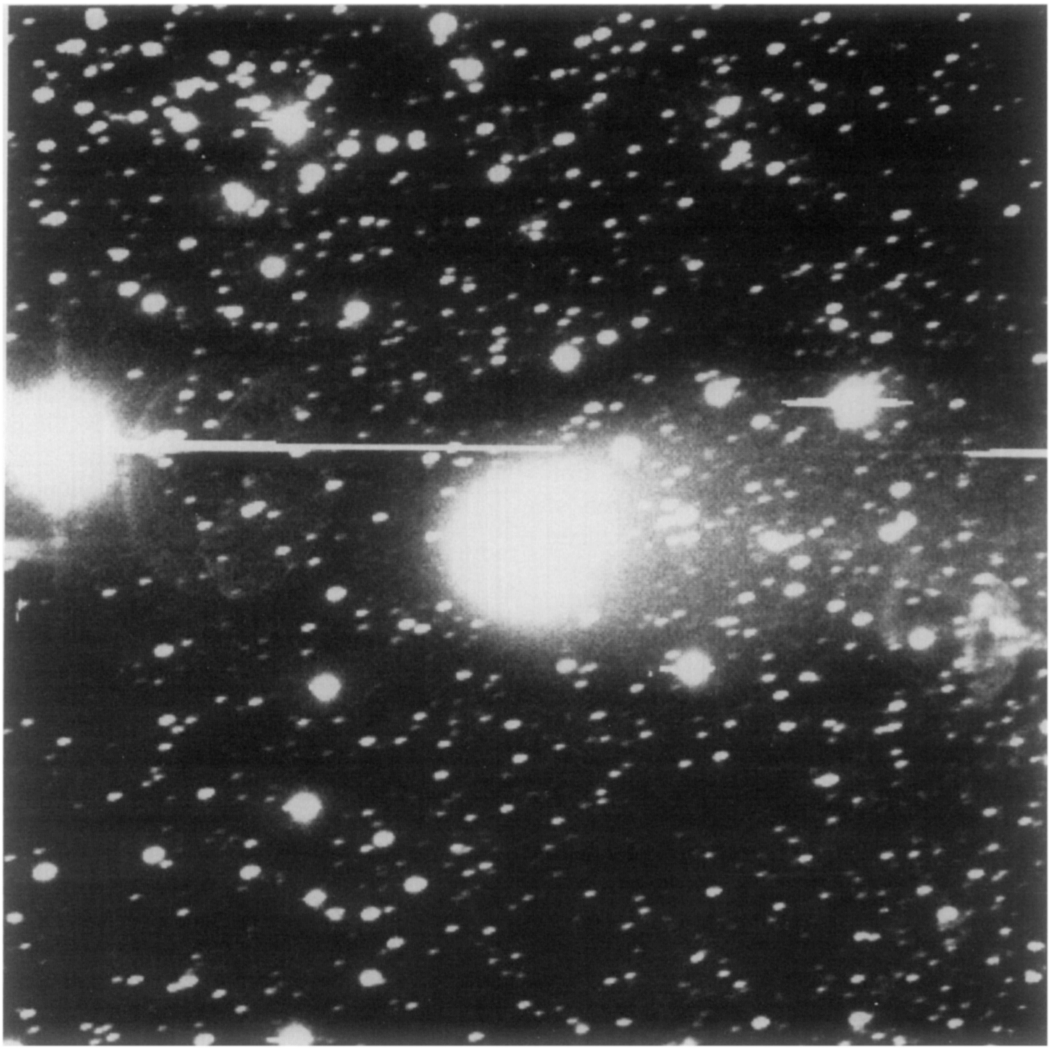

FIG. 1. CCD image of comet Bowell obtained UT 1982 March 23, when $R = 3.37$ AU, $\Delta = 3.16$ AU, and $\alpha = 17°$. The width of this r image corresponds to 1.1×10^9 m at the comet. West is to the right, north to the top. Note the bright dust coma and the extended dust tail. The long streaks are caused by bright stars which saturated the CCD.

length range 0.5 to 0.9 μm using the CCD camera and techniques described in Paper I. The observations were taken on a range of dates in a 2-year interval (see Table I). The atmospheric seeing during each observation was from 1 to 3 arcsec FWHM. Individual images reach to approximately Thuan and Gunn (1976) magnitude, $r = 23$. For a description of the other filters used see Wade *et al.* (1979).

A representative CCD image of comet Bowell, taken at wavelength 0.65 ± 0.05 μm, is shown in Fig. 1. The image reveals both the bright, almost circularly symmetric coma of the comet and the faint tail. This broadband image records the distribution of the solid grains in the coma and type II tail. The main features of the grain coma are the relatively well defined outer boundary and especially, the convex nose.

