What Happened to Comet C/2002 O4 (Hönig)?

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Abstract. *The evolution of comet C/2002 O4 (Hönig) is investigated from its discovery to its disappearance, and the issue of its fate is addressed. It is suggested that the comet was discovered while in outburst and that a significant fraction of its initial mass had already been lost by the time this episode terminated before mid-August 2002. The outburst, which apparently engulfed the entire subkilometer-sized nucleus, began 2–3 days before discovery, extending over a period of more than 10 days and perhaps as long as 3–4 weeks, with a peak dust-production rate of* $\sim 10^7$ *g/s, much higher than that of Halley's comet at the same heliocentric distance. The total mass of comet C/2002 O4 expended during the event is estimated at 1–2* $\times 10^{13}$ *grams, a significant fraction of its nucleus mass. The tail orientation pattern suggests that the activity-driven dust production was confined largely to the period of time from* $\sim$ *90 to 50 days before perihelion (early July to mid-August), so the comet may have been active before the outburst. The event set off a process of runaway erosion of the remaining mass of the nucleus, leading to the comet's complete disintegration into dust and minor fragments near perihelion, as indicated by the sudden fading, the loss of nucleus condensation, and the sizable nongravitational perturbations of the orbital motion. If, contrary to the evidence, the nucleus had survived essentially intact and had become dormant, the comet's motion would have been much more compatible with the gravitational law. A model of the light curve suggests that the latent energy of erosion for the nucleus of comet C/2002 O4 was only* $\sim$ *10000 cal/mole, lower than the sublimation heat of water ice. Thus, the comet's disintegration was nearly spontaneous.*

1. Introduction

At the end of September 2002, various cometary web sites reported that comet C/2002 O4 (Hönig) had been fading rapidly just days before reaching perihelion on October 1.98 ET at a heliocentric distance of $r = 0.776$ AU. Discovered on July 22, when it was 1.51 AU from the sun, the object passed within 10° of the north celestial pole in mid-August, but nothing unusual was noticed about it during the first two months of observation.

One of the alerts, released on September 30 on a German website[1], was a message announcing that comet C/2002 O4 had become "very diffuse," displaying "hints of disintegration" in images such as one taken by M. Jäger on September 29.78 UT. In fact, all images taken in the period of time from September 28 to October 1 showed dramatically the progressive loss of the nucleus condensation during the 72 hours. The next known image, taken on October 10 by K. Kadota[2], showed only a faint straight tail with no traces of the nucleus condensation (cf. Green 2002). The complete absence of the comet's head was subsequently confirmed by additional images exposed on October 11, 16, and November 6 by Y. Ohshima[3] and on October 27 by Kadota himself.

Prior to this investigation, the nature and timeline of the process of disappearance of comet C/2002 O4 was unknown. Indeed, it even was not clear *per se* whether the comet disintegrated or has only temporarily become dormant. It is shown below that the published images, light curve, orbital motion, and other available information offer an extraordinary insight into the story of comet C/2002 O4 and allow one to answer in some detail the question of what really happened to this object.

2. Tail Appearance and Evolution

The morphology of the tail of comet C/2002 O4 in the images taken in late September and in October exhibits a great deal of similarity with the tails of other comets in the process of their disappearance. Outstanding examples are C/1999 S4 (LINEAR), C/1996 Q1 (Tabur), and C/1925 X1 (Ensor). Images of the first two can be seen, for example, at the web site of the Črni Vrh Observatory[4], while two photographs of comet C/1925 X1 were published by Schorr

[1]`http://www.fg-kometen.de`, the homepage of the *Fachgruppe Kometen der Vereinigung der Sternfreunde* (Working Group on Comets of the Organization of Star Friends).

[2]`http://www.astro.web.sh.cwidc.net/ageo/comet/200204`

[3]`http://www.hi-ho.ne.jp/hirohisa-sato/Index/c2002o4.htm`

[4]`http://www.fiz.uni-lj.si/astro/comets`

(1926). The comets were investigated, respectively, by Weaver et al. (2001), by Fulle et al. (1998b), and by Sekanina (1984). The authors concluded independently that each of these comets dissipated, the strongest evidence being available for comet C/1999 S4, thanks to the observations with the Hubble Space Telescope (HST) and the European Southern Observatory's Very Large Telescope (VLT).

One trait that these and other similar comets have in common is the sudden drop in activity occurring *before perihelion*. The perihelion distances were 0.323 AU for comet C/1925 X1, 0.840 AU for comet C/1996 Q1, and 0.765 AU (nearly identical with that of C/2002 O4) for comet C/1999 S4. The surviving tails of these comets have been shown to be composed of dust, dominated by relatively large particles (greater than ~ 100 microns in size).

2.1. Nature of the Tail

What kind of a tail did comet C/2002 O4 display? The early images, taken in late July and early August, did not show much of an appendage. The comet exhibited a diffuse coma a few arcmin in diameter, which was distinctly elongated to the southwest. From the spectral sensitivity of the employed CCD detectors, one suspects the observed traces of the tail to be probably made up of dust, but short plasma emissions may have also contributed to the observed appearance. As time went on and the earth was gradually approaching the comet's orbital plane, the tail lengthened and became more prominent. This effect appears to be due to an optical-depth enhancement caused by the increasingly more-pronounced edgewise projection, which is diagnostic of the tail's dust nature and never associated with ion tails. Only hours before the earth's transit across the plane, an image was taken by V. Gonano, L. Monzo, and M. Maestrutti[5] with a Baker-Schmidt camera, a CCD array, and an infrared filter. The appearance of the tail was the same as in other images taken with no filter at about that time. A binocular observation made nearly simultaneously by M. Meyer[6] demonstrates that the tail appeared visually to be much longer than in the images, possibly due to the loss of contrast in reproduction. Interestingly, the tail continued to project as a fairly narrow feature for almost the whole month after the earth's transit across the orbital plane, but I am unaware of any image in which the typical filamentary structure of a plasma tail could be detected. The closest the tail got to looking like an ion feature was on M. Jäger's[7] exposure from August 21. Starting in the second week of September, the tail finally began to widen, acquiring the more characteristic proportions of a dust formation.

In summary, it is probably safe to assume that the tail was made up entirely, or almost entirely, of dust at all times. Its somewhat peculiar shape was apparently a combined effect of the geometry (especially the nearness to the orbital plane) and the temporal distribution of dust production.

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TABLE 1

EPHEMERIS FOR DUST-TAIL ORIENTATION OF COMET C/2002 O4 (EQ. J2000.0).

Date 2002 (0h ET)	Time from peri-helion (days)	Comet's distance (AU) from		Earth's cometo-centric latitude	Position angle[a]		Predicted position angle P.A. and apparent length L for dust tail formed at given time before perihelion[b]									
							100 days		80 days		60 days		40 days		20 days	
		Earth	Sun		PA(*RV*)	PA(−*V*)	P.A.	L	P.A.	L	P.A.	L	P.A.	L	P.A.	L
July 25	−68.98	0.789	1.470	+24°	227°	200°	219°	0′.3	227°	<0′.1	...	...	...	...	...	...
Aug. 4	−58.98	0.674	1.333	+14	211	196	206	0.8	208	0.2	210°	<0′.1	...	...	...	...
14	−48.98	0.655	1.199	0	173	173	173	1.5	173	0.7	173	0.1	...	...	...	...
24	−38.98	0.727	1.071	−13	73	87	79	2.2	78	1.2	76	0.4	73°	<0′.1	...	...
Sept. 3	−28.98	0.854	0.954	−22	45	72	58	2.8	56	1.8	53	0.8	49	0.1	...	...
13	−18.98	1.000	0.859	−28	30	68	51	3.4	48	2.4	45	1.4	40	0.5	31°	<0′.1
23	−8.98	1.142	0.796	−32	15	64	45	4.2	43	3.2	39	2.1	34	1.0	24	0.1
Oct. 3	+1.02	1.265	0.776	−35	358	59	39	5.2	36	4.1	33	2.9	27	1.7	18	0.5
13	+11.02	1.359	0.805	−37	340	53	32	6.4	30	5.3	26	4.0	21	2.6	12	1.1
23	+21.02	1.421	0.876	−39	322	48	26	7.6	23	6.5	20	5.2	14	3.7	5	1.9
Nov. 2	+31.02	1.455	0.977	−40	309	45	20	8.8	17	7.8	14	6.5	8	4.9	0	2.9

[a] ***RV*** is the projected extended radius vector (antisolar direction); −***V*** is the projected reverse orbital-velocity vector (direction of the orbit behind the comet).

