Exploding Comet 17P/Holmes

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Abstract. *The light curve and dust-halo expansion curve of comet 17P are constructed, examined, and compared with those of other comets that experienced outbursts. The 2007 megaburst of 17P is unrivaled as the most powerful event of this kind on record. The proposed scenario for the megaburst involves an exothermic reaction caused by a transition of water ice from low-density amorphous phase to cubic phase in a reservoir spread below a pancake-shaped thick layer of* 10^{14} *g of terrain on the nucleus' surface. The resulting explosion jettisoned this layer of inert mass into the atmosphere as a major fragment that began to crumble precipitously into a rapidly expanding cloud of microscopic dust immediately upon the lift-off. Fewer than 50 events of this magnitude would consume the entire comet.*

1. Introduction

The explosion of comet 17P/Holmes in late October 2007 has brought the issue of cometary outbursts once again to the forefront of scientific interest and debate. A particular point of contention is the question of whether an episode of this magnitude is so extraordinary as to defy comparison with less prominent flare-ups of other comets. Another critical point is the reference to the past behavior of comet 17P/Holmes, which was observed to experience two major outbursts some 10 weeks apart during its discovery return in 1892-1893.

To address these and other related issues, it is desirable to examine the properties of these events and establish similarities and diversities among them. This paper is intended to contribute to the understanding of these fascinating events.

2. Brightening, Flaring Up, Outbursts, Explosions, and Megabursts

Comet outbursts have a tendency to begin essentially the same way but continue to proceed in different ways. This in all probability depends on the contents and particle-size distribution of dust released during the active phase of outburst. The term *outburst* is used indiscriminately, regardless of whether the process is still *in progress* at the time of observation or what is seen is the outcome of an event that had already terminated. There are good reasons for this, since often it is difficult to determine the state of nuclear activity in real time, not to mention that increased activity may be intermittent.

Observationally, the early phase of an outburst is described by three parameters: the self-explanatory time of onset $t_{\rm onset}$; the rise time $\Delta t_{\rm rise}$, which is the time interval between the onset time and the time of peak brightness $t_{\rm peak}$ (an alternative parameter in lieu of the rise time); and the amplitude $\Delta H_{\rm peak}$, which is the difference between the magnitudes at the onset and at peak brightness. If the *intrinsic* peak brightness holds constant for a period of time on a plateau, then $t_{\rm peak}$, which is interpreted as the termination time of the event's active phase, is the time when the plateau is first reached (Sec. 5). Generally, the derived set of parameters describes the early phase of a given outburst satisfactorily, but not uniquely, because the same parametric set fits equally well a great variety of brightness-increase scenarios.

The late phase of an outburst is hard to characterize quantitatively, as especially dust-rich outbursts have a tendency to linger until eventually their effects become indiscriminately small. In powerful outbursts, the peak may extend into a prolonged plateau, along which the brightness subsides very gradually. For the short-period comets, traces of an outburst may be detected for more than one revolution about the sun. A long-term evolution could get particularly complex when the outburst accompanies a fragmentation event.

The appearance of a "stellar nucleus" and its steady expansion into a "disk" of nontrivial dimensions is the usual feature that describes the early phase of outburst evolution. The bright stellar nucleus is of course nothing but the first detection of the expanding cloud of ejecta that, to a greater or lesser degree, include dust particulates. The active phase can last from a fairly small fraction of a day to many tens of days. The duration of short outbursts is probably dictated by the comet's rotation period, with the "hot spot" active from sunrise to sunset, then cooling down on the dark side of the nucleus. It is more than likely that the source flares up again with the next sunrise, etc. Because the atmosphere is then already filled with dust, the detection of events recurring on short time scales is usually difficult, but their products may sometimes be observed as multiple inner halos or other discrete features. Outbursts with long rise times are almost invariably due to a sequence of intermittent episodes of increased activity arising from one or more regions on the nucleus.

Besides being an important physical process, the gradual expansion of a dust cloud or halo (not to be confused with incomplete halos — observed, *e.g.*, in comets C/1858 L1 or C/1995 O1) is also very helpful in our efforts to understand the event. Observations of the halo's growing diameter with time in the early phase of expansion provide an opportunity to determine the event's onset time with relatively high accuracy (a small fraction of a day), which is invaluable in correlation studies of fragmenting comets. As a bonus, the rate at which the cloud expands, in projection onto the plane of the sky, measures directly the expansion velocity whose magnitude is critical for the understanding of the physical processes involved. It turns out that the linear dependence on time that fits the cloud expansion in the early phase of evolution breaks down later, as the ejecta begin to display morphology, asymmetries, etc. For comets at larger heliocentric distances, such as 17P/Holmes, the apparent linearity is sustained longer, as it takes more time for the integrated effects of solar-radiation pressure to make an indelible imprint in particle motions. Especially if the expansion velocity is high, it may completely dominate the radiation-pressure effects for days or even weeks.

The amplitudes of frequent comet outbursts are about 1-2 magnitudes, equivalent to a brightening by a factor of a few. Of course, activity of comets changes constantly, but phenomenologically a brightening by less than 1 mag (a factor of $\sim$2 or less in brightness) is not considered an outburst, unless one is prepared to accept that comet activity consists of nothing but outbursts. Events with amplitudes of some 5-10 magnitudes (an increase by a factor of hundreds to thousands) are much less common, and such a comet becomes the object of great interest to observers. Events with amplitudes greater than 10 magnitudes (a factor of 10,000 or more) are entirely exceptional and, in the age of rapid communication, such an object becomes an instant sensation. To distinguish these events from "ordinary" outbursts, one can describe them as *explosions* or, like I do in this paper, as *megabursts*.

3. Brief History of Comet 17P/Holmes and Some of Its Nucleus' Properties

A member of the Jupiter family of short-period comets, this object orbits the sun at present between 2.05 and 5.2 AU with a period of about 7 years. Approaches to Jupiter are fairly common, with a close one, to 0.54 AU, having occurred in December 1908. An approach to 0.86 AU is due in April 2051. Discovered by Edwin Holmes (1839-1919)[1] in London on 1892 November 6, shortly before midnight UT, the comet was then in outburst. It was independently discovered by T. D. Anderson, Edinburgh, on November 8 and by J. E. Davidson, Mackay, Australia, on November 9. A second outburst, first reported by Palisa (1893), took place in mid-January 1893. During both events, the comet was visible to the naked eye as an expanding disk of light that gradually grew more nebulous.

Thanks largely to the careful and repeatedly updated orbital determination by Zwiers (1895, 1897, 1906), the comet was recovered in both 1899 and 1906 by, respectively, Perrine (1899) and Wolf (1906a, 1906b), but then lost for the next seven returns until Roemer (1964) recovered it as the first of several long-lost comets whose orbital motions had been integrated and perihelion times predicted by Marsden (1963).

Comet 17P/Holmes has been observed at each return since 1964, appearing — until the onset of the 2007 megaburst — always as an inconspicuous telescopic object. However, the temporal distribution of observations leaves much to be desired, at the early as well as recent apparitions, perhaps due in part to prevailing skepticism that the comet could ever again mimic its behavior in 1892-1893 in any significant measure. Indeed, in the light of the 2007 megaburst, one is perplexed to read, for example, that Barnard (1896), after having witnessed the two 1892-1893 outbursts, did not think that the comet "will ever be seen again" and believed that the object "was of only a temporary nature". The obvious lesson for one to learn from this is to be careful not to hastily "condemn" the comet once again.

Because comet 17P/Holmes was not at all observed at seven returns to perihelion and rather poorly observed at all the remaining returns except when discovered and at present, it cannot be argued that the comet never flared up to some degree (not necessarily as much as in 1892-1893 or 2007) during the 16 intervening revolutions about the sun. In fact, there is a report by Wolf (1906b) that is puzzling: only 25 hours prior to the recovery plate of 1906 August 29, on which the comet was plainly detected as an object of magnitude 15.5 with a round halo, this observer took, with the same 41-cm Bruce telescope of the Königstuhl Observatory, a 4.1-hour long exposure on which he found no trace of 17P/Holmes.

In the past several years, two independent investigations were published on the nuclear size of 17P/Holmes (Lamy *et al.* 2000; Snodgrass *et al.* 2006). They led to nearly identical results implying an average diameter of 3.3 km. Both papers assumed for the nucleus a geometric albedo of 4 percent and a phase coefficient of 0.035 mag/deg. Snodgrass *et al.* also made an effort to derive the rotation period, but all four of their potential solutions — between 7.2 and 12.8 hours — were weak, implying in any case an amplitude of only 0.3 mag. In studies of the megaburst, the knowledge of the nucleus is essential for estimating the comet's mass. With Richardson and Melosh's (2006) value for a bulk density of cometary nuclei, 0.4 g/cm^3, the mass of the nucleus of 17P comes out to be 7.5×10^{15} g, which in the following provides a crude upper limit on the mass of the dust and gas clouds released during the megaburst.

4. The Light Curve in the 1986-2007 Apparitions

The comet's brightness variations during the apparitions of 1986, 1993, 2000, and 2007 (with perihelion in March-May) can systematically be examined only along the outbound leg of the orbit. The objective is to establish the degree

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[1] A. C. D. Crommelin wrote in the Jan. 1919 issue of the *J.B.A.A.* (**29**, 84-85), regarding "the lamented death of Mr. Edwin Holmes", that "Mr. Holmes was an original Member of the [British Astronomical] Association, and retired in 1918 at the age of 79". No formal obituary is known to have been published in the astronomical literature, though Arthur Mee (1919, *J.B.A.A.* **29**, 113) later added some kind remarks about Holmes. Guy Hurst has kindly reported his preliminary research (augmented by Gill Hallatt) into online genealogical/census records, revealing that an Edwin Alfred Holmes was born in the first quarter of 1839 in the Sheffield district of England, and a 1901 census reveals an Edwin A. Holmes (born Sheffield) living at 87 Hornsey Rise, Islington (just north of London) with his wife Selina (aged 57); also, a death is registered in Edmonton (just north of London) of an Edwin A. Holmes in the first quarter of 1919 at age 80. Further, the papers of E. A. Holmes in the Royal Greenwich Observatory archives (shelfmark *RGO 45/40*) have a photograph of "the late Edwin Alfred Holmes", and note his observatory as having been at Hornsey Rise via another photograph from May 1901. So there seems to be no doubt that these records all refer to the discoverer of comet 17P. Edwin Holmes can be found at age 12 in the 1851 census in Dudley, given as the son of James (an iron moulder) and Hannah Holmes. Edwin Holmes married Selina Stevens (of Saint Leonards, Shoreditch) on 1864 Mar. 28, and their child Ernest A. Holmes was born ca. 1875 in Islington. Edwin A. Holmes was listed as a glass merchant and glass cutter in Islington via the 1881 and 1891 censuses. – *Ed.*

of stability of the light curve from return to return during periods of normal (low) activity. In this paper the light curve is understood to be a plot of time, reckoned from perihelion, against a *normalized* magnitude H_Δ, which is corrected for personal and instrumental effects (to the extent possible) and referred to a geocentric distance Δ of 1 AU by subtracting the term of $5 \log \Delta$.