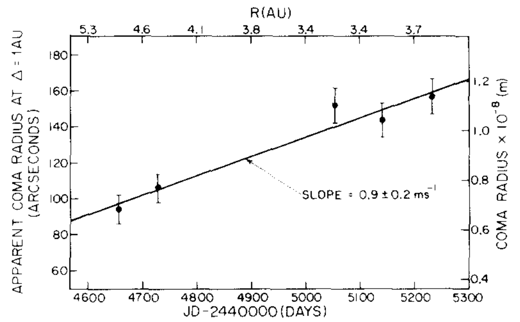

FIG. 2. Expansion of the coma of comet Bowell. The data are listed in Table I and described in the text. The linear least squares fit is shown.

The extent of the coma in the direction perpendicular to the plane of the orbit of the comet cannot be appreciably influenced by solar radiation pressure. Furthermore, the orbit of comet Bowell is inclined to the ecliptic by only 2°. Consequently, the width of the coma in the direction perpendicular to the projected tail axis can be used as a measure of the true coma width (Sekanina, 1982). CCD images taken at wavelength 0.65 μm were used to determine the radius of the coma by taking surface brightness plots along lines perpendicular to the comet tail. The ever steepening surface brightness profile near the edge of the coma (e.g., see Fig. 1 of Paper 1) enabled an accurate measurement of the coma radius by extrapolation of the observed surface brightness. The measured radii are given in Table I. The uncertainties listed in columns 4, 5, and 6 of Table I result from uncertainties in the magnitude of the sky background in each frame.

The measured radii, corrected to $\Delta = 1$ AU, are plotted versus Julian Day Number in Fig. 2. The figure reveals that the coma radius is a linearly increasing function of time. The slope of the least squares fit straight line is

$$v = 0.9 \pm 0.2 \text{ m sec}^{-1} \quad (1)$$

which is the best estimate of the coma expansion rate. By extrapolation, the coma is found to have had zero radius at Julian Day

$$\text{JD}(0) = 2443760 \pm 700 \text{ days} \quad (2)$$

corresponding to a period centered on September 1978. At this time, more than a year before discovery, the comet was at heliocentric distance $R \simeq 10$ AU. The significance of relations (1) and (2) will be discussed shortly.

The CCD images of the coma show no evidence for a central brightness spike which might be associated with the cometary nucleus. The central surface brightness profiles are instead consistent with blurring of the extended coma by atmospheric seeing. A central brightness excess of 50% would be readily detectable in the profiles. Using this visibility criterion, an upper limit to the product of the 0.65-μm wavelength geometric albedo, g, with the square of the radius of the nucleus (r_n, meters) may be set at

$$gr_n^2 \lesssim 6 \times 10^6 \text{ m}^2 \quad (3)$$

For example, taking $g = 0.14$ (the geometric albedo of the coma grains, from Paper 1) gives $r_n \lesssim 6.5 \times 10^3$ m.

Estimates of the mean size of the optical grains in comet Bowell can be obtained from measurements of the effects of radiation pressure on the morphology of the comet. In principal, both the length of the tail and the extension of the coma in the direction toward the sun can be used to estimate the grain size. However, comet Bowell is observed at such small phase angles that only the tail length imposes a significant constraint on the grain size.

The apparent length of the comet tail as determined on UT 1982 March 23 (JD = 2445052; see Fig. 1) was $L' > 220$ arcsec in the plane of the sky. The phase angle, heliocentric, and geocentric distances of the comet at the time of observation were 17°, 3.37 AU, and 3.16 AU, respectively. Hence, the true length of the tail was approximately $L > 1.7 \times 10^9$ m. If the tail grains were ejected from the nucleus on JD(0) then the equation of uniformly accelerated motion gives the grain acceleration $A > 2.6 \times 10^{-7}$ m sec^{-2}. The grain radius may be estimated from $a = 3F_0Q_{pr}/4cR^2\rho A$,