[b] The tail is assumed to contain dust grains that are subjected to radiation-pressure accelerations not exceeding 0.2 percent of the solar gravitational acceleration; these grains are all greater than 0.76 millimeter in diameter for a density of 0.5 g/cm^3 and greater than 2.8 millimeter in diameter for 0.2 g/cm^3.

[5] http://www.uai.it/sez_com/2002o4

[6] http://cfa-www.harvard.edu/icq/CometMags.html

[7] http://www.fg-kometen.de/pix/pc02o4_e.htm

2.2. *Tail Orientation*

Since a history of dust production (including its termination) can be extracted from the dust tail's orientation pattern, a high priority in an investigation of comet C/2002 O4's fate should be examining the relevant properties of its tail. For this purpose I calculated a dust-emission ephemeris, which is presented in Table 1. The first four columns are self-explanatory. The fifth column lists the earth's cometocentric latitude, its angular deviation from the comet's orbital plane as viewed from the object — a very critical parameter. Since a dust tail's axis always lies in the comet's orbital plane (or very close to it), the tail is projected edge-on, as viewed by a terrestrial observer, at the time the earth transits across the orbital plane; no information is then available on the tail's spatial orientation. Usually, one cannot extract useful data from images taken at cometocentric latitudes smaller in absolute value than some 10°. In the case of comet C/2002 O4, this unfavorable period of time extended for about two weeks, centered on August 14, the earth's transit time. The sixth and seventh columns of Table 1 show the position angles (reckoned from the north through the east) of, respectively, the extended radius vector **RV** (i.e., the antisolar direction) and the reverse orbital-velocity vector −**V** (i.e., the direction of the orbit behind the comet), both in projection onto the plane of the sky. These two vectors determine the boundaries of the sector in which the entire dust tail is to be contained. The position angle of the extended radius vector approximates the directions of dust ejecta released at times shortly preceding the observation time, while the position angle of the reverse orbital-velocity vector defines the direction of concentration of the earliest dust ejecta.

Outside the period of unfavorable earth-comet configuration, the times of significant dust production can be estimated by measuring orientations of the dust-tail axis and comparing them with the ephemeris in Table 1. While the accuracy of this approach is much lower than that of a comprehensive and time-consuming dust-tail analysis, it provides meaningful information on the object's dust-production history. Particles assumed to have been ejected from comet C/2002 O4 between 100 and 20 days before perihelion (i.e., between 2002 June 24 and September 12) are predicted to line up in the tail along straight lines in the position angles (P.A.) that are listed in the respective columns on the right-hand side of Table 1, together with the predicted tail lengths L (in arcmin) referring to a population of grains subjected to solar-radiation-pressure accelerations not exceeding 0.002 the solar gravitational acceleration (or ~ 0.0012 cm/s^2 at 1 AU from the sun). The diameters of these dust particles are density dependent, but exceed 0.11 cm at a density of 0.5 g/cm^3 and 0.28 cm at 0.2 g/cm^3.

2.3. *Constraints on Dust Production*

Cursory inspection of the tail orientations in a number of late-September images, and comparison of them with the position angles in Table 1, revealed immediately the tail's major departure from the direction of the antisolar direction. Indeed, the comet was then almost exactly to the north of the sun, but the entire body of the tail, including its leading boundary, was pointing clearly to the northeast, indicating the absence of dust ejecta for quite some time prior to perihelion. Still more obvious deviations of the tail from the antisolar direction were noticed in the October images, in which the tail was directed toward the north-northeast, whereas a tail made up of near-perihelion dust emissions should have pointed toward the northwest. It thus became obvious that *the comet's dust production did not begin to decrease significantly in late or mid-September, but much, much earlier.*

To obtain better estimates for the timing of the dust-emission activity of comet C/2002 O4, the tail orientation data were collected either as reported in the literature or measured by the author (Z.S.) on a number of selected images. The measurements could only be made on images with the cardinal directions identified or with star trails, from whose positions the orientation could be established. A list of such images is presented in Table 2. The first five columns contain the same quantities as Table 1, while the remaining six show, respectively, the tail's measured or reported position angle and length, the derived ejection time and peak solar-radiation-pressure acceleration (in units of the solar gravitational acceleration) to which dust in the tail was subjected, the observer(s), and the source of information.

The results of this exercise are astonishing: all 23 determinations of the effective time of dust ejection consistently show that it occurred more than 50 days before perihelion, and 17 of these determinations, which are considered to be reasonably accurate, yield an average of 70 ± 9 days before perihelion. Thus, evidence based on the tail orientation data suggests that comet C/2002 O4 was producing dust primarily in the period of time from some 90 to 50 days preperihelion (from early July until mid-August 2002), when its heliocentric distance ranged from $r \sim 1.76$ to 1.21 AU. The discovery time, 72 days before perihelion, happens to be in the midst of this period of activity. The results, especially those derived from the images taken in the period September-October, also indicate that the tail indeed consisted mainly of heavy grains, subjected to radiation-pressure accelerations of only a few thousandths of the solar gravitational acceleration (cf. Sec. 4).

In the light of the surprising findings regarding the dust production's temporal profile, it is desirable to study the comet's brightness behavior, the next subject of this paper.

3. The Light Curve

It is fortunate that, due to its geocentric path that made it a circumpolar object in much of Europe and North America during August and the first half of September, the comet was observed extensively by many amateur observers, and a very dependable light curve could be constructed from a large number of magnitude estimates. My primary source was the *International Comet Quarterly* website (see footnote 6), supplemented with several data points from the Jet Propulsion Laboratory's 'Comet Observation Home Page', which is maintained by C. S. Morris[8]. The analysis followed a

[8] `http://encke.jpl.nasa.gov/RecentObs.html`

TABLE 2

ORIENTATION AND LENGTH OF THE TAIL OF COMET C/2002 O4 (EQ. J2000.0).

Date 2002 (UT)	Time from perihelion (days)	Earth's cometocentric latitude	Position angle		Observed position angle of tail	Observed apparent length of tail	Derived dust ejection time[a]	Derived radiation pressure acceleration[b]	Observer(s)	Note
			PA(***RV***)	PA(−*V*)						
July 27.65	−66.33	+22°	223°.4	199°.4	213°	1′.8	(−129)	(0.003)	Kadota	1,2
27.85	−66.13	+22	223.1	199.4	215	3	(−109)	(0.005)	Sanchez	1
28.84	−65.14	+21	221.6	199.1	217	2.5	−85	0.029	Ligustri, Degano	3
Aug. 2.88	−60.10	+15	213.0	197.1	211	2.5	−71	0.072	Ligustri, Degano	3
3.90	−59.08	+14	211.0	196.4	~205	1	(−106)	(0.002)	Tichá, Tichý	4
5.70	−57.28	+12	207.0	195.0	207	4	...	...	Kadota	2
7.99	−54.99	+9	201.0	192.3	199	1	(−77)	(0.005)	Nicolini	3
12.91	−50.07	+2	180.4	178.8	182	6	...	...	Ligustri	3
13.90	−49.08	0	173.7	173.6	174	8	...	...	Gonano et al.	3,5
13.91	−49.07	0	173.7	173.5	175	18	...	...	Meyer	6
14.04	−48.94	0	172.7	172.7	174	6	...	...	Ligustri	3,5
15.89	−47.09	−3	155.8	158.6	157	5	...	...	Kopplin	7
19.01	−43.97	−7	117.1	124.3	117	...	...	...	Jäger	7,8
19.97	−43.01	−8	105.6	114.2	107	5	(−58)	(0.045)	Degano	3
21.07	−41.91	−9	94.2	104.3	97	...	(−73)	...	Jäger	7
30.85	−32.13	−19	50.9	74.0	58	4	−67	0.008	Ligustri, Degano	3
Sept. 1.90	−30.08	−21	46.9	72.6	56	6.5	−69	0.011	Kopplin	7
2.91	−29.07	−22	45.1	72.0	57	5	−87	0.005	Kopplin	7
5.81	−26.17	−24	40.5	70.8	49	2.5	−54	0.007	Montanucci	3,5
7.79	−24.19	−25	37.6	70.1	48	3.5	−57	0.008	Ligustri, Savani	3
8.84	−23.14	−26	36.1	69.7	48	3.5	−60	0.006	Kopplin	7
14.80	−17.18	−29	27.7	67.6	47	3	−78	0.002	Ligustri	3,5
28.77	−3.21	−33	5.9	60.9	37	4	−67	0.003	Ligustri	3,5
29.77	−2.21	−34	4.2	60.4	37	2.5	−71	0.002	Ligustri	3,5
30.75	−1.23	−34	2.4	59.8	37	5	−74	0.003	Sostero	3,5
30.76	−1.22	−34	2.4	59.8	36	4	−68	0.002	Jäger	5,7,8
Oct. 1.75	−0.23	−34	0.7	59.2	36	3	−72	0.002	Ligustri	3
10.82	+8.84	−36	343.9	54.1	30	6	−78	0.002	Kadota	2
16.80	+14.82	−37	332.9	51.0	23	8	−57	0.004	Ohshima	9
27.83	+25.85	−39	315.3	46.3	19	6	−73	0.002	Kadota	2