The 2007 brightness data for comet 17P/Holmes have been collected primarily from the *International Comet Quarterly*'s website (`http://www.cfa.harvard.edu/icq/icq.html`), but most quiescent-phase magnitudes have come from the *Minor Planet Electronic Circulars*, with a few from the *International Astronomical Union Circulars* 8886 and 8887. The light curve through 2008 January 7, based on more than 500 observations and plotted in Figure 1, shows that in more than five months following perihelion, from mid-May to just before the megaburst began in late October 2007, the comet had been fading systematically by nearly three magnitudes. While the average rate was only 0.02 mag/day, the low orbital eccentricity and the resulting narrow range of heliocentric distances r imply a steep r^{-16} drop when measured this way. The whole light curve could be constructed thanks to the fact that K. Kadota's important set of CCD magnitudes could be calibrated by linking it, because of temporal overlap, with the post-megaburst naked-eye brightness estimates reported by a large number of observers. The comet is expected to be under observation for several more months.

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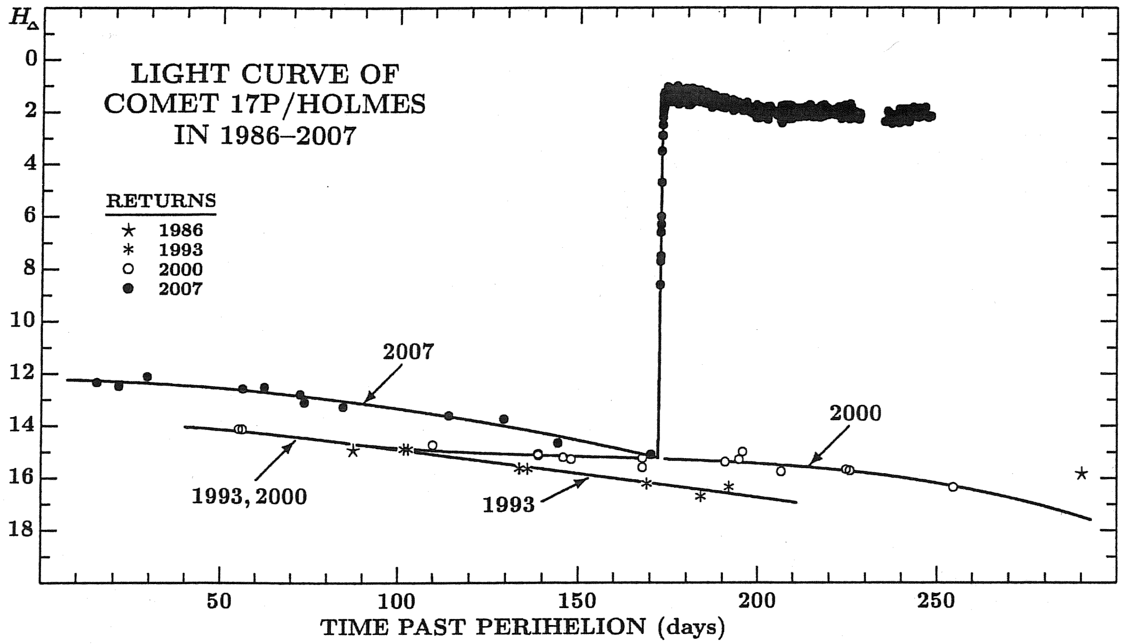

Figure 1. Light curve of comet 17P/Holmes at the apparitions during 1986-2007. The magnitudes H_Δ are visual magnitudes corrected for personal and instrumental effects and normalized to a unit geocentric distance. The observations are represented by apparition-specific symbols. Note the plateau persisting after the brightness peak.

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The 2000 light curve in Figure 1 is based on the magnitude data by six observers, five of which (including Kadota) used CCD detectors and one (M. Jäger) the photographic technique. The data were gathered partly from the *ICQ*, partly from the *Minor Planet Circulars*, and for Jäger from the journal *Schweifstern*. Jäger's observations were important, because they extended the covered arc by 50 days toward perihelion. Jäger's magnitude correction was determined by comparing his and Kadota's nearly-simultaneously-obtained magnitudes for six similarly faint comets observed in 2000 with the same instrumentation as 17P. It appears that the comet was somewhat fainter, but fading more slowly than in 2007.

The 1993 light curve is based on the CCD magnitudes from the *ICQ*, reported by two observers, J. W. Scotti and A. Nakamura. The data were linked to Kadota's "system" via Nakamura, who also observed the comet in 2000. Between 100 and 170 days after perihelion, the comet seems to have been systematically fainter than in 2007 by 1 to 1.5 mag.

Only two CCD magnitudes are available for 1986; a crude estimate from the recovery observation by J. Gibson (*IAUC* 4225) and another data point nearly 7 months later by Scotti, who used the same observing equipment as in 1993. Gibson's magnitude scale was simply assumed to be the same as Scotti's, and it appears that his estimate fits the light curves from 1993 and 2000 surprisingly well. On the other hand, Scotti's magnitude shows the comet to be about 1.5 mag brighter than indicated by the light curve of 2000. Even more importantly, comparison of Scotti's own 1986 and 1993 magnitudes suggests that 290 days after the 1986 perihelion the comet was intrinsically brighter by 0.3 mag than it was 134 days after the 1993 perihelion.

In summary, Figure 1 shows that the comet's activity, as described by its light curve, varies from return to return. It is not clear to what extent this is caused by the comet's changing perihelion distance, which decreased from 2.17-2.18

AU in 1993-2000 to 2.05 AU in 2007. However, one should be rather skeptical because in 1986, when the comet was brighter, the perihelion distance was nearly identical with that of 2000.

5. The Megaburst of 2007

As shown below, this event was fortunately caught fairly soon after its onset, as indicated (*IAUC* 8886) by the reported "nuclear" magnitude 8.4 at the time of discovery by J. A. Henríquez Santana on October 24.067 UT; by the high rate of brightening, 0.5 mag/hr, over a period of six hours (yielding magnitude 5.4 on October 24.317 UT); and by the descriptions of a stellar or almost-stellar appearance of the comet in confirmation images taken by R. Naves and M. Campas and by F. Kugel and C. Rinner within hours of discovery.

The available magnitudes are not very helpful in an effort to determine the event's precise onset time, as the slope of the light curve varies, becoming less steep with time as the plateau is being approached (Figure 1). A promising result was obtained by Hsieh *et al.* (2007) from photometry of images taken with the SuperWASP-North facility between Oct. 23.99 and 24.10 UT. They fitted the data on the assumption that the comet's brightening was due to an optically thick dust coma that was expanding at a constant rate and found that the outburst began on approximately Oct. 23.8 UT, or 172.3 days after perihelion.

An independent estimate for the onset time can be obtained from direct measurements of the dust halo's diameter (Sec. 2). However, care has to be taken of two complications, both of which are apparent from Figure 2, where I show one of many images of comet 17P/Holmes — this one taken on Nov. 4. The first complication is the gaseous outer coma, which extends far beyond the dust halo; it has no sharp boundaries and it should not be confused with the latter. The second complication is that the practically perfect roundness of the dust halo, commonly reported by observers in late October, was no longer preserved in images taken from early November on, as exemplified in Figure 2.

Wagner *et al.*'s observations (*IAUC* 8887) illustrate that, to an imaging observer, the dust halo could become contaminated by the gas coma even in the early phase of the event's evolution, when the gas coma was more difficult to separate from the dust halo than in November. In Wagner *et al.*'s spectra taken on October 25, the spatial continuum profile along the slit extended to a diameter of 1.5 arcmin, whereas the CN (0,0) emission was traced over a diameter of at least 4.8 arcmin.

The observed dust-coma roundness and its persistence are consistent with a source of great extent and an event of global proportions on the scale of the comet's nucleus (see Sections 8.3 and 9). Because the phase angle was small (17° or less), the earth faced the comet nearly head-on, with much foreshortening in the radial direction. Because 17P was nearly 2.5 AU from the sun, dust particles were subjected to relatively small solar-radiation pressure (only about $\frac{1}{6}$ that at 1 AU), whose temporally integrated effects were insignificant relative to the effects of the expansion velocity for at least one week after dust injection. Only over a longer period of time, into November, did the integrated effects of radiation pressure become noticeable.

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Table 1. Dust halo diameters in an early phase of the 2007 megaburst of comet 17P/Holmes.

Date October 2007 (UT)	Reported halo diameter: apparent (arcsec)	Reported halo diameter: linear (10^3 km)	Residual (10^3 km)	Observer (reference)
25.17	121	143	+20	C. Sherrod (Note 1)
25.18	90	106	−18	R. M. Wagner (IAUC 8887)
26.4	215	248	+18	J. Young (CBET 1111)
27.15	246	285	−9	J. M. Trigo-Rodriguez (CBET 1118)
27.41	255	301	−16	Sherrod (Note 1)
28.32	348	411	+16	Sherrod (Note 1)
29.12	408	481	+17	Sherrod (Note 1)
30.1	426	505	−44	Trigo-Rodriguez (CBET 1118)
30.19	482	568	+11	Sherrod (Note 1)
31.11	545	642	+5	Sherrod (Note 1)

Note 1. See http://www.arksky.org.

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To avoid the two problems mentioned above, I restricted the dust-halo-size data set only to the results obtained from CCD images or spectra taken before the end of October and with larger-aperture and/or Cassegrain-type telescopes that ensure high-enough spatial resolution. One measure of coma diameter was rejected, attributed to a contamination by the CN or C_2 coma. Table 1 presents the data set and the residuals from a linear fit yielding an onset time of October 23.7 ± 0.2 UT, or 172.2 days after perihelion (at 2.435 AU from the sun) and a projected expansion velocity of 0.50 ± 0.02 km/s. This onset time is in excellent agreement with Hsieh *et al.*'s (2007) determination from the light curve, and the expansion velocity is exactly in the middle of an interval derived by Snodgrass *et al.* (2007).

Figure 2. Image of comet 17P/Holmes taken by Michael Jäger (near Krems, Austria) on 2007 November 4.81 UT, about 12 days after the megaburst had begun. The image is a co-addition of five 6-min exposures taken with a 20-cm f/2.75 astrograph (German Sigma CCD camera with KAF6303 chip) and a blue filter from an "RGB set". The bar at the bottom indicates a scale of 45′; north is up and east is to the left. The diameter of the bright inner halo of dust is 1.05 million km; its northern and eastern boundaries are sharp, while its southern boundary is blurred and slightly elongated. The diffuse bluish-green gas coma extends well beyond the yellowish dust halo. The sun is in the north-northeastern direction. (Image courtesy of M. Jäger, reproduced with permission.)