TABLE II

COMET BOWELL J MAGNITUDES

JD 244+	R (AU)	Δ (AU)	α (deg)	J	ϕ (arcsec)	CHOP (arcsec)	ΔJ_1	ΔJ_2	J_c	Source
4551	5.62	6.27	8	14.32 ± 0.05	10.3	35 NS	0.03	−0.00	14.35	A'Hearn *et al.*, 1981
4674	4.80	3.84	4	13.65 ± 0.05	8	20 NS	−0.24	−0.11	13.30	Veeder and Hanner, 1981
4704	4.61	3.64	3	12.89 ± 0.10	11.5	14 EW	0.15	−0.08	12.96	Campins *et al.*, 1982
4709	4.58	3.63	5	14.00 ± 0.10	6	6 NS	−0.55	−0.26	13.19	Paper 1
4719	4.52	3.63	7	13.43 ± 0.10	8.7	10 EW	−0.15	−0.19	13.09	Campins *et al.*, 1982
4734	4.43	3.68	9	13.19 ± 0.10	11.5	14 EW	0.15	−0.17	13.17	Campins *et al.*, 1982
4739	4.40	3.71	11	13.13 ± 0.10	7.8	10 EW	−0.27	−0.16	12.70	Campins *et al.*, 1982
5092	3.40	2.70	14	12.91 ± 0.09	6	6 NS	−0.55	−0.25	12.11	G. Neugebauer (private communication, 1982)
5118	3.45	2.51	8	12.26 ± 0.05	8	20 NS	−0.24	−0.00	12.02	[a]
5152	3.53	2.52	2	12.6[b]	7.5	18 NS	−0.31	−0.00	12.29	Koornshef and Shuster, 1982

Note. The columns have the following meanings:

1	JD	Julian Day Number of the observation, minus 2,440,000
2	R	heliocentric distance (in AU) of the comet
3	Δ	geocentric distance (in AU) of the comet
4	α	phase angle (in degrees) of the comet
5	J	measured J magnitude of the comet
6	ϕ	angular diameter (in arcsec) of the diaphragm within which J was measured
7	CHOP	beam chop amplitude (in arcsec) and the direction of chop in the plane of the sky
8	ΔJ_1	magnitude correction for diaphragm size
9	ΔJ_2	magnitude correction for beam chop amplitude
10	J_c	$= J + \Delta J_1 + \Delta J_2$
11	Source	source of the J magnitude measurement

[a] Unpublished measurement by the author, taken at IRTF.

[b] No error quoted.

where $F_0 = 1300$ W m^{-2} is the solar constant, Q_{pr} is the radiation pressure efficiency factor (of order unity), $c = 3 \times 10^8$ m sec^{-1} is the speed of light, R is the heliocentric distance in AU, and $\rho = 10^3$ kg m^{-3} is the assumed grain density. Substitution gives $a < 1 \times 10^{-3}$ m, in agreement with the value $a \sim 3 \times 10^{-4}$ m quoted by Sekanina (1982). (It should be noted that Sekanina's estimate of the grain radius would also seem to be an upper limit, although he does not say so, since his photographs provide only a lower limit to the length of the tail.) The grains in the tail of the comet are not larger than about 1 mm.

III. BROADBAND PHOTOMETRY

A majority of the published photometric observations of comet Bowell have been taken at near infrared wavelengths. A list of J (1.2 μm) magnitudes was compiled in order to follow the change in the apparent brightness of the comet with time. The list is presented in Table II.

TABLE III

SUMMARY OF COMET BOWELL COLOR MEASUREMENTS

JD	ϕ (arcsec)	J–H	H–K	Source
4709	6	0.5 ± 0.1	0.0 ± 0.1	Paper 1
4674	8	0.46 ± 0.07	0.03 ± 0.07	Veeder and Hanner, 1981
5092	6	0.37 ± 0.12	0.09 ± 0.11	G. Neugebauer (private communication, 1982)
5118	8	0.45 ± 0.07	0.02 ± 0.07	[a]

[a] Unpublished measurements by the author, taken at IRTF.

The K (2.2 μm) magnitudes published by Campins *et al.* (1982) were converted to J magnitudes by using the empirical color J–$K = 0.46 \pm 0.04$. The data listed in Table III provide evidence that the broadband near infrared colors of comet Bowell have remained constant within the uncertainties of measurement, justifying the magnitude transformation. The uncertainties on the derived Campins *et al.* J magnitudes in Table II have been enlarged to reflect the additional uncertainties introduced by the J–K transformation.

The published magnitudes have been corrected for two observational effects. First, the magnitudes were corrected to correspond to a 10-arcsec-diameter diaphragm. For this purpose, the integrated brightness within a diaphragm of diameter ϕ was assumed to follow $B(\phi) = K\phi$ with K an unspecified constant (e.g., see comet Bowell profile in Fig. 1 of Paper 1). Then $\Delta J_1 = 2.5 \log(\phi/10)$. Second, the raw J magnitudes were obtained using beam chop amplitudes which were smaller than the radius of the coma, so that the "reference beams" were contaminated by coma light. The necessary beam chop correction, ΔJ_2, was empirically determined from measurements of a CCD image taken at wavelength 0.65 μm. Artificial aperture photometry was performed on the CCD image in order to estimate the relative coma signals in the chopped beams. It was assumed that the coma surface brightness law at 0.65 μm was similar to that at J (1.2 μm). It was also assumed that the intrinsic coma surface brightness law did not change drastically with time. The beam chop correction is seen (Table II) to be relatively unimportant since it is only slightly larger than the formal uncertainties of the J magnitudes, in most cases.