[a] Corresponding to the position angle of the tail's axis and expressed in days from perihelion; negative sign indicates time before perihelion. A parenthesized value means that ejection time is uncertain because the tail's dust nature is unclear (July 27.85), or the tail is too diffuse and/or short (July 27.65 and Aug. 3.90), or Earth is too close to the comet's orbital plane (Aug. 7.99, 19.97, and 21.07).

[b] Corresponding to the apparent tail length for the given ejection time and expressed in units of the solar gravitational acceleration (0.593 cm/s^2 at 1 AU from the Sun).

NOTES:
1. Hergenrother (2002).
2. http://www.astro.web.sh.cwidc.net/ageo/comet/2002O4.
3. http://www.uai.it/sez_com/2002o4.
4. http://www.klet.org/ck02o040.html.
5. http://encke.jpl.nasa.gov/images/02O4.
6. http://cfa-www.harvard.edu/icq/CometMags.html.
7. http://www.fg-kometen.de/pix/pc02o4_e.htm.
8. http://www.astrostudio.at/defaultNets.htm.
9. http://www.hi-ho.ne.jp/hirohisa-sato/Index/c2002o4.htm.

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(text continued from page 225)

standard procedure. The visual magnitude estimates and a limited number of CCD magnitudes have been standardized, to the extent possible, by applying corrections for personal and instrumental effects, and then normalized to a unit geocentric distance Δ by an inverse power law.

The magnitude standardization procedure consisted of visually comparing temporally overlapping light curves based on observations made by individual observers (separately for each instrument, when more than one was used) and minimizing the scatter among them by shifting them up or down, as needed, along the magnitude axis. If any two light curves by different observers/instruments did not overlap one another in time, effort was made to employ additional light curves by others to span the gap. In this trial-and-error manner, constant corrections for all the accepted, reasonably uniform data sets were eventually obtained and subsequently normalized to a common photometric system, for which I adopted the brightest among the personal light curves. Any data set for which an appropriate correction could not be determined was rejected. Isolated magnitudes – one or two per observer and instrument – were ignored, with the exception of the discovery magnitude estimate that was used, even though it was uncorrected for personal and instrumental effects. Thus, as usual, the normalized magnitude $H_\Delta(t,r)$ is related to the standardized apparent magnitude $H(t,r,\Delta)$ by

$$H_\Delta(t,r) = H(t,r,\Delta) - 5\log_{10}\Delta, \qquad (1)$$

where Δ is in AU.

Altogether, 146 magnitudes by 19 observers were employed, covering the period July 22 through October 1. The uncorrected magnitude estimate at the time of discovery appears to match the comet's brightness behavior in the early period of time after discovery quite well. Crude postperihelion estimates of the residual tail's brightness were not included in this data set.

The brightness was plotted against time and heliocentric distance in a search for the most complete description of the light curve possible.

3.1. *Temporal Variations*

In order to fit the light curve plotted as a function of time, attempts were made to use various polynomials of $t-T$, where T is the time of perihelion passage. A very satisfactory fit was achieved using the following quartic polynomial:

$$H_\Delta(t) = H + a(t-T) + b(t-T)^2 + c(t-T)^3 + d(t-T)^4, \qquad (2)$$

with a mean residual of $\pm$ 0.15 mag, where $H = 9.53 \pm 0.12$, $a = 0.186 \pm 0.017$, $b = 0.00753 \pm 0.00092$, $c = 0.000144 \pm 0.000019$, and $d = 0.00000115 \pm 0.00000013$. Figure 1 shows that this polynomial matches the observations extremely well at $t < T - 20$ days (that is, before September 12 and at heliocentric distances, r, exceeding 0.86 AU). The peak brightness was reached nominally at $t_{\rm peak} = T - 29.24$ days, on September 2, at which time $H_\Delta(t_{\rm peak}) = 7.77$. Because of the finite lifetime of the dust ejecta in the cloud surrounding the nucleus, the comet's dust production must have peaked long before early September, a constraint that is consistent with the conclusions in Sections 2.3 and 5.

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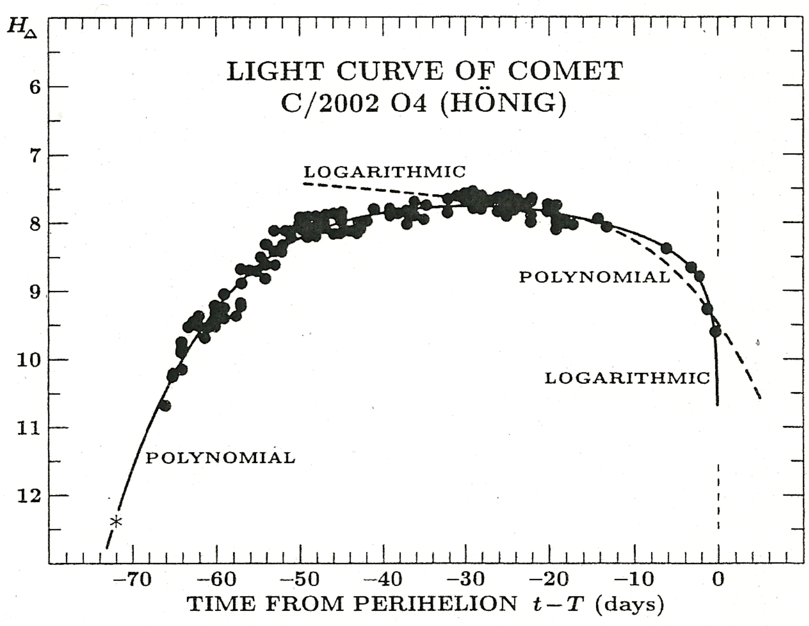

Figure 1. The magnitude $H_\Delta(t)$ of comet C/2002 O4, normalized to 1 AU from the earth, plotted as a function of time reckoned from the perihelion time T = 2002 Oct. 1.98 ET. The bullets are 145 data points based on the reported visual or CCD magnitudes, which were standardized, to the extent possible, by applying corrections for personal and instrumental effects. The asterisk is the uncorrected brightness estimate made at the time of discovery. The two fitted curves are, respectively, a quartic polynomial approximation described by Equation (2) and labeled **POLYNOMIAL**, *and a simple erosion law described by Equation (5) and labeled* **LOGARITHMIC**. *The polynomial fits the observed light curve extremely well at times $t \leq T - 20$ days, while the logarithmic law at times $T - 20$ days $\leq t < T$. At $t = T - 20$ days both functions give the same magnitude and the same slope.*

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Near perihelion, the polynomial does not fit the extraordinarily steep drop in the observed light curve. In this 20-day time span, a much better match is offered by a simple law based on the assumption that the comet was indeed disintegrating completely. In the first approximation, I adopt that (i) the nucleus was eroding away rapidly at a constant rate $\dot{R}$ with time and (ii) the normalized brightness $\Im_\Delta(t)$ varied with some power ν of the contracting nuclear radius $R(t)$,

$$\Im_\Delta(t) \propto [R(t)]^\nu \propto \left[R_0 - \dot{R} \cdot (t - t_0)\right]^\nu, \tag{3}$$

where $R_0 = R(t_0)$ was the initial nucleus radius at time t_0, before the erosion process set in. Introducing the time of demise $t_{\rm fin}$, when $R(t_{\rm fin}) = 0$, one obtains $R(t) = \dot{R} \cdot (t_{\rm fin} - t)$ and

$$H_\Delta(t) = H_1 - 2.5\nu \log_{10}(t_{\rm fin} - t), \tag{4}$$

where H_1 is the normalized magnitude one day before the object eroded away completely. Assuming that $t_{\rm fin} = T$, I obtain an excellent fit to the light curve in the period $T - 20$ days $< t < T$ (September 12 through October 1, $r \leq 0.86$ AU) using the formula:

$$H_\Delta(t) = H - A \log_{10} |t - T|, \tag{5}$$

where $H = 9.22 \pm 0.08$ and $A = 1.050 \pm 0.073$. This law is represented in Fig. 1 by a curve labeled **LOGARITHMIC**; at $t = T - 20$ days, it predicts the same magnitude ($H_\Delta = 7.85$) and the same fading rate ($\dot{H}_\Delta = +0.02$ mag/day) as the polynomial (equation 2). One would expect that if physical erosion of the nucleus is indeed the cause of the precipitous drop in the comet's brightness just before perihelion, the instantaneous rate of fading should vary as the surface area, in which case $\nu = 2$ and the slope in Eq. (5) should be 5 instead of 1.05. However, the finite lifetime of erosion products lingering in the immediate proximity of the contracting nucleus should cause the observed rate of fading to appear to be much slower.