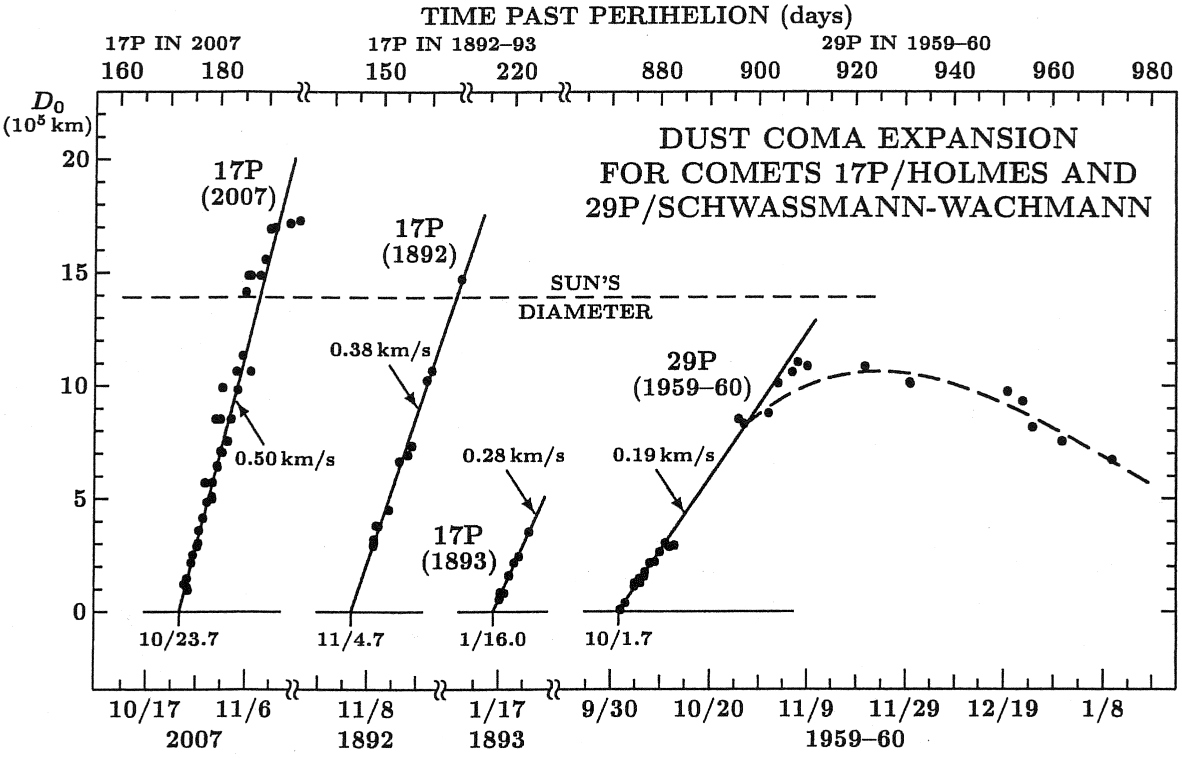

Figure 3. Dust coma expansion with time in the aftermath of an outburst; D_0 is the linear diameter of the dust coma or halo. The 2007 megaburst of comet 17P/Holmes is compared with the two outbursts of the same object in 1892 and 1893 and with an outburst of comet 29P/Schwassmann-Wachmann at the beginning of October 1959 as observed by Beyer (1962). The stagnation and subsequent decline in the coma dimensions in his data is an effect of the ever greater fraction of the coma's outer regions being unaccounted for as their surface brightness dropped below the detection limit.

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Figure 3 shows that the parameters derived from the expanding dust halo's dimensions in Table 1 during the early phase of the megaburst's evolution fit reasonably well a selected set of coma diameters reported from later days. However, as the surface brightness of the coma was steadily decreasing, the uncertainties in the size estimates were increasing with time, as did the effects of radiation pressure and other perturbing sources.

I now turn to the light curve of the megaburst in an effort to estimate the total mass of the dust population in the comet's atmosphere. As new particulates were constantly injected into the coma at high rates during the event's active phase, while none were for some time leaving it, the amount of dust kept growing in the coma until the major activity ceased (amounts of dust injected during periods of low activity can be neglected, given the comet's enormous brightness at the time). While one has no means of measuring the dust mass directly, the total cross-sectional area of the scattering particles is readily available from the brightness data, given that the coma is optically thin. The standard light curve, like that in Figure 1, falls short of providing information on the total cross-sectional area of dust because the normalized magnitude H_Δ does not account for the effects of heliocentric distance r. The appropriate quantity is the *intrinsic* magnitude H_0, which is corrected for both the geocentric and heliocentric distances. This magnitude, plotted in Figure 4, is related to the normalized magnitude H_Δ used in Figure 1 by applying the heliocentric correction

$$H_0 = H_\Delta - 5 \log r, \tag{1}$$

where r is in AU. Amazingly, the comet's intrinsic magnitude along the post-event plateau was between magnitudes 0 and -1! As shown in Figure 4, the time of active-phase termination of the megaburst is determined by the instant the peak magnitude $(H_0)_{\rm peak}$ has just been reached. The only effect that can complicate this straightforward exercise is particle fragmentation if it proceeds in parallel with dust injection and thereby increases the observed cross-sectional area. Thus, there is a tradeoff in the sense that the ease with which this information is obtained is balanced by the uncertainties in the particle-size distribution function and some optical-dust properties that must be estimated or assumed (geometric albedo, phase function, etc.).

One finds from Figure 4 that the plateau was approached in just about 24 hr after the onset and finally reached in another 19 hr or so, implying a rise time $\Delta t_{\rm rise} = 1.8 \pm 0.4$ days (estimated error), a peak normalized magnitude $(H_\Delta)_{\rm peak} = 1.4 \pm 0.2$ and a peak intrinsic magnitude $(H_0)_{\rm peak} = -0.53 \pm 0.12$. However, these results are preliminary, based on a selected set of 92 naked-eye observations, and the rise time is considered particularly uncertain. Since the

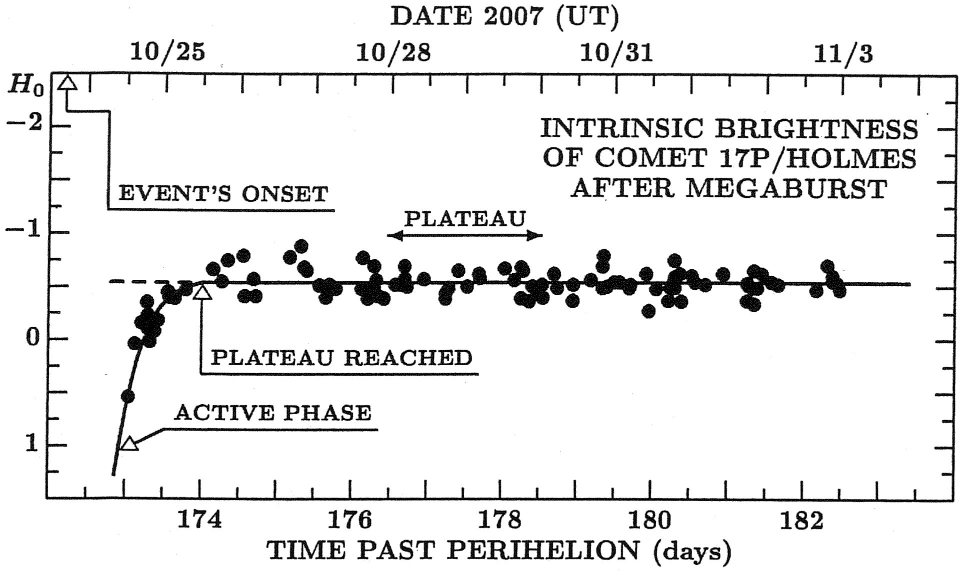

Figure 4. Close-up view of the temporal variations in the intrinsic magnitude H_0 *of comet 17P/Holmes, normalized to the unit geocentric and heliocentric distances, during the megaburst in 2007. The perfectly flat plateau was reached at the time of peak brightness, 174 ± 0.5 days after perihelion, or around October 25.5 UT, when the active phase of the megaburst terminated. The plateau is determined by the intrinsic peak magnitude of −0.53 ± 0.12, based on a limited sample of 92 naked-eye observations used. The event's onset time is marked for reference.*

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normalized magnitude at the very end of the quiescent phase is about 15.3, the amplitude of the megaburst is $\Delta H_{\rm peak} \simeq 14$ mag. To the extent that the contributions to the maximum visual brightness from both the dust released in the quiescent phase and the gas emissions can be neglected, the peak magnitude indeed measures the total cross-sectional area, $X_{\rm dust}$, of dust particles injected into the expanding cloud during the megaburst. With the heliocentric distance of 2.44 AU at the beginning of the plateau and the particles' geometric albedo of 4 percent, one finds from the relationship between the intrinsic magnitude and the cross-sectional area of a sunlight-scattering body

$$X_{\rm dust} = \frac{5.7 \times 10^7 \ {\rm km}^2}{\Phi(\alpha)}, \tag{2}$$

where $\alpha \leq 17^\circ$ is the phase angle and $\Phi(\alpha)$ is the dimensionless phase law normalized to $\Phi(0^\circ) = 1$. For the relevant values of α, $\Phi(\alpha) < 1$.

The enormous cross-sectional area, $X_{\rm dust}$, implies a major role for optically important, microscopic grains and suggests that the particle-size distribution function may be steeper than usual. This is convenient computationally because the total mass of injected dust depends on the minimum particle size, $h_{\rm min}$, that can be more easily constrained than the unknown maximum size, $h_{\rm max}$. Thus, I write for the differential distribution of particle diameters, h:

$$f(h)dh = n_0 h^{-k} dh, \tag{3}$$

where n_0 is a normalizing constant, and the power index $k > 4$. This distribution law gives for the total cross-sectional area of dust injected into the comet's atmosphere during the megaburst

$$X_{\rm dust} = \frac{1}{4}\pi n_0 \int_{h_{\rm min}}^{h_{\rm max}} h^{2-k} dh \simeq \frac{1}{4}\frac{\pi n_0}{k-3} h_{\rm min}^{3-k}, \tag{4}$$

and for the total mass $\mathcal{M}_{\rm dust}$ of this dust,

$$\mathcal{M}_{\rm dust} = \frac{1}{6}\pi n_0 \rho_{\rm dust} \int_{h_{\rm min}}^{h_{\rm max}} h^{3-k} dh \simeq \frac{2}{3}\rho_{\rm dust} X_{\rm dust} h_{\rm min} \frac{k-3}{k-4}, \tag{5}$$

where $\rho_{\rm dust}$ is the mean bulk density of the dust particulates. Because of the assumed predominance of microscopic dust in the coma, $\rho_{\rm dust}$ must be greater than the nucleus' bulk density (Sec. 3). I adopt $\rho_{\rm dust}/\Phi(\alpha) = 1.5$ g/cm^3. Equation 5 then yields mass $\mathcal{M}_{\rm dust}$ as a function of two parameters, $h_{\rm min}$ and k, as shown in Figure 5.

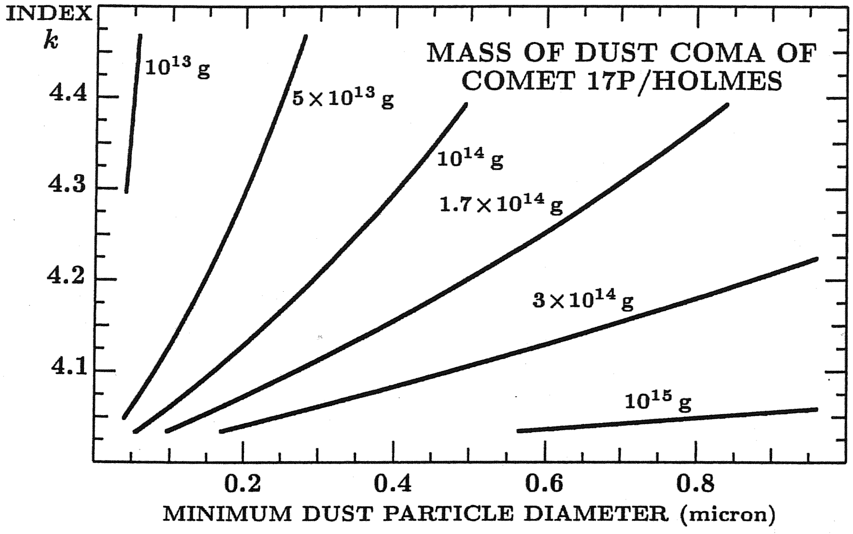

Figure 5. Mass of dust injected into the coma of comet 17P/Holmes in the aftermath of the megaburst, starting 2007 October 23, as a function of the minimum dust-particle diameter $h_{\rm min}$ and the power index k of the size distribution function $h^{-k}dh$. See Sec. 5 for more details.