The J_c magnitudes listed in Table II result from observations taken at phase angles in the range $2 \leq \alpha$ (degrees) ≤ 14. The magnitudes should be corrected for the intrinsic phase function of the grains. However, there exists hardly any information concerning the phase coefficients of cometary grains at small phase angles. Consequently, no phase angle correction was applied in the present analysis. It should be noted that unless the grains have strongly peaked backscattering, $|dJ/d\alpha| > 0.04$ per degree, the differential phase corrections would amount to <0.5 magnitude. Experiments in which the J_c magnitudes were "corrected" with hypothetical phase coefficients much larger than 0.04 magnitude per degree noticeably increased the scatter of the data points near JD 2444700 and JD 2445100.

The corrected magnitudes, J_c, are plotted as a function of Julian Day Number in Fig. 3.

IV. DISCUSSION OF THE COMA EXPANSION

The slow expansion of the coma indicated by Fig. 2 and Eq. (1) is a major result of the present work. The measured expansion rate is in formal agreement with the value determined by Sekanina (1982). It must be noted, however, that the coma radius uncertainties listed in Table I and shown in Fig. 2 are solely those due to uncertainties in the brightness of the sky background in each image. Additional uncertainties, resulting from the form of the extrapolation function, have been neglected from the discussion. However, these uncertainties are likely to be small and systematic in nature and will not affect the measured *rate* of expansion of the coma. In this regard it will be observed that

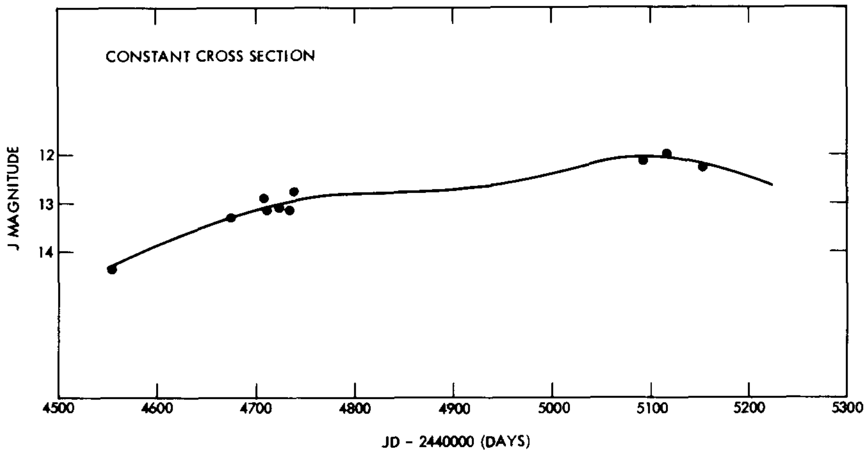

FIG. 3. J_c photometry of comet Bowell versus Julian Day number. The data are listed in Table II and described in the text. Note the small amplitude of the variation of the magnitude. The solid line represents a fit obtained by assuming a static dust coma of constant cross section.

the coma radii reported by Sekanina (1982), when reduced to $\Delta = 1$ AU, are about 15 arcsec ($\sim$15%) smaller than the corresponding radii in Table I. This difference is most likely due to the different extrapolation methods employed and the different sensitivities of the CCD and photographic observing systems.

It is important to know whether the observed expansion velocity equals the velocity of the grains ejected from the nucleus or whether it is a "wave" velocity. In the latter case, the radius of the coma might change slowly in response to a variable grain destruction process, although individual grains would approach the coma edge at relatively high speeds. The continuous increase of the coma radius through perihelion may be interpreted as (weak) evidence against the wave interpretation, since most conceivable destructive processes are correlated with R and would be symmetric about perihelion. In the remainder of this paper we will assume that the measured coma expansion velocity equals the true grain velocity. We note that the observed expansion velocity strictly refers only to the fastest grains near the edge of the coma: grains nearer the center could, in principle, be traveling more slowly.

The coma expansion rate, $v \simeq 1$ m sec^{-1}, is small in comparison with the speed computed from Delsemme's (1982) modification of Bobrovnikoff's (1954) empirical relation, $V_{\rm BD} \simeq 250$ m sec^{-1}. The expansion rate is also small in comparison with the speed of sound in the coma at the temperature of the nucleus ($\sim$140°K), namely $v_s \simeq 400$ m sec^{-1}. The former observation suggests a fundamental difference between the coma of comet Bowell and the comae of Bobrovnikoff's comets. The latter observation may suggest that the grains in comet Bowell have a peculiar size distribution peaked toward grains of large radius so that the gas/grain coupling is poor. Alternatively, the latter observation may suggest that the grains are not ejected by gas drag from sublimated volatiles. The coincidence between the coma expansion rate and the gravitational escape speed of a kilometer-sized nucleus suggests the operation of a low energy process, barely able to lift grains from the nucleus against gravity. We briefly describe one possible process.