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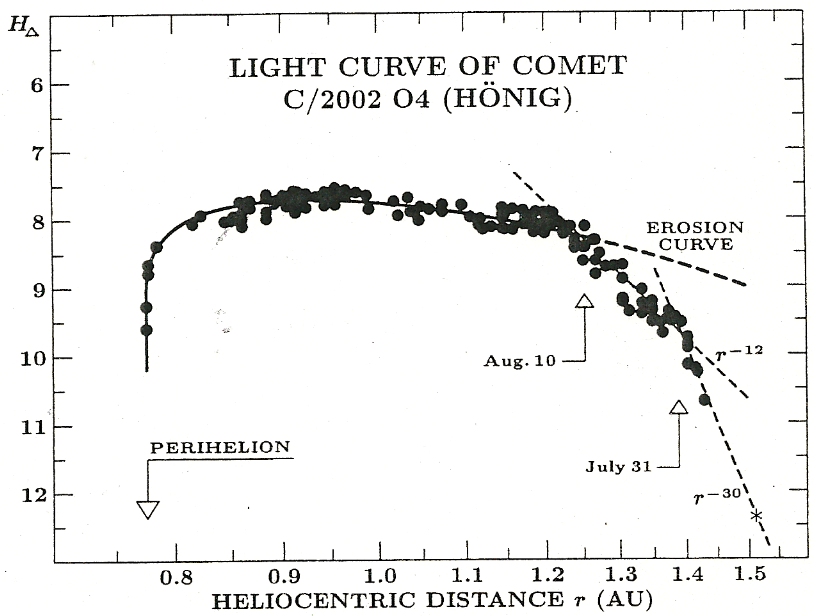

Figure 2. The magnitude $H_\Delta(r)$ of comet C/2002 O4, normalized to 1 AU from the earth, plotted as a function of heliocentric distance, r. The bullets are 145 standardized data points, as described in the caption to Fig. 1, the asterisk is the reported magnitude estimate at discovery. The two short-dash curves show the brightness variations that are consistent with the power laws r^{-30} and r^{-12}, matching reasonably well the magnitude observations at $r > 1.39$ AU (before July 31.0 UT) and $1.39 \geq r > 1.25$ AU, respectively. The data points at $r \leq 1.25$ AU (after August 10.0 UT) are fitted most satisfactorily by a law labeled **EROSION CURVE** *and derived from a comprehensive erosion model, which was recently developed to study the light curves of the SOHO sungrazers. For the nucleus of comet C/2002 O4, this model implies a latent energy of erosion of only 10000 cal/mole, which is less than the sublimation heat of water ice.*

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3.2. *Variations with Heliocentric Distance*

The evolution of the light curve as a function of heliocentric distance can be divided into three consecutive stages (Fig. 2). In the first nine days after discovery (July 22–30), the comet is found to have been brightening as r^{-30}. This is equivalent to $\dot{H}_\Delta \simeq -0.3$ mag/day, a rate that is sufficiently high to be symptomatic of cometary outbursts or flare-ups. Indeed, the amplitude and the rise time of one of the outbursts of C/2001 A2 (LINEAR) imply the same average brightening (Sekanina *et al.* 2002). Thus, I submit that *comet C/2002 O4 was discovered while in outburst.*

On July 31, when $H_\Delta = 9.7$ at 1.39 AU from the sun, the second stage began. The comet was brightening at a rather slower pace, but still as steeply as r^{-12}. The equivalent average daily rate was −0.14 mag/day, about one half the rate before July 31. This stage appears to have extended for 10 days, terminating 53 days before perihelion, on August 9, when the normalized magnitude reached 8.3 at 1.25 AU from the sun. The reason for the sudden change in the slope of brightening is unknown, but I suggest that it had to do with dust-production variations (or activity in general) during the outburst, just before July 31 (see Sec. 5).

On about August 10, the comet's brightening slowed down dramatically, signaling the arrival of the third stage. The normalized brightness varied as $r^{-2.5}$ in mid-August, at $r \simeq 1.2$ AU, but only as r^{-1} in late August, at $r \simeq 1$ AU. A plateau was reached between 0.9 and 1 AU, followed by the comet's accelerated fading at < 0.9 AU and by its disappearance at perihelion.

The timing coincidence between the cessation of the comet's steep brightening on approximately August 10 and the termination of the principal dust-emission activity in mid-August, as established in Sec. 2.3, is likely to be physically significant. It could mean that by about this time the comet's sublimation (of water ice and other volatiles) and associated production of dust was essentially brought to an end, and that, *from mid-August on, any lingering "activity" of comet C/2002 O4 was supported by, or related to, its nucleus erosion*, as proposed in Sec. 3.1.

To examine this possible scenario in some detail, I made an attempt to fit the third stage of the light-curve evolution by an erosion model that I recently developed (Sekanina 2002) for an in-depth investigation of the light curves of the sungrazing comets discovered with two coronagraphs onboard the *Solar and Heliospheric Observatory* (SOHO). I propose that the process of nucleus erosion for comet C/2002 O4 was dominated by runaway bulk fragmentation, which started at a particular time and proceeded continuously at a rate that is assumed to follow the same type of law as sublimation. The most critical parameter of the model is an effective latent energy of erosion, which is analogous to the latent heat of sublimation.

The result of the fitting procedure is shown as **EROSION CURVE** in Fig. 2. The curve matches the observations extremely well, strengthening the notion that this portion of the light curve signals the comet's complete disintegration rather than temporary dormancy. Interestingly, the results indicate that the erosion energy of the nucleus was only ~ 10000 cal/mole and that therefore *it was in fact easier to erode the nucleus of comet C/2002 O4 than to sublimate water ice from its surface*, which requires 11500 cal/mole at a temperature of 200°K. The model also provides information on the rate of nucleus contraction due to erosion as a function of time. The comet's brightness is found to have peaked 27 days before perihelion, on September 5, at a heliocentric distance of 0.93 AU, at which time the nucleus size was 0.78 its "initial" size, in mid-August. The nucleus dimensions are calculated to have decreased to 0.90 of the initial dimensions at 40 days before perihelion (August 23), to 0.63 at 20 days before perihelion (September 12), to 0.44 at 10 days before perihelion, and to 0.22 the initial size at 1 day before perihelion (October 1.0 ET). The nucleus is calculated to have disintegrated into a cloud of boulders and dust within a few days after perihelion.

4. The Orbit

As the interval of comet C/2002 O4's observations was growing longer, the knowledge of its orbit was gradually improving. First, a parabolic approximation was used and the planetary perturbations were ignored. Starting with early September, however, four sets of osculating orbits, fully accounting for the effects of the planets, were successively published by Marsden (2002a, b). With no nongravitational terms incorporated into the equations of motion, the original orbit[9] came out to be hyperbolic, the reciprocal semimajor axis always amounting to $(1/a)_{\rm orig} < -0.0004$ AU^{-1}.