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Because the dust cloud was reported to be distinctly yellow in color, the Rayleigh scattering by grains smaller than $\sim$ 0.1 micron in diameter did not prevail, which suggests from Figure 5 that the mass of the dust cloud was greater than 10^{13} g. A mass near 10^{15} g or greater would imply that a substantial fraction of the nucleus was injected into the coma, a scenario that seems unrealistic because there is no indication that the comet's existence has been threatened. Considering the options offered by Figure 5, I conclude that the total mass of injected dust was near 10^{14} g, or about 1-2 percent of the comet's total mass. With the provisional value of the rise time, the mass-injection rate of dust during the active phase comes out to be about

$$\dot{\mathcal{M}}_{\rm dust} \approx 6-7\times10^{8}\,{\rm g/s}. \tag{6}$$

An additional mass was locked in the gas emissions, by which the dust injection was driven. Judging from the fairly high dust-expansion velocity of 0.5 km/s, the gas-emission rate may have been comparable, or nearly comparable, to the dust-injection rate. Combi *et al.*'s (2007) results are more in line with this expectation than the data based on the observations made more than 5 days after the event's onset (Salyk *et al.* 2007, Schleicher 2007).

As observing will continue until at least April 2008, the light curve (Figure 1) will remain incomplete for months, and it is too early to speculate about the megaburst's lingering effects over a long period of time. In Figure 6, a comparison of the observed brightness with the predicted light curve for a constant cross-sectional area of dust particles in the coma shows some, but no major, mismatch in that the observations run below the expected level, yet parallel to it since the second half of November.[2] The fact that, for nearly 60 days, about the same (rather than ever-decreasing) fraction of the dust ejecta has been reported may suggest their partial, but continuing, replenishment during the comet's diminishing post-event activity (Sec. 8.5).

6. Comparison With Outbursts of Comet 17P/Holmes in 1892-1893

Bobrovnikoff's (1943) extensive overview of the comet's discovery apparition with a complete list of references represents an excellent account of the observations made and offers their physically sound interpretation. Below I take issue with only a few specific conclusions made by Bobrovnikoff.

Since the comet was discovered in outburst, the amplitude of this event remains unknown, even though Richter's (1949) guess was a minimum of 4-5 magnitudes. However, the onset times of both outbursts can be determined with reasonable accuracy, thanks primarily to Barnard's (1896) meticulous measurements of the expanding coma. His coma-diameter data for the first outburst were in excellent agreement, and could be linked, with those by Denning (1893). Spectroscopic observations (e.g., Campbell 1893, Kammermann 1893a, Vogel 1893) consistently showed the continuous spectrum to dominate, with only a faint "green line" (C_2 emission band) sometimes also reported. Campbell (1893) noted that, on 1892 November 8 and 9, this feature was better seen outside "the bright parts" of the comet, that is, outside the cloud of injected dust. There is no doubt that Barnard measured the expanding dust coma and that therefore his observations were as helpful for determining the onset times in 1892-1893 as the data from Table 1 in 2007. Orlov

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[2] A very preliminary examination of brightness observations of 17P from January-March 2008 suggests that this conclusion will probably apply for the comet's light curve during the entire period of time after the megaburst.

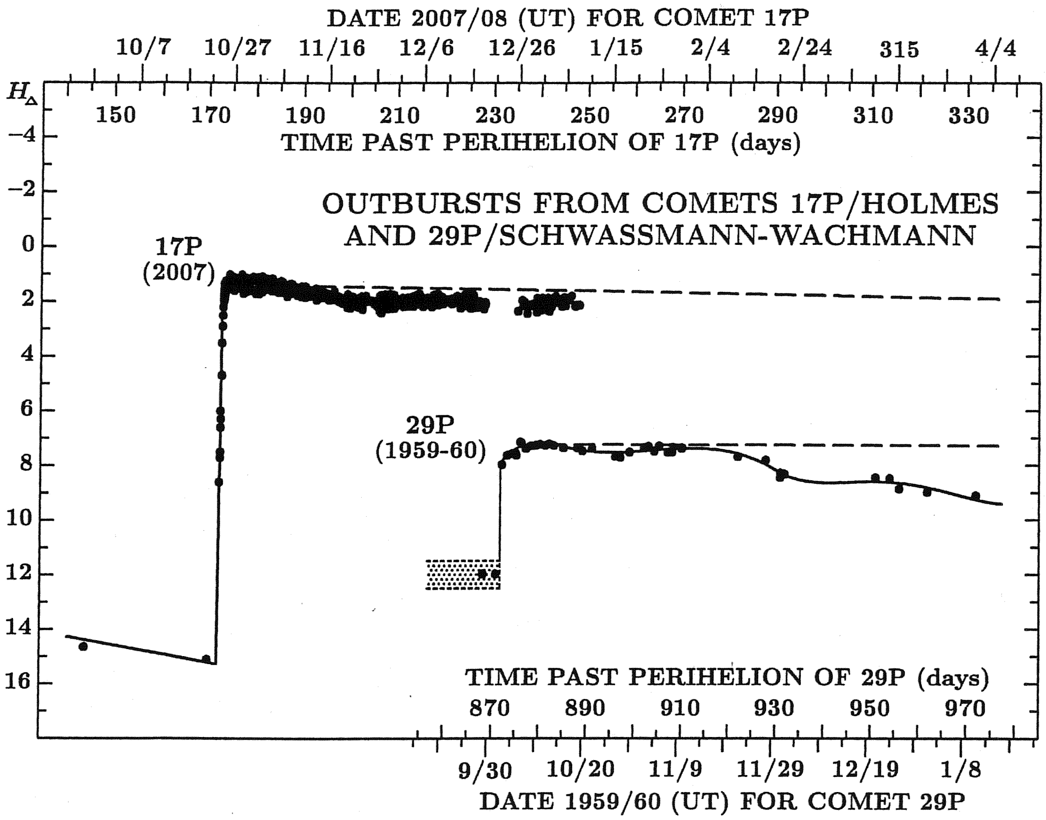

Figure 6. Light curve of the 2007 megaburst of comet 17P/Holmes compared with the light curve of comet 29P/Schwassmann-Wachmann as observed by Beyer (1962) around the time of its outburst at the beginning of October 1959. The magnitudes H_Δ are as in Figure 1. The dashed, nearly horizontal lines are the light curves predicted for the case of a constant cross-sectional area of dust particles in the coma. Note that both comets display a prolonged and very slow intrinsic fading along the plateau. The first two data points for comet 29P are crude guesses based on the available information provided by Beyer (1962) on the one hand and by Roemer (1959) on the other hand.

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[text continued from page 10]

(1940, 1945) combined Barnard's coma-diameter measurements with other observers' estimates and found that the comet developed two halos on both occasions: a high-speed one (0.95 km/s in November and 2.06 km/s in January) and a low-speed one (0.42 km/s in November and 0.38 km/s in January). My rigorous analysis shows that the high-speed features did not exist and that the expansion rates were somewhat lower for the low-speed halos: 0.38 ± 0.01 km/s with the onset on November 4.7 ± 0.4 UT, 143.7 days after perihelion at a heliocentric distance of 2.39 AU, and 0.28 ± 0.02 km/s with the onset on January 16.0 ± 0.2 UT, 216.0 days after perihelion at 2.64 AU from the sun. This result for the second event is in good agreement with that by Bobrovnikoff (1943), who from a total of 34 data from January 16-23, grouped into 10 normal places, found an expansion velocity of 0.27 km/s and the onset time of January 15.6 UT. From the onset time for the first event, it follows that the comet was discovered 2.3 days into the outburst. Apparently the last observation made before the second event began was that by Hough (1893) with the 47-cm equatorial of the Dearborn Observatory on January 15.1 UT, 0.9 day before the onset, when the comet appeared as a faint nebulosity.

As is the case with even the best-observed 19th-century comets, only rather fragmentary information is available on the light curve of comet 17P/Holmes in 1892-1893. Nevertheless, Bobrovnikoff (1943) compiled a list of 40 brightness estimates between November 10 and March 16 UT, while Richter (1949) provided more abbreviated information for the January event only, but the same data treated as total magnitudes by Bobrovnikoff were considered to be "nuclear" magnitudes by Richter. There are three types of useful data that can be used to obtain some idea on the comet's prominence in the sky shortly after the outbursts. The first is comparison with M31 (whose total visual magnitude is around 3.5),[3] close to which the comet was located in November. To my knowledge, the only observer who claimed

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[3] as measured by S. J. O'Meara (1998) via the Morris/O'Meara "Modified Out" method, and separately via photoelectric photometry by de Vaucouleurs *et al.* (1991), with the involved reduction explained by Buta (1995) and Buta *et al.* (1995); Bortle (1984) measured total visual mag 4.4 via naked eye and the VBM method (cf. Green 1996), which underestimates the brightness of apparently large celestial objects, providing a lower (fainter) magnitude limit (The M31 magnitudes are published on p. 29 in this issue of the *ICQ*).

that the comet was considerably brighter (though smaller in size) than M31 was Copeland (1893) on November 10 UT. However, his conclusion may refer to the surface, rather than total, brightness of the two objects. Barnard (1896) said explicitly that with the naked eye on November 9.2 UT "the comet was just as bright, exactly, as the brightest part of the Great Nebula of Andromeda" and continued that on November 10.1 UT, it "was brighter to the naked eye than the brightest part of the Andromeda nebula." Elsewhere he remarked (Barnard 1892) that the next night (Nov. 11 UT) "it may possibly have been a little brighter yet." This suggests that the comet's brightness was apparently still increasing some 5-6 days after the event's onset. Two days later (Nov. 13 UT), Barnard (1896) noted, that to the naked eye, the comet was "certainly less bright" and this he confirmed on November 14.2 UT. On November 17 UT he noted that to the naked eye the comet "was still stellar but fainter," while five days later "it appeared much fainter than the Andromeda nebula." Engelhardt (1893) made a similar comment based on his observation of November 26.9 UT. Bobrovnikoff's (1943) composite light curve has a peak as late as November 12.9 UT, fully 8.2 days after the outburst's onset.

The second type of brightness data in 1892-1893 was comparison with the nearby stars. Because the comet had a sharp nuclear condensation in the early phase of expansion, there is a danger that these magnitudes do not refer to the total brightness. Barnard (1896) found with the naked eye on November 10.2 UT that "the comet looked like a small star and almost equal to ν Andromeda," whose visual magnitude is 4.5 (via the Hipparcos/Tycho spacecraft catalogue). On November 14 UT, Coit (1892) called the comet about $1\frac{1}{2}$ mag fainter than μ Andromedae, whose visual magnitude is 3.9. On January 17.2 UT, about one day after the onset of the second outburst, Barnard (1896) reported that the comet in "the finder . . . could not possibly be distinguished from an 8th magnitude star." This estimate may closely describe the total brightness, as according to Bobrovnikoff (1943) all observers stated that on January 17 UT "practically the whole light of the comet was concentrated in the nucleus," On the same night Barnard remarked that over a period of 2 hours "there was no question that the nucleus was brightening."