Sunlit grains on the surface of a cometary nucleus may acquire positive electric charge as a result of the loss of photoelectrons to shadowed regions. The charged grains may be affected by the resulting electrostatic fields of surrounding grains and surfaces. Houpis and Mendis (1981) have balanced electrostatic and gravitational forces to find that only grains of radius $a <$ 0.4 μm may be electrostatically ejected from a kilometer-sized nucleus. However, these authors appear to have neglected the adhesion which commonly binds small grains with forces far greater than the weights of the bound grains. As a result of the adhesive forces, the electrostatic repulsion can grow very large before the grain–grain bonds "snap," leading to the ejection of relatively large grains. On the Moon, snap electrostatic ejection lofts 5-μm dust grains to heights of order 0.3 m (Rennilson and Criswell, 1974; De and Criswell, 1977; Pelizzari and Criswell, 1978). The corresponding ejection speeds are $v_c \simeq 1$ m sec^{-1}, comparable to the speed of expansion of the coma of comet Bowell.

The evaluation of this "electrostatic snap" ejection mechanism requires knowledge of the contact forces between ice grains at low temperatures. The forces between cometary grains may be determined by sintering over cosmical periods and are thus very hard to evaluate. The adhesion occurring between small ice spheres has been experimentally investigated, generally at or very close to the ice melting point. At these temperatures, the adhesion may be enhanced by the presence of a surface water layer: thus most experimental data cannot be directly applied to cometary ice grains which may never have been close to the melting point. One measurement of the adhesive force between ice spheres has been made at $T = 266$°K, a temperature below the range in which a surface water layer is thought to exist. Matsumaru (1974) obtained an adhesive force $F = 9 \times 10^{-7}$ N between ice spheres of radius $a \simeq 13$ μm. The "snapping" of two grains attracted by force F would lead to a grain ejection speed $v_c \gtrsim (2Fa/m)^{1/2} \simeq (F/2\rho a^2)^{1/2}$ where a, ρ, and m are the grain radius, density, and mass, respectively. Taking $\rho = 1000$ kg m^{-3}, we find $v_c \simeq 1.6$ m sec^{-1}. Thus, it is at least plausible that electrostatic snapping of grain bonds could eject 10- to 100-μm grains from the nucleus of comet Bowell and thereby account for the slowly expanding coma.

V. DISCUSSION OF THE PHOTOMETRIC OBSERVATIONS

The main feature of the comet Bowell light curve, shown in Fig. 3, is its small amplitude. Between R = 5.6 AU and R = 3.4 AU, J_c changes by only 2 magnitudes. Almost all of the observed variation can be ascribed to geometric effects. Whereas the apparent brightness of an asteroid should vary as $R^{-2}\Delta^{-2}$, the distributed surface brightness of the coma leads to a slower variation. Since the *surface* brightness of comet Bowell is inversely proportional to the local impact parameter (Paper 1, Fig. 1), the integrated brightness within a specified diaphragm should vary as $R^{-2}\Delta^{-1}$. A model in which a static, constant cross section coma is assumed is illustrated in Fig. 3. Evidently, this inert, static coma model provides an acceptable fit to the data.

A complication arises from the slow expansion of the coma. In the interval of the observations, uniform expansion would open a central hole in the coma with a diameter about 40% of the diameter of the coma on the last date of observation. The absence of such a hole may simply mean that the coma does not expand uniformly at all radii. Alternatively, it may indicate that about 40% of the total grain cross section was produced from the nucleus during the interval of observations. We cannot easily distinguish between these two interpretations, although the latter would seem to be the less plausible of the two. They may be summarized by the statement that not more than about 40% of the total grain cross section was produced from the nucleus between R = 5.6 AU and R = 3.4 AU.