The incorrectness of a simple-minded interpretation of this result in terms of an interstellar origin of comet C/2002 O4 is underscored by a prominent systematic trend in the values of the original semimajor axis. Evidence is provided by Marsden's four sets of orbital elements, which link all accurate astrometric positions starting with the first reported observation on July 27.65 UT and ending with the observations made, respectively, on September 2.90, 10.83, 13.90, and 23.44 UT. The intervals of heliocentric distances corresponding to these time spans are listed in the third column of Table 3. As the quality of the orbital elements gradually improved, one would expect $(1/a)_{\rm orig}$ to converge to some limit. Instead, the fourth column of the table shows that it became ever more negative with time, implying a systematically increasing hyperbolic excess. The obvious question is why was it so?

4.1. Nongravitational Perturbations

It is shown below that a systematic trend of this kind is exactly what one should expect if the comet is subjected to nongravitational forces. If the orbital arc is short enough, as it is in the case of comet C/2002 O4 — less than two months — a formal gravitational solution does not necessarily leave systematic residuals from the observed orbital track. Instead, the nongravitational forces distort the orbital elements in order to accommodate the forced value of the fundamental quantity employed — the Gaussian gravitational constant $k_\odot$ for the sun. Indeed, the nongravitational forces that cometary nuclei are subjected to have a strong tendency to act in a direction opposite that of the sun's

[9]The original orbit of a comet is determined from its osculating orbit by integrating the object's motion from the epoch of osculation back in time to a sufficiently large heliocentric distance (usually ~ 50 AU or so) and referring it to the barycenter of the solar system rather than to the sun.

gravitational force. The motions of active comets that do not disintegrate on short time scales are usually affected by small but detectable retrorocket-like forces due to sublimation of volatile substances predominantly from the sunward side of their nucleus surface. In the case of comet C/2002 O4, one suspects that a significant fraction of the nongravitational force comes from solar radiation pressure, once the bulk of the comet's mass is distributed in sufficiently small fragments. Regardless of the ratio of the relative contributions from the two sources, the object orbits the sun in a gravity field that is slightly weaker than the sun's and whose effective Gaussian gravitational constant $k_{\rm eff}$ is very slightly smaller than $k_\odot$, while the orbital elements are derived with $k_\odot$.

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TABLE 3

LEAST-SQUARES FIT TO ORIGINAL RECIPROCAL SEMIMAJOR AXIS OF COMET C/2002 O4 FROM MARSDEN'S ORBITAL RUNS.

	Orbital run					Residual $o-c$
Run No.	Dates covered by astrometry, 2002 (UT)	Range of distances from Sun, r (AU)	Original reciprocal semimajor axis, $(1/a)_{\rm orig}$ (AU^{-1})	Average true anomaly, $v_{\rm aver}$	No. obs. used	for $(1/a)_{\rm orig}$ from weighted solution (AU^{-1})
1	July 27.65–Sept. 2.90	1.434–0.955	-0.000520 ± 0.000096	$-69^\circ.27$	946	+0.000053
2	July 27.65–Sept. 10.83	1.434–0.877	-0.000694 ± 0.000054	−64.76	984	−0.000029
3	July 27.65–Sept. 13.90	1.434–0.852	-0.000717 ± 0.000031	−63.07	1088	−0.000018
4	July 27.65–Sept. 23.44	1.434–0.794	-0.000772 ± 0.000021	−58.72	1135	+0.000011

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It is easy to find out the effect of this slight discrepancy on the orbit. Consider a comet moving about the sun in an elliptical orbit with a period P, unperturbed by the planets. This orbital period is related to the semimajor axis a by the third Keplerian law. From the condition of P = constant, a differentiation of the expression provides the following relationship between the slight changes in k and $1/a$ (dropping, from now on, the subscript):

$$d\left(\frac{1}{a}\right) = -\frac{2}{3}\left(\frac{1}{a}\right)\cdot\frac{dk}{k_\odot}. \qquad (6)$$

This equation shows that when a gravitational constant ($k_\odot$) *greater* than the correct one ($k_{\rm eff}$) is employed in an orbital solution, the reciprocal semi-major axis resulting from such a solution is *smaller* (*more negative*) than is the correct $1/a$ value.

One can now make two conclusions: (i) the finding that the original orbit of comet C/2002 O4 derived with the use of $k_\odot$ was hyperbolic does not exclude the possibility that its true orbit was elliptical; and (ii) formula (6) makes it possible to investigate the magnitude of $k_{\rm eff}$ in terms of variations in $1/a$. The second conclusion is important not only because the changes in $1/a$ are readily available, but also because of the need to find out how these variations propagate along the orbit, an issue that is not addressed by Eq. (6).

4.2. Variations in Semimajor Axis Along the Orbit

It is well known that, for any k, a radial (nongravitational) acceleration $j_{\rm R}(t)$ (reckoned positive in the antisolar direction), to which the nucleus of a comet is subjected at time t, causes the following instantaneous change in the reciprocal semimajor axis:

$$d\left(\frac{1}{a}\right) = -\frac{2e}{k\sqrt{p}}j_{\rm R}(t)\sin v(t)dt, \qquad (7)$$

where e is the orbit eccentricity, $p = q(1+e)$ the parameter of the orbit, q the perihelion distance, and $v(t)$ the true anomaly at time t. Because the issue of the sign of $d(1/a)$ has already been settled, only the absolute value of the effect is of interest from now on. After substituting dv for dt from the second Keplerian law, one finds:

$$\left|d\left(\frac{1}{a}\right)\right| = \frac{2e}{k^2p}j_{\rm R}(r)r^2|\sin v|dv. \qquad (8)$$

An acceleration due to the nongravitational force driven by water-ice sublimation varies approximately as r^{-2} near the sun, but more steeply at heliocentric distances beyond ~ 2 AU. An acceleration due to sublimation of more volatile substances (e.g., CO_2, CO, etc.) varies as r^{-2} to much larger distances, while solar radiation pressure varies as r^{-2} at all distances from the sun. Since the comet was discovered only 1.5 AU from the sun, an approximation of variations in the effective nongravitational acceleration $j_{\rm R}$ in Eq. (8) by this law is entirely appropriate. I thus adopt

$$j_{\rm R}(r) = j_0(r_0/r)^2, \qquad (9)$$

where $r_0 = 1$ AU and j_0 is the nongravitational acceleration at 1 AU, the quantity of major interest in this study. When (9) is inserted for $j_R(r)$ in (8), the equation can immediately be integrated. Further, replacing v with $\frac{1}{2}v$, the integration of equation (8) up to an arbitrary location in the preperihelion branch of the orbit, reached by the comet at time $t = t(v)$, yields

$$\frac{1}{a} = f_0 - g_0 \cos^2 \frac{1}{2}v, \tag{10}$$

where f_0 is an integration constant (nominally, $1/a$ extrapolated to the previous aphelion), and

$$g_0 = \frac{4er_0^2}{k^2 p} j_0. \tag{11}$$

Expression (10) is, of course, the equation of a straight line on a plot of $1/a$ versus $\cos^2 \frac{1}{2}v$, with g_0 being the slope.

4.3. Results from the Orbital Calculations

Each value of the original semimajor axis derived by Marsden (2002a, b) is, just as all the other elements, a function of the distribution of the employed astrometric observations along the given orbital arc, from the first measured position, at time $t_{\rm beg}$, to the last position, at $t_{\rm end}$, used in the orbital solution (Table 3). Let the true anomalies at these boundaries be, respectively, $v_{\rm beg}$ and $v_{\rm end}$, and let the observations be distributed more or less uniformly between $t_{\rm beg}$ and $t_{\rm end}$. Then the value of $1/a$ should, according to equation (10), refer to a point very near the middle of the corresponding interval. Thus, the term $\cos^2 \frac{1}{2}v$ on the right-hand side of (10) can closely be approximated by an average value in the relevant orbital arc,

$$\langle\cos^2 \frac{1}{2}v\rangle = \frac{1}{2}\left(\cos^2 \frac{1}{2}v_{\rm beg} + \cos^2 \frac{1}{2}v_{\rm end}\right). \tag{12}$$

The average true anomaly $v_{\rm aver}$, defined as

$$v_{\rm aver} = 2 \arccos \sqrt{\langle\cos^2 \frac{1}{2}v\rangle}, \tag{13}$$

and listed in the fifth column of Table 3, completes the information needed to find the parameters f_0 and g_0 from Eq. (10). Although the number of used astrometric observations increased by only 20 percent from the first to the last run (column 6), the formal error of the semimajor axis, depending critically on the length of the orbital arc, decreased by a factor of 4.6. For this reason, I employed a *weighted* least-squares solution to find

$$f_0 = +0.00115 \pm 0.00022 {\rm AU}^{-1} \tag{14a}$$

$$g_0 = +0.00254 \pm 0.00030 {\rm AU}^{-1}. \tag{14b}$$

The residuals $o - c$, observed minus calculated, are listed in the last column of Table 3, confirming that the solution is very satisfactory, because no residual exceeds 0.6 the formal mean error in the values of the original reciprocal semimajor axis.