The third type of brightness information addressed the comet's visibility with the naked eye. A number of independent reports of this kind appears to be quite consistent. Barnard (1896) saw the comet via naked eye in the period of November 9-25 UT, but not on December 6 UT, as he specifically emphasized. Coit (1892) reported the comet to be distinctly visible to the naked eye on November 14 UT, while Kammermann (1893b) made such a sighting on November 15.7 UT, and Renz (1893) on November 23.7 UT. Gruss (1893) described the comet as larger but fainter on November 17 UT compared to November 13. Russell (1893) quoted Davidson, the independent discoverer, as saying that the comet was "just visible to the naked eye" on November 21 UT and, similarly, Updegraff (1892) found it barely visible to the unaided eye on November 26.2 UT. After the second outburst, Kobold (1893) saw the comet with the naked eye as a faint spot of light on January 16.9 UT. Kammermann (1893a) noticed that the brightness slightly increased between January 17.8 and 18.8 UT. This is consistent with the description by Holetschek (1917), who, reviewing his observations in Vienna, found the comet somewhat larger and brighter on January 18 UT compared with January 16 and again on January 20 UT compared with January 18, but not on January 23 UT compared with January 20. Lovett (1893) reported the comet visible to the naked eye on January 20.0 UT. Thus, the comet's brightness reached the peak some 4-5 days after the onset of the second outburst; in terms of the rise time, there is not much difference between the two 1892-1893 events. Lovett's result is, however, in sharp conflict with Bobrovnikoff's light curve that gives for this date the magnitude range of 6.9-7.2. It thus appears that the comet was then perhaps $1\frac{1}{2}$ to two magnitudes brighter than Bobrovnikoff claimed.

Reviewing and summarizing his observations two decades later, Barnard (1913) assigned the following magnitudes to the comet: 1892 Nov. 10, 4.8; Nov. 13, 5.1; Nov. 14, 5.2; Dec. 6, 12.5; 1893 Jan. 17, 7.9-8.1; Jan. 18, 7.8. The amplitude of the second outburst is rather uncertain. Few observations were made shortly before this episode occurred, as the comet became by then quite faint. Kobold (1893), observing on January 11 and 12, remarked that on the second night the comet could be fairly well seen near a 10th-mag star, but not in its immediate proximity. Holetschek (1917) adopted an apparent magnitude 15 for the period January 11-14. Guessing magnitude 5 for the peak brightness, one finds an amplitude of $\sim$ 10 magnitudes. Referring to a binocular observation by T. W. Backhouse on January 11.0 UT, Bobrovnikoff (1943) disagreed with Holetschek and concluded that the total increase in brightness amounted to only some 2.8 magnitudes and that it was by no means sudden. However, Barnard's (1896, 1913) description quoted above shows that the nucleus brightened fairly quickly. And if nearly all light of the comet at the time was in the nucleus, a conclusion that Bobrovnikoff subscribed to, the comet's brightness increase must have been rapid as well. The most probable amplitude of the second outburst can be estimated to be near 4-6 magnitudes.

Based on these data, the peak intrinsic magnitudes $(H_0)_{\rm peak}$ during the two outbursts of 1892-1893 are estimated at, respectively, 1.9 and 1.2, the cross-sectional area of injected dust $X_{\rm dust}$ at, respectively, 6 and 12 $\times$ 10^6 km$^2/\Phi$, and, on the same assumptions as before, the total mass of dust injected into the comet's atmosphere at, respectively, 1 and 2 $\times$ 10^{13} g. Together, the two events are believed to have accounted for only $\sim$ 30 percent of the mass of dust lost in the 2007 megaburst. With the approximate values for their rise times, the events' corresponding average mass-injection rates of dust become, respectively, 2 and 5 $\times$ 10^7 g/s.

It may come as a surprise that the peak intrinsic brightness and the amount of dust injected into the coma was greater during the second outburst given that the comet appeared brighter during the first one, when it was also longer visible to the naked eye. However, the comet was at much larger heliocentric and geocentric distances at the time of the second event, making it appear at equal intrinsic brightness 1.2 mag fainter than at the time of the first one. Thus, the period of naked-eye visibility during November should be compared with the visibility in a small telescope after mid-January. Indeed, Wilson (1893) reported the comet to be easily visible in the finder of the 41-cm refractor of the Goodsell Observatory until February 17 UT, more than four weeks after the outburst. Similarly, Backhouse observed the comet with his binoculars as late as February 10 UT (Bobrovnikoff 1943).

Contrary to the light curve presented by Bobrovnikoff (1943), there is a reason to believe that evidence on a brightness plateau after each outburst is hidden in the 1892-1893 data. The comet's expanding dimensions were the source of the observers' dilemma of fully accounting for the brightness contributions from remote areas of the coma, a task that even the most experienced ones were unprepared to handle. One can therefore argue that during the discovery apparition the comet's total magnitude was increasingly underestimated in the post-outburst periods of time.

Three additional points should be made on the 1892-1893 outbursts. First, referring to a photograph taken with a 15-cm Willard lens on November 11 UT, Barnard (1896, 1913) detected, toward the southeast of the comet, a faint hazy tail that widened out into an irregular mass 39′ in diameter, centered 48′ from the comet. The existence of this feature was confirmed the same night during low-power sweeps with the 30-cm reflector of the Lick Observatory, but it was never seen again. See Whipple (1984) for more recent efforts to examine this issue.

Observing the comet on 1892 November 23 UT, Renz (1893) noticed that two tail-like bands emanated from the condensation (which was about 20 arcsec in diameter) in the southeastern direction; they showed up only a little in the coma and did not extend beyond its boundaries. This description may refer to the same phenomenon observed extensively in the 2007 megaburst as streaks and interpreted to be tails of very small, disintegrating fragments that were too faint to detect (Sekanina 2007, Gaillard *et al.* 2007).

Richter (1949) asserted that the January 1893 event consisted of two successive outbursts separated from each other by less than 1.7 days. My examination of Richter's argument fails to confirm his conclusion, but such a scenario cannot be ruled out because multiple events that closely follow each other are notoriously difficult to recognize (Sec. 2).

7. Comparison With Outbursts of Other Comets

A great variety of outbursts is known to have been experienced by comets, including some of the most celebrated ones, such as 1P/Halley (e.g., Bobrovnikoff 1931; Green and Morris 1987; Feldman *et al.* 1986; Larson *et al.* 1990; West *et al.* 1991; Sekanina *et al.* 1992), C/1942 X1 (Whipple-Fedtke-Tevzadze; *e.g.*, Beyer 1947), C/1975 V1 (West; *e.g.*, Sekanina and Farrell 1978), and C/1995 O1 (Hale-Bopp; *e.g.*, Liller 2001). While, for gaining insight into the nature of outburst mechanisms, it is unnecessary to prepare a complete or near-complete list of flaring-up comets, it is useful to select some well-documented examples and describe the events in detail.

To a degree, this was done by Richter (1949) in his effort to find a potential relationship between comets and solar activity. He assembled data on several comets with outbursts, including 17P/Holmes, 12P/Pons-Brooks, C/1888 D1 (Sawerthal), C/1899 E1 (Swift), etc., and searched for correlations — unfortunately too tenuous by today's consensus.

The object of Richter's primary interest was comet 29P/Schwassmann-Wachmann, for which he compiled a large set of magnitude estimates, first from 1927 until 1939 (Richter 1941), later extending it until 1950 (Richter 1954), with a further extension until 1977 completed by Whipple (1980). Yet, perhaps the most homogeneous sample of magnitude data available for this comet was published by Beyer (1962), referring to a major flare-up that began in October 1959. I employ this data set below to provide an example of an explosive event in 29P to compare it with 17P.

7.1. Comparison With Comet 29P/Schwassmann-Wachmann

The light curves of the 2007 megaburst of 17P and the October 1959 outburst of 29P are shown side-by-side in Figure 6. The first two data points in the plot of 29P, shortly before the outburst began, are guesses based in part on Beyer's (1962) negative observations from September 27.92 and 30.96 UT, when the comet was fainter in his 26-cm refractor than visual magnitude 13.0 (a normalized magnitude H_Δ fainter than 9.5). According to Beyer (1962), neither a trace of a coma nor a starlike condensation brighter than magnitude 15.0 could be detected under the prevailing observing conditions on the 27th. On the 30th, the air was very clear but not steady and stars fainter than magnitude 13 could only be seen to flicker at times. Beyer referred to a communication from J. Schubart that on this date the comet failed to show on patrol plates at the Sonneberg Observatory, which can nearly reach magnitude 14 (cf. also Hoffmeister 1960). On the other hand, a stellar nuclear condensation of photographic magnitude 18.0 with some coma was exposed on a plate taken with a 102-cm reflector on September 25 (Roemer 1959, Roemer *et al.* 1966). Although the comet may have been fainter, Beyer's arguments and the fact that Roemer's nuclear magnitudes are known to be below the total brightness by 2-3 magnitudes for faint comets (and more for the brighter ones), make me adopt magnitude 15-16 for the brightness of 29P in late September 1959, which converts to a normalized magnitude 12 ± 0.5 in Figure 6. The comet had undergone a small outburst one month earlier, at the beginning of September, reaching photographic magnitude 12 in the images taken by Van Biesbroeck (1961) with a 208-cm reflector, but this event was already subsiding by September 8. Still, a quiescent, or low-activity, phase may not have been completely restored by the end of September.

While the amplitude of the October 1959 outburst of 29P, probably in the range of 4+ to 5+ magnitudes, is rather poorly known, the event is otherwise described very well. Beyer's (1962) measurements of the dust-coma diameter, presented on the right-hand side of Figure 3, show that it was seen to be steadily expanding for more than a month. Derived from the data obtained under favorable observing conditions, the expansion velocity was equal to 0.19 ± 0.01 km/s, while the onset time was found to be October 1.7 ± 0.2 UT, when the comet was 871.8 days past perihelion and 5.96 AU from the sun. Thus, the outburst began the night the comet was first detected by Beyer, only hours before his observation.