Although the above static coma model provides a simple, self-consistent description of the photometry of comet Bowell we have computed other models in the hope of finding equally successful descriptions. We have previously noted that the slow coma expansion casts doubt on gas drag as the agent responsible for the ejection of grains from the nucleus. The photometric observations provide an independent constraint on the sublimation outgassing of the nucleus. In steady state, the rate of production of grain cross section, dC/dt ($m^2\ sec^{-1}$), will be proportional to the sublimation rate of the nucleus, dm/dt ($kg\ m^{-2}\ sec^{-1}$). The sublimation rate can be estimated by adopting the Clausius–Clapeyron approximation for the gradient of the solid–vapor phase boundary (Glasstone, 1946). Then,

$$\frac{dm}{dt}(T) = \left(\frac{\mu m_H}{2\pi kT}\right)^{1/2} P_0 \exp\left(\frac{\mu m_H L}{kT_0}\right) \exp\left(\frac{-\mu m_H L}{kT}\right) \quad (4)$$

where μ is the molecular weight of the sublimating material, m_H is the mass of a hydrogen atom, and k is Boltzmann's constant. The sublimating material has a latent heat L, and the phase boundary passes through a pressure, temperature reference point P_0, T_0. The nucleus temperature, T, must be found by solving the thermal equilibrium equation at the sublimation surface (e.g., see Delsemme and Miller, 1971). The solution for T depends upon the albedo and emissivity of the nucleus and on its spin period and spin axis. Since none of these quantities is known we have chosen to compute T for a rapidly spinning (isothermal) nucleus having a range of albedos. The resulting models should provide a rough approximation to the true equilibrium sublimation rate.

The sublimation rate was computed along the orbit of comet Bowell using the P_0, T_0, μ, and L values appropriate to H_2O, NH_3, and N_2 ices. These ices were selected to represent weak, intermediate, and strong sublimation, respectively. Their selection was not meant to imply that these particular substances may be present on the nucleus.

The apparent magnitude of the model dust coma, reduced to $R = \Delta = 1$ AU, is computed from

$$J(t) = J_0 - 2.5 \log \left[\int_t^{t_0} \frac{dC}{dt} \cdot dt\right] \quad (5)$$

where

$$t_0 = t - 3\phi\Delta/4v. \quad (5b)$$

Here, the instantaneous rate of change of grain cross section, dC/dt, is assumed to be proportional to the instantaneous equilibrium sublimation rate computed from Eq. (4). The quantity dC/dt is equal to the magnitude of the difference between the rate of cross section production at the time of observation, t, and the rate at time t_0. The time difference $t - t_0$ is a measure of the time taken for grains to cross the projected diaphragm. To order of magnitude, $\phi \approx 10$ arcsec, $\Delta \simeq 4.5 \times 10^{11}$ m, $v = 1\ m\ sec^{-1}$, giving $t - t_0 \sim 2 \times 10^7$ sec. This is sufficiently large that the heliocentric distance changes significantly in the diaphragm crossing time. In Eq. (5) we have neglected the possibility of optical gaseous emission from the coma.

The J magnitude models are plotted in Fig. 4, as are the observed magnitudes from Table II. The illustrated models include the geometric brightness variation and represent the best fits obtained by varying the nucleus albedo and emissivity within wide ranges. Each model has been normalized to the data by selecting an appropriate value of the constant J_0. The figure shows that the model involving equilibrium sublimation of H_2O fails to provide a convincing match to the data. In particular, the amplitude of the model light curve greatly exceeds the amplitude of the observed light curve. The model amplitude could be reduced by assuming a slowly rotating nucleus, but would still be larger than the observed amplitude. The fit could be improved by adopting nucleus albedos <0.02, but such low values are implausible. The poor fit provided by the equilibrium H_2O sublimation model is not surprising, since the sublimation rate of H_2O is an extremely strong

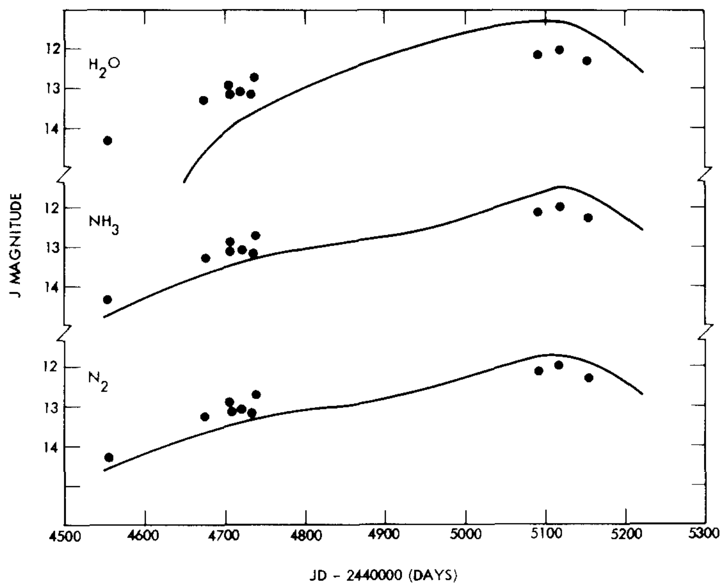

FIG. 4. J_c photometry of comet Bowell compared to equilibrium sublimation models corresponding to H_2O, NH_3, and N_2 ices.

function of heliocentic distance for $R > 3$ AU. The H_2O model is also unreasonable because a nucleus of many hundreds of kilometers would be needed to produce substantial activity at $R \gtrsim 5$ AU and such a nucleus would violate the constraint imposed by Eq. (3).