With $k \simeq k_\odot = 0.0172021$ AU$^{\frac{3}{2}}$/day and the elements $p \simeq 1.5531$ AU and $e \simeq 1.00086$ from the most updated orbit by Marsden (2002b), one finds from Eq. (11)

$$j_0 = (2.92 \pm 0.34) \times 10^{-7} {\rm AU/day}^2 = (5.84 \pm 0.69) \times 10^{-4} {\rm cm/s}^2. \tag{15}$$

The resulting value of j_0 indicates the presence of a major effect. Compared with other comets in the orbit catalogue by Marsden and Williams (2001), *comet C/2002 O4 belongs to the objects whose motions deviate from the gravitational law most significantly*, even though quantitative comparison is difficult because for all extensively observed comets in the catalogue, whose nongravitational parameters could be derived, both the radial and transverse components were calculated. My result is equivalent to a radial nongravitational parameter of $A_1 \simeq 29 \pm 3$ units in a scenario in which $A_2 \equiv 0$ and $A_3 \equiv 0$.

The finding of this dynamical effect settles the crucial issue of *what happened to comet C/2002 O4: it truly disintegrated into a cloud of minor fragments and dust*, apparently much like comet C/1999 S4 (LINEAR) and other similar objects. Indeed, *if comet C/2002 O4 remained intact and became dormant, its orbital motion would have been (almost) purely gravitational.*

Interpreted as a combined effect of solar radiation pressure and a sublimation-driven nongravitational force, the acceleration j_0 obviously sets an upper limit on either source. Since the solar gravitational acceleration at 1 AU from the sun is 0.593 cm/s^2, the radiation pressure effect is less than 0.0010 ± 0.0001 units the solar attraction. This constraint is equivalent to a *lower* limit on dust-particle diameters of 0.23 cm for an assumed bulk density of 0.5 g/cm^3 and 0.58 cm for 0.2 g/cm^3. This minimum size is greater than the size of the smallest particles in the tail derived in Sec. 2.2 by only a factor of ~ 2.

One can now set some constraints on the true original orbit of the comet. Unfortunately, its size cannot be determined with very high accuracy, because the initiation time for the major nongravitational forces is unknown. However, since the comet was active at discovery, one can safely conclude that the nongravitational perturbations of its orbital motion had started before July 22. If one accepts, rather conservatively, that the activity began as early as $\sim$ 90 days before perihelion (in early July; see Sec. 2.3), then $v \simeq -97^\circ$ and $(1/a)_{\rm orig} = +0.00003 \pm 0.00025$ (AU)$^{-1}$, showing that the original orbit could have been with a nearly equal probability an ellipse or a hyperbola. The rather uncertain estimate for the time of the earliest activity (late May; see Table 2) requires a true anomaly of about -109° and implies that an elliptical original orbit would then be fairly likely, with a reciprocal semimajor axis of $+0.00029 \pm 0.00024$ AU^{-1} and a probable orbital period of some 200,000 years. However, this result is very uncertain, not only because of the doubts about the timing of the activity initiation, but also because the orbit was affected by an unknown transverse component of the sublimation-driven nongravitational perturbations.

5. A Model for the Outburst

Outbursts, or flare-ups, of comets are rather common, but upon the termination of such an episode the affected object usually returns gradually to its original appearance. Thus, as a rule, the light curve of an outburst is characterized by a short rise time followed by a long time of decline. These brightness variations are accompanied by simultaneous morphological changes of the coma. Such a behavior is, for example, repeatedly displayed by comet 29P/Schwassmann-Wachmann and many others. As already mentioned in Sec. 3.2, an excellent example of recurring outbursts was recently presented by comet C/2001 A2 (Sekanina *et al.* 2002). One of the implications of outbursts, seldom mentioned in the literature, was pointed out long ago by Richter (1948), who concluded that a high proportion of unconfirmed comet discoveries (fairly common in the days of slow communication) may refer to very faint objects accidentally caught in outburst and promptly lost as their brightness subsides to normal level.

It should be emphasized that comet C/2002 O4's outburst was fundamentally different. Its rise time was relatively long, more than 10 days in duration, and there was no decline to follow. Thus, the process of sudden activation involved not just a local, isolated source of volatile ices on the nucleus, but it apparently embraced a major reservoir extending over a significant fraction of the surface, since between July 31 and August 9 the comet continued to brighten rapidly, even though at a rate that was not as high as before (Fig. 2). It seems that a comet can keep a minor or moderate outburst under control, but not one of catastrophic proportions in relation to the size of its nucleus. A large comet, such as 29P/Schwassmann-Wachmann, can survive intact more powerful outbursts than can a small comet like C/2002 O4.

During this critical period of time, comet C/2002 O4 was observed in the thermal infrared by Sitko *et al.* (2002) on August 1.54 UT. Their results indicate the presence of submicron-sized grains, with the superheat[10] amounting to 1.15 $\pm$ 0.08 and a silicate feature[11] peaking $\sim$ 20 percent above the continuum. The reported magnitude in the narrow $[M]$ passband (centered at a wavelength of 4.8 microns) suggests a fairly small total cross-sectional area of the dust, only $\sim$ 30 km^2, although this may in part be an unknown aperture effect. In any case, at about the same time, on July 31.0 UT, the total visual brightness (Sec. 3.2), if due entirely to dust scattering of solar light, implies a cross-sectional area of $\sim$ 9000 km^2, assuming a geometric albedo of 0.04. For a particle density of 0.5 g/cm^3 and a relatively flat particle-size-distribution power law with a slope of -2.8, the mass M_d of the comet's dust cloud corresponding to the cross-sectional area on July 31 is estimated at

$$M_d = 1 \times 10^{13} a_{\rm max} \ \ \text{grams}, \tag{16}$$

where $a_{\rm max}$ (in cm) is the radius of the largest dust particle (or fragment). Even with a conservatively low estimate of $a_{\rm max} \simeq 1$ cm, the derived mass of the ejecta is equivalent to that of a sphere more than 0.4 km in diameter!

The dust-production rate depends critically on the lifetime of the grains in the coma. However, since the dominating large particles are always ejected from cometary nuclei with low velocities, on the order of tens of meters per second at the most, and since the coma of comet C/2002 O4 was at the beginning of August estimated at $\sim$ 5 arcmin, or $\sim$ 200,000 km in diameter, it is not difficult to show that the lifetime of large particles could easily extend over several weeks in the least. Thus, it is conceivable that virtually all the dust ejected since the beginning of the outburst was accumulating in the coma in late July and early August.

A simple model, formulated on this premise, allows one to describe the outburst in greater detail. The event's inception is assumed to have occurred at time $t_{\rm beg}$ and its termination at $t_{\rm end}$. The temporal profile of the dust-production rate $\dot{M}_d(t)$ is postulated to be symmetrical and parabolic in shape, reaching a peak value of $\dot{M}_{\rm peak}$ at time $t_{\rm peak} = \frac{1}{2}(t_{\rm beg} + t_{\rm end})$, that is,

$$\dot{M}_d(t) = 4\dot{M}_{\rm peak} \frac{(t - t_{\rm beg})(t_{\rm end} - t)}{(t_{\rm end} - t_{\rm beg})^2}, \tag{17}$$

where $t_{\rm beg} < t < t_{\rm end}$. It is assumed that $\dot{M}_d = 0$ at $t \leq t_{\rm beg}$ and $t \geq t_{\rm end}$, even though this generally is not so. The

[10] Superheat, brought about by a low infrared emissivity of submicron-sized dust particles, is defined as a ratio of the particle temperature to the blackbody temperature at the same heliocentric distance, $T_{\rm dust}(r)/T_{\rm BB}(r) > 1$.