The light curves of the megaburst of 17P and the 29P event in Figure 6 display remarkable similarities. The latter shows a clear plateau extending, with a minor dip in the middle, over at least 40 days. The dip does not coincide with, and is not due to, the Moon's interference. Rather, there may have been a second outburst before the end of October, resupplying the coma with new dust. Morphologically, the dust coma of 29P differs from that in 17P, as even though it begins as a disklike feature, within weeks it starts showing a ring-shaped appendage, thus providing evidence on the rotational motion of the source with the comet's nucleus. Because of the nearly circular orbit of 29P, the temporal variations in the normalized magnitude H_Δ and the intrinsic magnitude H_0 are practically identical over the period of

100 or so days displayed in Figure 6, with the intrinsic brightness being greater by about 3.9 magnitudes. The peak intrinsic magnitude of 29P during this event was $(H_0)_{\rm peak} = 3.4$ and the rise time between 4 and 10 days. Calibrated with the optical constants used for the megaburst, the total cross-sectional area of injected dust is found to have been $\mathcal{X}_{\rm dust} = 1.5 \times 10^6$ km$^2/\Phi$, where the phase effect is even less important than in the megaburst, considering the phase angle of 3°. The injected mass of dust is, accordingly, $\mathcal{M}_{\rm dust} \approx 2.7 \times 10^{12}$ g and the dust-mass-injection rate

$$\dot{\mathcal{M}}_{\rm dust} \approx 3 - 8 \times 10^6 {\rm g/s}. \tag{7}$$

In terms of dust injection, the megaburst of 17P was nearly 40 times as powerful as this outburst of 29P. Although some outbursts of this comet have a greater amplitude than 5 magnitudes, the comet seldom becomes significantly brighter than during the October 1959 event (peak apparent visual magnitude 10.7). For example, the brightest entry in Richter's (1954) list is 9.4 photographic (close to 8.7 visual) during January 1946, which implies an injected mass of dust less than 10 times the amount above. Only if the particle-size distribution function for 29P is flatter, with large grains contributing a much greater fraction of mass, could the contrast between the two comets be mitigated. Fulle (1992) indeed found the average size distribution's power index for this comet to be $k = 3.3 \pm 0.3$ based on his examination of the comet's tail in a single 1989 image. He derived a dust-injection rate that is fully one order of magnitude *lower* than in expression 7 (above), but his results refer only to dust between 5 microns and 2 cm in diameter. In addition, the comet apparently was not in strong outburst when the 1989 image was taken. Even though the dust-injection rate must increase sharply during each major outburst, these events do not necessarily contribute significantly to the dust-mass loss because of their short duration, especially because 29P is now known to be continually active, even between outbursts (Jewitt 1990). In any case, because of the characteristic morphology, there is no doubt that these outbursts have a distinctly local, rather than global, character.

7.2. Comparison With Comet 41P/Tuttle-Giacobini-Kresák

Discovered in 1858, lost until accidentally rediscovered in 1907, and then lost again — in spite of orbit determination efforts (Pickering 1914; Crommelin 1928) — until 1951, when the comet's identity at the three apparitions spanning more than 90 years was conclusively established at last (e.g., Cunningham 1951; Kresák 1953). This is the beginning of the story of this intrinsically faint comet that eventually became best known for its enormous outbursts in 1973, 115 years after it had been first observed.

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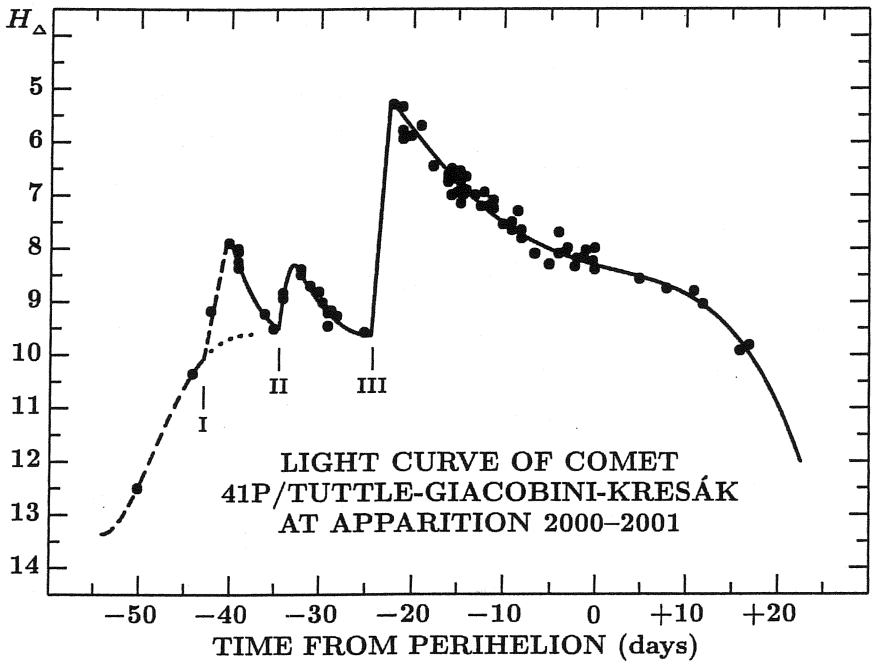

Figure 7. Light curve of comet 41P/Tuttle-Giacobini-Kresák at its 2000-2001 apparition. The magnitudes $H_\triangle$ are as in Figure 1. The onset times of outbursts II and III are, respectively, about 35 and 24 days before the perihelion passage, which occurred on 2001 Jan. 6.97 ET. The onset time, amplitude, and rise time of the first outburst are uncertain. Poor knowledge of the portion of the light curve up to the peak of the first outburst is emphasized by being drawn by a dashed curve. The dotted portion refers to the expected shape of the light curve in the absence of the first event. Note that all three outbursts took place earlier relative to perihelion than the first episode in 1973.

The two 1973 outbursts were described by Kresák (1974). According to his account, the first event began less than a week before perihelion. The rate of brightening was about 3 mag/day and the rate of subsequent fading some 1.2 mag/day. With an estimated amplitude of 9 magnitudes, the comet was back to its usual, low-activity phase only 11 days after the outburst had commenced. One month later, the comet flared up again. Kresák (1974) found that the amplitude was again 9 magnitudes, but the rise time was shorter and the brightness subsided rapidly to an elevated level about 3-4 magnitudes above normal, at which point the rate of fading slowed down considerably. The information on the second outburst was augmented by the data from spectrographic observations made on two nights near peak light (Fehrenbach 1973; Swings and Vreux 1973). Strong bands of C_2, C_3, and CN were detected as well as emissions of CH and CH^+, together with a weak to medium-strength continuum. This is consistent with the absence of a post-outburst plateau, as the subsiding branch of the light curve is essentially accounted for by the lifetimes of the detected daughter molecules, which at the heliocentric distances involved are on the order of a few days. Also consistent with the inconspicuous continuum is the absence of a sharply-bounded expanding dust halo.

The light curve of 41P covering both outbursts was published by Kresák (1974). An independent rendition of the light curves from the apparitions in 1951, 1962, and 1973, readily displaying the comet's dramatically changing behavior from return to return, has been available elsewhere (Sekanina 1984). More recently, the comet flared up again at the apparition of 2000-2001. The light curve based on the data collected mostly from the *International Comet Quarterly* is presented in Figure 7, which shows that this time the comet experienced *three* outbursts during a period of three weeks. Comparison with the apparition of 1973 reveals major differences, the only common features being the rapid rates of brightening and fading, again implying no post-outburst plateau and no dust-halo formation.

The first outburst of 2000-2001 is outcropping in Figure 7 from the steeply increasing light curve of the comet on its approach to the sun. Poorly covered by the observations, this segment of mounting activity up to the peak of the first outburst is depicted by a broken curve in Figure 7. The outbursts of 2000-2001 did not rival the 1973 events in terms of the amplitude or peak brightness. However, relative to perihelion, they all occurred before the first outburst of 1973 had.

With the exception of the rapid rate of brightness surge at the very beginning of each outburst of 41P, there appears to be no common ground with the megaburst of 17P, or, for that matter, with the presented example of such events in 29P. The inconspicuous continuum in the spectrum, implying a relatively low content of dust in the coma, is likely to be at the center of these differences.

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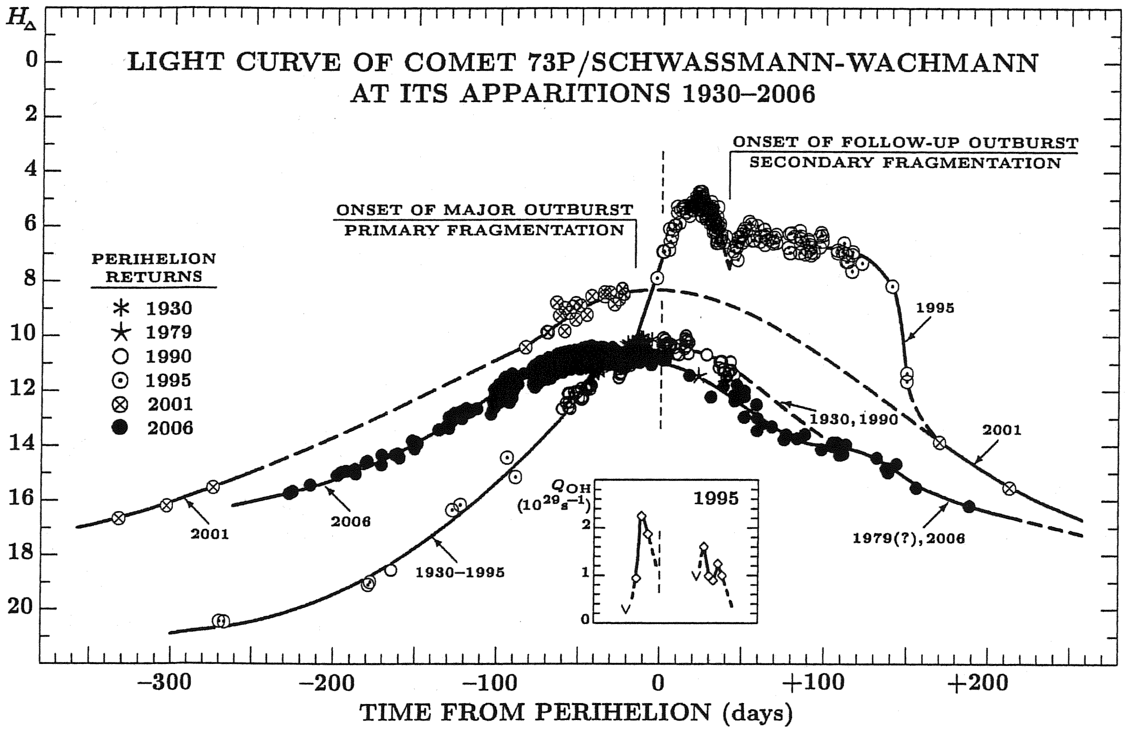

Figure 8. Light curve of comet 73P/Schwassmann-Wachmann at each of its six apparitions 1930, 1979, 1990, 1995, 2001, and 2006. As in Figures 1 and 6, plotted is the normalized magnitude H_Δ. In 1930, the comet's perihelion distance was 1.01 AU, while since 1979 it has remained at 0.93-0.94 AU. The onset times of the two 1995 outbursts coincided with the events of nuclear fragmentation (Sekanina 2005). After the comet split, the brightness refers to the principal fragment C. The 1995 perihelion occurred on September 22.89 ET; fragment C passed through its 2006 perihelion on June 6.96 ET. The inset shows the 1995 temporal variations in the hydroxyl production rate, measured by Crovisier et al. (1996).

7.3. Comparison With Comet 73P/Schwassmann-Wachmann

Discovered during a close approach to the earth in 1930, this is another intrinsically faint comet that after 12 weeks of observation was lost and missed for 9 revolutions about the sun, until it was rediscovered as a new comet in 1979. Its appearance remained unimpressive until 1995, when a sudden surge of OH emission was noticed at radio wavelengths in early September, some two weeks before perihelion (Crovisier *et al.* 1996). Given a small elongation from the sun, the magnitude observations were scant (with gaps) in September and early October 1995, yet indicating that the comet was brightening very slowly, but more or less steadily, for fully five weeks, then declining more rapidly (Figure 8). The observers' accounts (on the pages of the *International Comet Quarterly*) of the comet's appearance in late September and during October repeatedly described a strong nuclear condensation, teardrop shape of the coma, a parabolic envelope or hood, and a fanlike tail, but there was only a single reference to a bright (but elongated) disk of material. There were reports of additional flare-ups in this period of time, which explains the unusually long rise time (36 days for 73P vs. $<$ 10 days for other comets examined in this investigation; cf. Sec. 8). Eight weeks after the onset of this series of events (with additional flare-ups and fading), a new upswing is apparent on the light curve, leading to a second, less conspicuous maximum (Figure 8), followed by a plateau that persisted for 10 weeks. Midway through this phase of evolution, Boehnhardt and Käufl (1995) reported that the comet began to display several nuclei.