The NH_3 and N_2 sublimation models are seen to provide successively better approximations to the observed light curve. In particular, the N_2 model has an amplitude only slightly greater than the observed amplitude. The improved fit is a result of the weak dependence of the N_2 sublimation rate on R. The NH_3 and N_2 models are not substantially improved by the adoption of a slowly rotating nucleus. In summary, if equilibrium sublimation is responsible for the ejection of grains into the coma of comet Bowell then the sublimating material must have a volatility comparable to that of solid N_2 in order to match the observed light curve. However, *all* sublimation models are difficult to reconcile with the small coma expansion rate.

VI. DISCUSSION OF THE ULTRAVIOLET OBSERVATIONS

As noted in the Introduction, OH production rates $Q_{OH} \simeq 10^{29}$ sec^{-1} at $R \simeq 5$ AU and $Q_{OH} \simeq 10^{28}$ sec^{-1} at $R \simeq 3.4$ AU (perihelion) have been reported by A'Hearn *et al.* (1982, 1983). The ultraviolet OH observations prompt at least two questions:

(1) What is the source of the large Q_{OH}?

(2) Why did Q_{OH} *decrease* with decreasing heliocentric distance?

Cometary OH is generally interpreted as a photodissociation product of H_2O (e.g., Feldman, 1982). This interpretation is substantiated by measurements of the hydrogen/hydroxyl production rate ratio $Q_H/Q_{OH} \simeq 2$ and by measurements which show that Q_{OH} varies with R in a way consistent with simple water ice sublimation theory (in some comets; see Feldman, 1982). A majority of the published OH observations refer to short period comets, however, and we must at least entertain the possibility that H_2O may not be the parent of OH in the very long period comet Bowell. In this regard we note that in comet Bowell, Q_{OH} does *not* vary with R in the manner expected from simple sublimation theory and furthermore, the production rate of OH at $R = 5$ AU is orders of magnitude greater than can be produced by sublimation of a water ice nucleus of a few kilometers radius. Unfortunately, there appear to be no measurements of Q_H with which to constrain the Q_H/Q_{OH} ratio. In the following discussion, we will *assume* that H_2O is the parent of OH although we know of no scientific justification for this assumption.

A *slowly* rotating greybody at the comet Bowell perihelion distance, $R = 3.34$ AU, would have a dayside surface temperature $T \simeq 179$°K. If made of H_2O ice, the dayside would sublimate at the rate $\dot{m} \simeq 9 \times 10^{-6}$ kg m^{-2} sec^{-1} corresponding to a flux of H_2O molecules $\phi \simeq 3 \times 10^{20}$ m^{-2} sec^{-1} (Washburn, 1928). The observed perihelion OH production could be supplied by sublimation from a nucleus of radius $r_n = (Q_{OH}/2\pi\phi)^{1/2} \simeq 2 \times 10^3$ m. A nucleus of this radius could easily satisfy the observational constraint expressed by Eq. (3). The corresponding quantities for a *rapidly* rotating greybody are $T_1 \simeq 150$°K, $\dot{m} \simeq 1.3 \times 10^{-8}$ kg m^{-2} sec^{-1}, $\phi \simeq 4 \times 10^{17}$ m^{-2} sec^{-1}, and $r_n = (Q_{OH}/4\pi\phi)^{1/2} \simeq 4 \times 10^4$ m. A nucleus of this radius would violate Eq. (3) for any plausible geometric albedo. Hence, the observed *perihelion* Q_{OH} may be consistent with equilibrium sublimation from a slowly rotating water ice nucleus, but not from a rapidly rotating one. The same conclusion has been reached by Keller (private communication referenced by A'Hearn *et al.*, 1983). This conclusion should not be taken to mean that activity at larger R is caused by sublimation of the nucleus.