[11] A silicate feature, near a wavelength of 10 microns (in the thermal infrared) is an excess emission due to submicron-sized silicate grains that extends above the thermal continuum curve.

model is depicted schematically in Fig. 3. The amount of mass accumulated in the coma by time t is equal to

$$M_d(t) = \int_{t_{\rm beg}}^{t} \dot{M}_d(t)dt = 2\dot{M}_{\rm peak}\frac{(t-t_{\rm beg})^2}{t_{\rm end}-t_{\rm beg}}\left[1-\frac{2}{3}\frac{t-t_{\rm beg}}{t_{\rm end}-t_{\rm beg}}\right]. \tag{18}$$

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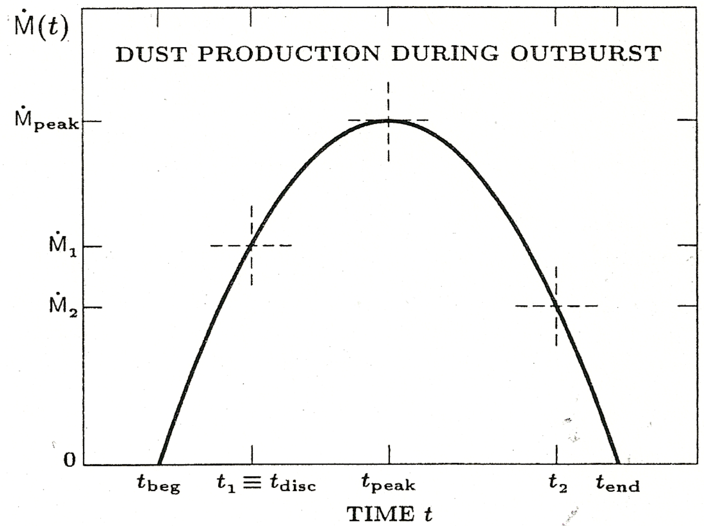

Figure 3. A model scenario for the outburst of comet C/2002 O4. The event commenced at time $t_{\rm beg}$ and terminated at $t_{\rm end}$. At $t_{\rm peak}$, halfway between $t_{\rm beg}$ and $t_{\rm end}$, the dust production rate attained its peak, $\dot{M}_{\rm peak}$. The production rates $\dot{M}_1$ and $\dot{M}_2$, reached, respectively, at time t_1 (equal to the time of discovery, $t_{\rm disc}$) and at time t_2, are used to constrain the model by stipulating that the ratio of the dust mass accumulated in the ejecta from $t_{\rm beg}$ to t_1 to the mass accumulated from $t_{\rm beg}$ to t_2 be consistent with the observed rate of brightness increase between t_1 and t_2. The dust mass variations are normalized by requiring the cross-sectional area of the dust accumulated in the coma to fit the comet's total visual brightness for chosen values of the dust albedo and bulk density and for an assumed law of the particle-size distribution.

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The total mass of dust, $M_{\rm total}$, ejected during the outburst, is of course equal to $M_d(t_{\rm end})$, or

$$M_{\rm total} = \frac{2}{3}\dot{M}_{\rm peak}(t_{\rm end}-t_{\rm beg}). \tag{19}$$

Since the average dust-production rate during the outburst is $\dot{M}_{\rm aver} = M_{\rm total}/(t_{\rm end}-t_{\rm beg})$, one finds at once from equation (19) that $\dot{M}_{\rm aver} = \frac{2}{3}\dot{M}_{\rm peak}$.

To constrain the outburst scenario, I stipulated its compliance with my finding in Sec. 3.2 that the comet's brightness, normalized to 1 AU from the earth, varied as r^{-30} between heliocentric distances $r_1 = r(t_1)$ and $r_2 = r(t_2)$ ($t_1 < t_2$). Identifying t_1 with July 22.0 (the time of discovery, $t_{\rm disc}$) and t_2 with July 31.0 UT, assuming that the particle-size-distribution law did not change with time, and accounting for an inverse-square-power-law effect of heliocentric distance on the brightness, one can write the mass ratio of the dust contained in the coma at the two times:

$$\mu_{12} = \frac{M_d(t_1)}{M_d(t_2)} = \left(\frac{r_1}{r_2}\right)^{-28} \simeq 0.091. \tag{20}$$

Comparing (18) with (20), the stipulated condition requires that

$$\mu_{12} = \left(\frac{t_1-t_{\rm beg}}{t_2-t_{\rm beg}}\right)^2 \frac{2t_1+t_{\rm beg}-3t_{\rm end}}{2t_2+t_{\rm beg}-3t_{\rm end}}, \tag{21}$$

from where one can establish the relationship between $t_{\rm beg}$ and $t_{\rm end}$ in terms of t_1, t_2, and μ_{12}. It is apparent that condition (21) leads to a cubic equation in $X \equiv t_{\rm end} - t_{\rm beg} > 0$ as follows:

$$X^3 - \frac{3}{1-\mu_{12}}\left[(t_{\rm end}-t_1)^2 - \mu_{12}(t_{\rm end}-t_2)^2\right]X + \frac{2}{1-\mu_{12}}\left[(t_{\rm end}-t_1)^3 - \mu_{12}(t_{\rm end}-t_2)^3\right] = 0. \tag{22}$$

The outburst could not terminate before time t_2 (July 31), because the comet's continuing steep brightening could not then be explained. However, the outburst may have been subsiding and eventually terminating after time t_2, as depicted in Fig. 3. However, a continuation of the outburst after mid-August is ruled out by the second sudden change in the light-curve slope near August 10.

Accordingly, the cubic equation was solved for outburst-termination times $t_{\rm end}$ between July 31 and August 16. For these $t_{\rm end}$ values, Eq. (22) has three real roots, only one of which is meaningful. The results, listed in Table 4, allow one to make the following conclusions: (i) the time of outburst inception is found to be fairly insensitive to the choice of the termination time; (ii) the comet appears to have been discovered some 2–3 days after the outburst had begun; (iii) the peak rate of dust production, although likewise fairly insensitive to the choice of solution, exhibits a broad minimum of 1.3×10^7 g/s for a termination date of August 5; (iv) the total mass of dust ejected during the event is found to have been $\sim$ 1–2 $\times$ 10^{13} g; and (v) the outburst apparently extended over a period of at least 11 days and possibly as long as 4 weeks, even though I prefer the solutions with the duration not exceeding $\sim$ 3 weeks.

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TABLE 4

MODEL SCENARIOS FOR THE OUTBURST OF COMET C/2002 O4.

Outburst termination		Outburst duration	Outburst inception		Peak rate of dust production	Distance from Sun at production peak	Total mass of dust lost in outburst
Date 2002 (UT)	Days after discovery	(days)	Date 2002 (UT)	Days before discovery	(10^7 g/s)	(AU)	(10^{13} g)
July 31.0	9.0	11.1	July 19.9	2.1	1.6	1.46	1.0
Aug. 2.0	11.0	13.4	19.6	2.4	1.4	1.45	1.1
4.0	13.0	15.6	19.4	2.6	1.3	1.44	1.2
6.0	15.0	17.8	19.2	2.8	1.3	1.43	1.4
8.0	17.0	19.9	19.1	2.9	1.3	1.42	1.6
10.0	19.0	22.0	19.0	3.0	1.4	1.40	1.8
12.0	21.0	24.1	18.9	3.1	1.4	1.39	2.0
14.0	23.0	26.2	18.8	3.2	1.5	1.38	2.2
16.0	25.0	28.2	18.8	3.2	1.5	1.36	2.5

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The peak dust-production rate on the order of 10^7 g/s is enormous and quite unexpected at a heliocentric distance near 1.4 AU. For example, the dust-production rate of Halley's comet reached $\sim 4 \times 10^7$ g/s at perihelion ($q = 0.59$ AU) according to Fulle *et al.* (1988). Their best-fit power law suggests that the production rate was only 1.5×10^6 g/s at 1.4 AU from the sun, just about a factor of 10 less than the result for comet C/2002 O4 in Table 4. From the extensive water-production-rate results by Schleicher *et al.* (1998), it appears that near perihelion the dust-to-water production-rate ratio of 1P/Halley was 1.5 on the average.

On the other hand, the production rate of solids from comet C/1995 O1 (Hale-Bopp) reached, for an assumed albedo of 0.04, 2×10^7 g/s already at a heliocentric distance of 4 AU (Fulle *et al.* 1998a), but, at the very low temperatures involved, much of this mass was apparently contained in water-ice grains. Indeed, Biver *et al.* (1999) found that, at 4 AU, the production rate was 1.5×10^6 g/s for water and 4×10^6 g/s for carbon monoxide, even though the H_2O-to-CO mass-outgassing-rate ratio was about 3 at perihelion (0.91 AU).