Some of the nuclear fragments, reported by these and/or other observers, were short-lived, but four (A-D) were given official designations, with nucleus C being recognized as the principal component. When it returned 5 years later, the fragment C was much brighter than the parent comet at the previous apparitions (Figure 8), and another companion was detected. A recent investigation of the fragmentation sequence and hierarchy of this assemblage of nuclei (Sekanina 2005) showed that one of the fragments observed in 2001 (called F) had never been seen before and that all the companions separated from the principal nucleus in the period of time spanned by the 1995 outbursts.

During the comet's extremely favorable return of 2006, with the minimum geocentric distance of less than 0.1 AU, new products of the advancing fragmentation process appeared before the observers' eyes almost daily. More than 60 fragments were officially catalogued and hundreds of additional short-lived ones were imaged as the comet continued to break apart into second- and higher-generation boulder-sized pieces during further and further episodes of cascading fragmentation.

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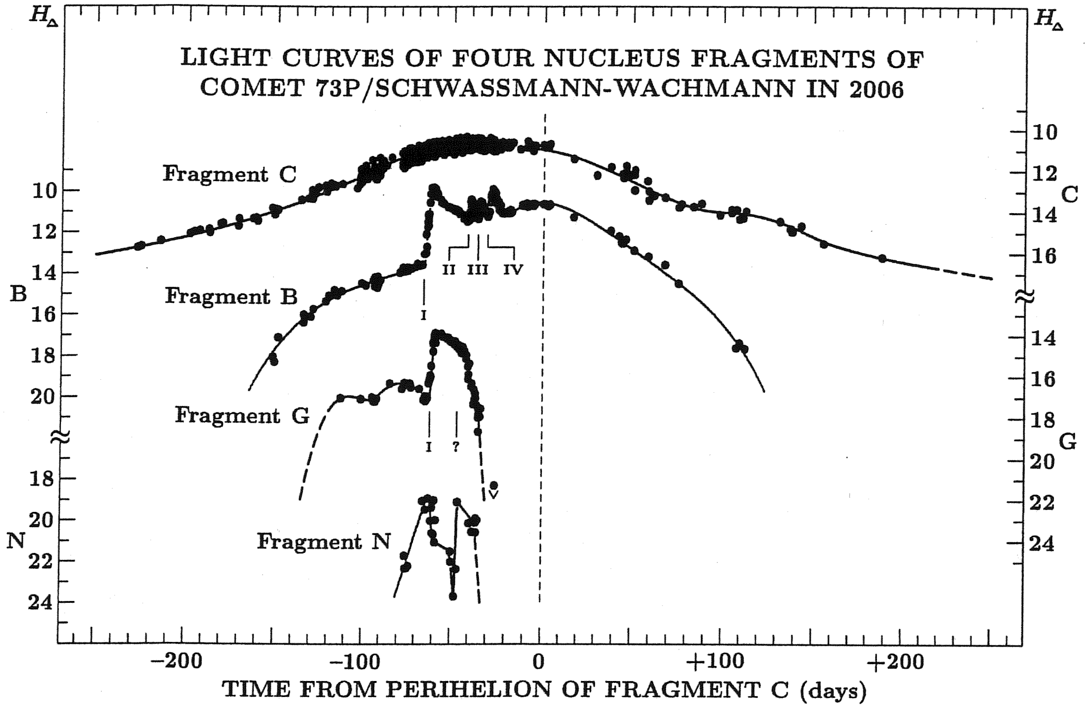

Figure 9. Light curves of four fragments of comet 73P/Schwassmann-Wachmann in 2006. The onset times of the outbursts of fragment B are, respectively, 66, $41\frac{1}{2}$, 36, and $30\frac{1}{2}$ days before perihelion of C (April 1, April 26, May 1, and May 7). The onset time of the major outburst of fragment G was $62\frac{1}{2}$ days before perihelion (April 5). A smaller outburst may have occurred 15 days later. The light curve for fragment B (upper-left scale) has been moved 3 magnitudes down relative to fragment C (upper-right scale) to avoid a congestion between the data points, as fragment B became brighter than C near the peaks of outbursts I and IV. The light curves of fragments G (lower-right scale) and N (lower-left scale) have been shifted similarly. The principal fragment C was at perihelion on 2006 June 6.96 ET, fragments B, G, and N followed, respectively, 0.97, 1.15, and 1.34 days later.

Closely associated with the rapid procession of breakup events was a series of outbursts, which with the exception of the principal nucleus were experienced by all fragments. The relatively smooth light curve of nucleus C is compared in Figure 9 with those of three companions, B, G, and N. Of these, B was the brightest and most persistent, while N was the faintest and of the shortest lifetime, its light curve consisting entirely of rapid fluctuations. On the other hand, on its approach to the sun in 2006, C was still significantly brighter than the presplit parent comet, but this lingering effect finally disappeared near and after perihelion (Figure 8).

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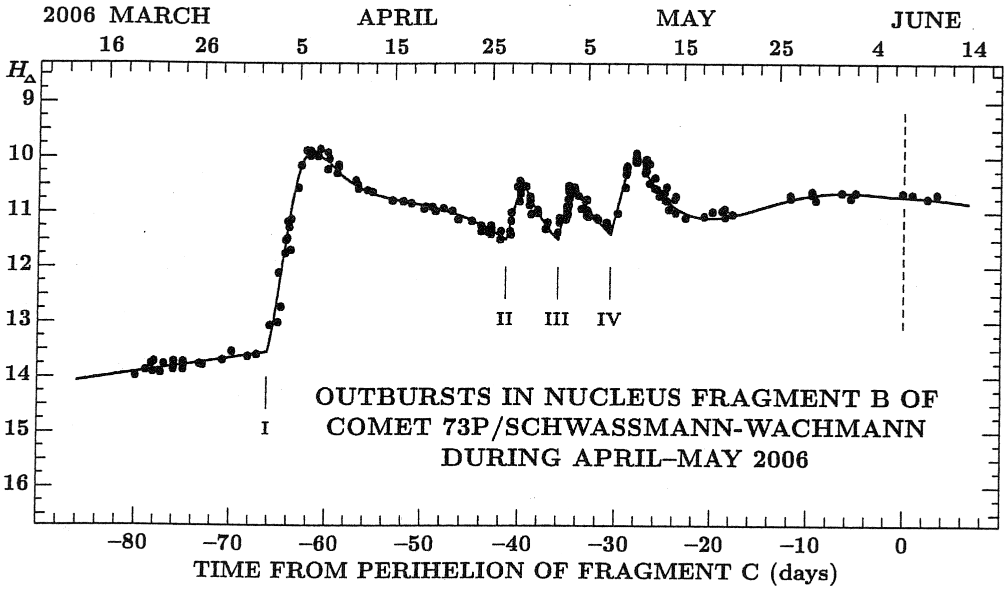

Figure 10. Close-up view of the light curve of fragment B of comet 73P/Schwassmann-Wachmann in April-May 2006, including the four outbursts. Even though the brightness subsides more slowly than it rises for each of them, no extended plateaus are apparent. Only selected observations, mutually consistent to within a few tenths of a magnitude, have been plotted.

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In terms of the production of higher-generation fragments, nucleus B was unquestionably the most prolific one, more so than nucleus G or the others. The runaway-like fragmentation of B was in five weeks accompanied by as many as four separate outbursts, whose sequence is fully resolved in close-up view in Figure 10. All outbursts of the companions exhibited the characteristic steep rise in brightness followed by a more gradual decline, but none was associated with the formation of a halo or a plateau, because there was not enough dust to sustain them.

Just as with 41P, the outbursts of comet 73P do not appear to have much in common with the megaburst of 17P. The displays of remarkable phenomena by 73P in both 1995 and 2006 document a very strong correlation between the outbursts and nuclear fragmentation for both the presplit parent nucleus and the assemblage of its fragments.

7.4. Comparison With Comet C/2001 A2 (LINEAR)

C/2001 A2 is a long-period comet, whose propensity for both flaring up and nuclear fragmentation (e.g., Jehin *et al.* 2002; Sekanina *et al.* 2002) was demonstrated extensively during a virtually uninterrupted period of observation between January and November 2001 approximately centered on the comet's passage through perihelion at 0.79 AU.

Until about three months before perihelion, the comet brightened at a fairly moderate rate (as an inverse fourth power of heliocentric distance), but then the rate increased and, less than two months before perihelion, a major outburst — of an estimated amplitude of 5 magnitudes — got underway. There was no plateau, but a higher level of activity was retained and a second outburst of a much smaller amplitude took place still before the comet reached perihelion. Two further outbursts, each about $1\frac{1}{2}$ magnitudes in amplitude, occurred between 10 and 50 days after perihelion. When last observed for photometry, at nearly 2.4 AU from the sun outbound, the comet was some 4 magnitudes, or 40 times, brighter intrinsically than at the same heliocentric distance on its way to perihelion. Thus, the behavior of the comet changed dramatically during its passage near the sun.

The nucleus' duplicity was first reported by Hergenrother *et al.* (2001) exactly one month after the first outburst. The nucleus designated as B, unquestionably the principal mass, was subsequently observed until mid-November, while companion A was seen over a period of only 20 days. Modeling the motion of A relative to B, Sekanina *et al.* (2002) determined that, within the uncertainties involved, the onset of the first outburst and the breakup of the parent nucleus into A and B coincided. It was also established that C, another fragment of the nucleus, separated from B at the time of the second outburst, and that three additional fragments, D, E, and F, all split off from what was left of B within four days of each other and nearly coinciding with the third outburst. This multiple breakup explains the unusually long rise time of the third outburst, exceeding by about five days the rise times of the other events. All these are remarkable correlations, which, nevertheless, need to be addressed in the context of two facts: (i) no outburst was observed to accompany the separation of G, the seventh nuclear fragment observed, and (ii) no known fragmentation event was associated with the last outburst. These issues are discussed in Sec. 8.2.

8. Explaining the Megaburst

The comparison of outbursts observed in the selected comets offers a wealth of information on this phenomenon in a number of ways. A list of active-phase parameters for 20 events summarized in Table 2 shows that, in any chosen category, the 2007 megaburst of 17P is unrivaled as the most powerful event of this kind on record. Before presenting a model for the megaburst, I address possible implications from the relationships (a) between outbursts and a halo formation and (b) between outbursts and nuclear fragmentation.