The production rate $Q_{OH} \simeq 10^{29}$ sec^{-1} observed at $R = 4.6$ AU (A'Hearn *et al.*, 1983) cannot be explained by sublimation of the nucleus at any reasonable temperature. Jewitt (1982) has suggested that the coma grains may be the primary source of gas in comet Bowell because of their very large total cross section, $C(\infty) \simeq 3 \times 10^9$ m^2, relative to that of the nucleus. If the grains are the source of the OH then the sublimation flux is $\phi = Q_{OH}/4C(\infty) \simeq 8 \times 10^{18}$ m^{-2} sec^{-1}. This flux would be expected from a water ice surface at $T \simeq 160$°K (Washburn, 1928). The coma grain temperature at $R = 4.5$ AU was measured to be $T = 140$°K with a 1σ uncertainty of 10°K (Paper 1). Hence, a grain temperature of 160°K is just consistent with the measured temperature, within the uncertainties of the determination. The $\approx$30°K temperature excess above the local greybody temperature (130°K) would result if the grain emissivity at 20 μm was about half the emissivity at 0.5-μm wavelength, and would not be unusually large compared to temperature excesses found in other comets (Ney, 1982).

A'Hearn *et al.* (1983) have reached a similar conclusion concerning the origin of the OH but have assumed a lower grain temperature and used a larger total grain cross section. Their large total grain cross section leads them to adopt a very small grain albedo, $g \simeq 0.0025$. However, combined thermal and near infrared observations suggest larger near infrared albedos $g \simeq 0.07$ to $g \simeq 0.15$ (Veeder and Hanner, 1981; Campins *et al.*, 1982; Paper 1).

We may test the sublimating grain coma hypothesis by comparing the total grain mass with the total mass loss. The total mass of the grains in the coma may be estimated as $m \approx \rho C(\infty) a$, where $\rho = 10^3$ kg m^{-3}, $C(\infty)$ m^2 is the total grain cross section, and a is the grain radius. Evidently, $m \simeq 3 \times 10^{12} a$ kg. Taking $a \lesssim 10^{-3}$ m (Sect. II) gives $m \lesssim 3 \times 10^9$ kg.

The total gas loss from the comet may be estimated from Fig. 6 of A'Hearn *et al.* (1983). By assuming the "quasi-equilibrium" behavior illustrated by A'Hearn *et al.*, the total number of OH radicals produced between $R = 5.5$ AU and $R = 3.4$ AU may be estimated as $N \simeq 10^{29}$ sec^{-1} $\times 3 \times 10^7$ sec $\simeq 3 \times 10^{36}$. The corresponding total mass loss is $M \simeq 9 \times 10^{10}$ kg. Since $M \gg m$ it may be concluded that the sublimating grain hypothesis is not consistent with the quasi-equilibrium scenario as described by A'Hearn. However, it is possible that a significant fraction of the cross section of comet Bowell is due to grains about $M/m \sim 30$ times larger than the tail grains ($a < 10^{-3}$ m). This would imply a very unusual grain size distribution but would not contradict existing observations of comet Bowell. It is also possible that the OH production is overestimated by the interpolations of the quasi-equilibrium model. If the mean OH production rate was $<1/30$ times the peak production rate, then $M/m \sim 1$. A very variable production rate is suggested in the outburst model of A'Hearn *et al.* (1983) and would not violate existing observational constraints.

VII. CONCLUSIONS

(1) Optical observations indicate that the coma of comet Bowell expands at 0.9 ± 0.2 m sec^{-1} in agreement with the conclusion of Sekanina (1982). The slow expansion suggests that either the grain size distribution is unusually peaked towards very large grains or gas drag is not responsible for the ejection of the grains from the nucleus.

(2) The coma radius extrapolates to zero in late 1978. Significant coma ejection was initiated at this time: the comet was at about $R \simeq 10$ AU. There is no evidence to suggest the coma grains were ever in orbit about the nucleus, as proposed by Sekanina.

(3) The product of the optical geometric albedo of the nucleus with the square of its radius is less than 6×10^6 m^2. A nucleus of a few $\times 10^3$ m radius and having a plausible geometric albedo is permitted by the data.

(4) The corrected J magnitude of the comet exhibits variations consistent with the presence of an inert grain coma. The light curve is also consistent with grain ejection caused by sublimation of a very volatile material, but the sublimation model is hard to reconcile with the observed slow coma expansion. The light curve is not readily matched by models involving sublimation of H_2O.

(5) A large part of the grain coma may be a relic of activity on the nucleus at $R \simeq 10$ AU: the ultraviolet OH observations provide evidence for subsequent activity at smaller R.

(6) The parent of the OH is unknown. The magnitude of the OH production rate at $R = 4.6$ AU and the variation of the production rate with R are both inconsistent with a simple H_2O nucleus model. However, a slowly rotating H_2O nucleus of radius $r_n > 3 \times 10^3$ m *could* produce the observed perihelion production rate by sublimation. If the OH produced at $R = 4.6$ AU results from steady sublimation of H_2O ice in the coma grains, then the grains must (a) be $\approx 30°$K hotter than greybodies at the same R, and (b) have radii $a \gg 3 \times 10^{-2}$ m. Neither (a) nor (b) strongly violates existing observational constraints.

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