These and similar results for other comets indicate that, under normal circumstances (when outgassing proceeds from only a very small fraction of the nucleus surface), one needs a very sizable nucleus (more than $\sim$ 10 km in diameter) to understand the dust-production rate listed in Table 4 for comet C/2002 O4. Indications are that this comet was *not* large. There are two categories of arguments to explain this apparent discrepancy.

Arguments of the first category point to problems with the assumptions. For example, it could be that much of comet C/2002 O4's light near 1.4 AU was radiated in the bands of molecular carbon rather than by scattering on dust; or the dust-particle-size-distribution function could be much steeper than assumed in equation (16), in which case the same observed cross-sectional area should correspond to a much smaller total mass of dust involved. Since no narrowband photometry of comet C/2002 O4 is available and its dust-size distribution function is unknown (ignoring the weak constraint based on the infrared observation of Sitko *et al.*), such arguments can be neither dismissed nor confirmed.

Is there, however, a plausible explanation even if the inferred mass of dust in the coma of comet C/2002 O4 is approximately correct? A critical issue is to find an adequate energy source. One favorable trait of the problem is that the mass of dust ejected during a major outburst like this may be considerably greater than is the mass of the volatiles that provide the energy needed. In other words, the dust-to-gas mass-production-rate ratio may be very high, perhaps as high as 10 or more, with the required mass-outgassing rate being merely $\sim 10^6$ g/s. Numerical evaluation of such a scenario is illuminating. At 1.4 AU from the sun, a water-sublimation rate per unit surface area is about 23 μg/cm^2/s at the subsolar point of the nucleus and, on the average, about 10 μg/cm^2/s over its sunlit hemisphere. The needed outgassing area is therefore estimated at $\sim$ 10 km^2 and the required effective diameter of the nucleus is $\sim$ 2.5 km, almost certainly much too large.

What are the numbers in the case of sublimation of carbon monoxide, which is substantially more volatile than water ice? A subsolar sublimation rate at 1.4 AU is now 300 μg/cm^2/s, and an average sublimation rate over the sunlit hemisphere is almost exactly one half this rate. Thus, the needed sublimation area on the sunlit hemisphere is $\sim$ 0.7 km^2, and the effective nucleus diameter is barely 0.7 km, a more plausible size. With the density used in equation (16), this comet would have initially had a mass of 8×10^{13} g, which means that up to three-tenths of its mass were expended in the outburst!

The picture that emerges from this scenario (not necessarily the only one) is that *the massive outburst of comet C/2002 O4 can be explained if the entire nucleus is assumed to have been engulfed in an explosion caused by a suddenly exposed reservoir of highly unstable ices*, typified by carbon monoxide. One can only speculate on the details of the process (such as a blowoff of an inert surface mantle, a rapid formation of an extensive network of surface fissures, etc.), but its global grip on the nucleus is clearly critical for a successful interpretation.

6. Summary and Conclusions

By examining the tail morphology and orientation of comet C/2002 O4, its light curve, and its anomalous orbital motion, and by modeling its major outburst, I was able to describe the apparent sequence of events experienced by the object and to address the issue of its disappearance.

The proposed scenario, which of course is only one of many, envisages that the comet was discovered while in a major, persevering outburst. This episode has been detected in both the light curve and the tail orientation data. Weak activity may have been going on for quite some time before the outburst inception, perhaps since the beginning of July or even earlier. The outburst was set off most probably during July 19, 2–3 days before discovery, and lasted until at least the end of July and perhaps as long as mid-August. The production of dust during the outburst reached very high rates (peaking at more than 10 tons/s) and the total mass of dust expended in the course of the event is estimated at some 10 to 20 million tons. The energy-balance considerations require that the entire subkilometer-sized nucleus be engulfed in an explosion triggered by highly volatile ices, such as carbon monoxide, from a major reservoir.

The developments that followed the outburst appear to be its product. By mid-August, the comet must have lost a significant fraction (up to $\sim$ 30 percent) of its initial mass and the remaining nucleus was so badly shaken by the explosion that it failed to stay in one piece. The extent of structural damage the comet suffered from stresses it had been exposed to during the outburst was simply too large. As a result, a process of nearly spontaneous, runaway bulk fragmentation set in, as illustrated by the very low latent energy of nucleus erosion — lower than the sublimation heat of water ice. The anomalous orbital motion of comet C/2002 O4 and subsequently the rapid fading and eventual disappearance of its nucleus condensation and the entire head in the immediate proximity of perihelion, in late September and at the very beginning of October, were all signaling the object's true and complete disintegration.

Because of the limited amount of observational information available, it is difficult to offer a more comprehensive account of the evolution of comet C/2002 O4. Still, the presented scenario illustrates the peculiar behavior of comets. Unlike asteroids, which in order to fragment need to collide with another object whose kinetic energy at impact exceeds the target's inherent structural strength, cometary nuclei, known to be very poorly cemented objects, have a tendency — some more, others less so — to succumb to effects of their own activity, which may appear to be relatively benign by noncometary standards.

Although fragmentation has long been known to affect comets occasionally, its impact on their nuclei has been greatly underrated. Probably the main reason for this bias is observational. The process of *runaway* fragmentation of comets also appears to be much more common than previously thought; it may in fact compete with deactivation in terminating the life of an active comet. Unlike dormancy, disintegration is of course irreversible. And even though the propensity for crumbling varies from comet to comet, continual cascading fragmentation is likely to play a major role in the life cycle of most (if not all) comets. Comet C/2002 O4 (Hönig) has just provided us with a glimpse of what cometary disintegration is all about.

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Φ Φ Φ

Yuji Hyakutake (1950-2002)

Yuji Hyakutake, the well-known Japanese amateur astronomer, died on 2002 Apr. 10 at a hospital in Kokubu City, Kagoshima prefecture, due to internal bleeding caused by a heart aneurysm.

Born in the city of Shimabara (Nagasaki prefecture), Hyakutake first became interested in astronomy when he saw the great sungrazing comet C/1965 S1 (Ikeya-Seki). After graduating from the Faculty of Fine Arts at Kyushu Sangyo University, he was employed as a platemaker at the Fukunichi Newspaper in the city of Fukuoka. His search for new comets began in earnest in 1989, when he built an observatory in his backyard. However, the surrounding skies suffered from severe light pollution, and his first few years were fruitless.

In 1993, Hyakutake moved to the town of Hayato in Kagoshima prefecture, where his wife Shoko had been born. The dark sky there encouraged him to become an even-more-devoted comet hunter and led to his initial discovery, C/1995 Y1 (Hyakutake). Surprisingly, he discovered his second comet C/1996 B2 (Hyakutake) only one month later and only three degrees from his first discovery position. C/1996 B2 came close to the earth ($\Delta = 0.1$ AU on Mar. 26) and became one of the greatest comets of the 20th century. As a result, Hyakutake's notoriety soared amongst the public and his peers. He was invited by the Adler Planetarium and Astronomy Museum and by the Perth Observatory to present talks at public lectures. He received an Honorary Citizen Award from the City of Chicago and the first Kagoshima Prefectural Honor Award. In September 1996, Hyakutake took office as the director at the public observatory known as "Star Land Aira", and he made significant contributions to the popularization of astronomy in Kagoshima until his death.

In spite of his international acclaim, Hyakutake's modesty remained intact, well reflected in the words he proclaimed: "The leading role is [played by] the comet. The discoverer should [only] be a scene-shifter", and "It should not be me that is congratulated, but the comet."

His family name "Hyaku Take" means "a hundred samurai" and was given to his ancestor by a Lord. It represented his work ethic, which was said to resemble that of "a hundred samurai". Considering his passion for comet searching and keen eyes, a new Hyakutake comet was widely anticipated, yet never come to fruition. He will be sadly missed, and the astronomy community would have to concur that we have lost a great comet hunter, whose efforts were also equivalent to that of "a hundred samurai". — *Akimasa Nakamura (Kuma, Ehime, Japan)*

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COMETS FOR THE VISUAL OBSERVER IN 2003

Alan Hale

Southwest Institute for Space Research

Two long-period comets discovered at large heliocentric distances, both with the potential of becoming prominent naked-eye objects when near perihelion in 2004, should be well-observed during their respective inbound approaches in 2003, which should in turn permit reasonably accurate projections for their peak brightnesses to be computed by the