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Table 2. Active-phase parameters of the megaburst of comet 17P/Holmes and other cometary outbursts.[a]

		Onset of event			Peak intrinsic magnitude	Amplitude	Rise time	Post-event plateau	Expansion velocity of dust	Mass of injected dust
Comet[b]	Event	Date (UT)	$t_{\rm onset} - T$[c] (days)	$r_{\rm onset}$[d] (AU)	(mag)	(mag)	(days)		(km/s)	(g)
17P	megaburst	2007 Oct 23.7	+172.2 ± 0.2	2.44	−0.53 ± 0.12	14 ± 0.5	1.8 ± 0.4	yes	0.50 ± 0.02	10^{14}
	discovery[e]	1892 Nov 4.7	+143.7 ± 0.4	2.39	1.9 ± 0.3	....	5–6	some	0.38 ± 0.01	10^{13}
	2nd	1893 Jan 16.0	+216.0 ± 0.2	2.64	1.2 ± 0.3	4–6	4–5	some	0.28 ± 0.02	2×10^{13}
29P	(Beyer)[f]	1959 Oct 1.7	+871.8 ± 0.2	5.96	3.4 ± 0.1	[4+]–[5+]	4–10	yes	0.19 ± 0.01	2.7×10^{12}
41P	#1[g]	1973 May 25.0	−5.0 ± 1.5	1.15	3.7 ± 0.4	9 ± 0.5	3.0 ± 0.5	no	≥0.5	....
	#2[g]	1973 Jul 5.0	+36.0 ± 1.0	1.24	3.5 ± 0.4	9 ± 0.5	2.0 ± 0.5	no	≥0.3	....
	I[h]	(2000 Nov 25)	(−43 ± 1)	(1.20)	(7.5 ± 0.5)	(2 ± 1)	(3 ± 1)	no	....	....
	II	2000 Dec 2.8	−35.2 ± 0.5	1.15	8.1 ± 0.3	1.5 ± 0.3	2.3 ± 0.4	no	....	....
	III	2000 Dec 14.0	−24.0 ± 1.0	1.10	5.1 ± 0.3	4.3 ± 0.3	2.0 ± 0.5	no	....	....
73P	major	1995 Sept 6.9	−16 ± 3	0.96	5.3 ± 0.3	5.0 ± 0.5	36 ± 4	no	....	....
	follow-up	1995 Nov 2.9	+41 ± 1	1.11	5.9 ± 0.2	1.4 ± 0.3	14 ± 5	yes	....	....
73P-B	I	2006 Apr 1.7	−66.2 ± 0.4	1.33	9.3 ± 0.3	3.7 ± 0.4	4.7 ± 0.7	no	....	....
	II	2006 Apr 26.4	−41.5 ± 0.5	1.12	10.2 ± 0.2	1.0 ± 0.3	1.7 ± 0.5	no	....	....
	III	2006 May 1.9	−36.0 ± 0.3	1.08	10.4 ± 0.2	0.9 ± 0.2	1.4 ± 0.4	no	....	....
	IV	2006 May 7.3	−30.6 ± 0.3	1.04	9.9 ± 0.2	1.3 ± 0.2	2.6 ± 0.5	no	....	....
73P-G	I	2006 Apr 5.5	−62.4 ± 0.4	1.30	13.5 ± 0.3	3.0 ± 0.4	5 ± 1	no	....	....
2001 A2	I	2001 Mar 28.5	−57.0 ± 1.0	1.31	6.4 ± 0.6	5 ± 0.6	3.0 ± 1.0	no	....	....
	II	2001 May 10.5	−14.0 ± 1.0	0.83	6.0 ± 0.2	1.1 ± 0.2	3.5 ± 1.0	no	....	....
	III	2001 Jun 5.0	+11.5 ± 1.0	0.81	5.4 ± 0.3	1.4 ± 0.3	8.0 ± 1.0	no	....	....
	IV	2001 Jul 11.5	+48.0 ± 1.0	1.19	6.2 ± 0.2	1.5 ± 0.2	2.5 ± 1.0	no	....	....

[a] All errors except for those of the expansion velocity entries and the onset time entries for comets 17P and 29P are estimated errors.

[b] Comet names: 17P = Holmes; 29P = Schwassmann-Wachmann; 41P = Tuttle-Giacobini-Kresák; 73P = Schwassmann-Wachmann; 73P-B and 73P-G = the comet's nucleus fragments B and G, respectively; 2001 A2 = LINEAR.

[c] Time of event's onset reckoned from the time of nearest perihelion passage; for fragments B and G of 73P, the reference time is the perihelion passage of the principal fragment C.

[d] Heliocentric distance of the comet at the time of onset.

[e] Comet discovered during this outburst.

[f] All information listed for this entry based on Beyer's (1962) physical observations.

[g] Based on the data presented by Kresák (1974).

[h] Parameters of this event are very uncertain, as discussed in Sec. 7.2.

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8.1. Relationship Between Outbursts and Halo Formation

Bobrovnikoff (1932) appears to be one of the first to get involved in a systematic investigation into halos in comets. His two primary objects of interest were 1P/Halley in 1910 and 1835-1836 and 12P/Pons-Brooks in 1883-1884, both of which he found to have exhibited numerous well-defined halos expanding with velocities of mostly near 0.5-0.6 km/s and moving under relatively low "repulsive accelerations" (solar radiation pressure). Bobrovnikoff emphasized that spectroscopic observations indicated that these were gas halos. During the 1986 apparition of Halley's comet, Schlosser *et al.* (1986) imaged the evolution of 15 prominent CN halos (which they called shells) and showed that the expansion velocities decreased from 1 km/s at 24 days after perihelion to 0.8 km/s by 36 days later. Subsequently, Schulz and Schlosser (1990) linked the CN halos to CN jets in a transition region about 80000 km from the nucleus and proposed that they both were produced by secondary sources made up of CHON particles.

The outbursts of comet 12P in 1883-1884 may have been a somewhat different story from that of 1P/Halley's CN halos. The evolution of the outburst on 1884 Jan. 1 was described in detail by Müller (1884a, 1884b) and by Vogel (1884), to whom both Bobrovnikoff (1932) and Richter (1949) referred in their studies. Both observers agreed that the three bands (of C_2) dominated the coma, but in the nuclear condensation and its immediate proximity the continuous spectrum prevailed. Vogel remarked that, as the outburst advanced in the evening of Jan. 1, the initially starlike nuclear condensation became a uniformly illuminated circular disk several arcseconds in diameter, whose spectrum was continuous. Vogel's two careful measurements of this disk's diameter made 33 minutes apart were used by Bobrovnikoff (1932) to derive an expansion velocity of 0.4-0.5 km/s. By the evening of Jan. 2, the nuclear condensation was much smaller, the disk from the previous night no longer visible. Müller (1884b), who observed the comet using both a photometer and a spectroscope, underscored that the main result of his photometric analysis of the data was the finding that the light coming from the nuclear condensation and its nearest outskirts between 1883 Nov. 10 and 1884 Jan. 14 had been primarily reflected sunlight, and that any intrinsic light had contributed only a minor part to the total brightness.

There are thus two types of product from an outburst. One type is a gas halo, which can come from the nucleus or from a secondary source, as described by Schulz and Schlosser (1990) for Halley's comet; the other type is a dust halo. These two products are apparently always present, as is illustrated by the fact that dust may be a carrier of the species needed for a gas halo, but depending on the mix (as well as on the detector used), one of them may be dominated by the other in the observations or not detected at all. Since 12P was obviously a dust-poor comet, the gas coma prevailed in its outbursts unless one took the pain to search for reflected sunlight. A relatively low dust content must also have been the reason for the observed character of the outbursts of 41P (Sec. 7.2) and C/2001 A2 (Sec. 7.4). In the case of the fragments of 73P, too little dust was involved regardless of whether it did or did not dominate the gas emissions.

The relationship between outbursts and a halo formation is therefore always positive, but rather large amounts of particulate matter are needed to display an expanding disk-like dust halo for many days or weeks after the event's onset. Even more dust is necessary to maintain a persisting post-outburst plateau in the light curve, as the halo's surface brightness continues to drop. Ultimately, it is the enormous mass of 10^{14} g carried in the dust cloud around 17P that is the key to understanding this megaburst.

8.2. Relationship Between Outbursts and Nuclear Fragmentation

In principle, the correlation between an outburst and a fragmentation event can be approached from one of two different generic standpoints. One is to consider the companion (or secondary) nucleus as a product of the standard (but highly variable) dust-emission process — namely, as the largest and most massive piece in the particle size/mass distribution of the population of dust ejecta. It is well-known that a size/mass limit to particles that can be accelerated away from the nucleus is determined by the equilibrium between the molecular drag force of the outflowing gas and the nucleus' gravitational attraction (e.g., Delsemme and Miller 1971). This limit increases with increasing radial outflow velocity, increasing mass-emission rate of gas per unit area of the source, and decreasing mass of the nucleus. Because for a given comet the gas-emission rate is the primary variable, the largest/most massive fragment of particulate ejecta during an outburst is greater than during "normal" activity, thus being easier to detect as a discrete mass.

The problem with this hypothesis is that the limit calculated from the appropriate condition is uncomfortably low compared to the expected sizes and masses of companion nuclei, and the approach becomes absurd for comets breaking up at very large heliocentric distances. If one finds a physical mechanism (Sec. 8.5) that is capable of providing the necessary power, it is conceptually feasible to turn the problem around and consider the separation of a large mass of refractory material from the rest of the nucleus and its lift-off into the atmosphere as the primary process, while the dust cloud is a product of the parallel, nearly simultaneous disintegration of some part of the lifting mass due to structural failure. The debris in the forming cloud has a certain particle size/mass distribution and a total cross-sectional area that is greater than that of the originally separating mass, thus causing, in general, a brightening or an outburst.

What happens in a particular case is determined by the response of the mass to the action of the forces involved in the process of separating and lifting. This response depends primarily on the mechanical strength: the more brittle the mass, the more crumbling it experiences and the greater amount of debris is generated. A variety of scenarios (cf. comet C/2001 A2 in Sec. 7.4) can be understood as a function of the size/mass-distribution law intrinsic to the population of the debris: the steeper the distribution's slope, the less likely the presence of a major fragment. There are two extreme scenarios. On the one hand, if the whole lifted mass is rather compact, little dust is released during the process and the fragmentation event is not accompanied by an outburst. On the other hand, if the lifted mass disintegrates in its entirety, the released amount of dust is enormous and the outcome is a major outburst with no detection of a sizable nuclear fragment. It is proposed that *the complete disintegration of a sizable mass of exceptionally poorly cemented refractory material splitting off from the nucleus of 17P into the atmosphere triggered the comet's megaburst.*

8.3. Pancake-Shaped Fragments of Split Comets and Layering on Cometary Nuclei

The nature of this mass is at this point a matter of conjecture. However, the observations and modeling of comets with multiple nuclei and the recent spacecraft-borne close-up imaging and interpretation of the surface morphology of cometary nuclei, especially that of 9P/Tempel, offer a breakthrough in an effort to understand these issues.

Table 3. Comparison of a major pancake-shaped nuclear fragment of a split comet with a thick layer on the nucleus of comet 9P/Tempel.

Object's property	Major pancake-shaped nuclear fragment (Sekanina 1982)	Thick layer on nucleus of 9P/Tempel	
		Thomas *et al.* (2007)	Belton *et al.* (2007)
Thickness (m)	$\sim 130^{a}$	$\lesssim 200$	~ 50
Base area (km^2)	1.6	~ 6	~ 5
Mass (g)^{b}	0.8×10^{14}	$\lesssim 4 \times 10^{14}$	$\sim 10^{14}$

[a] This is an average thickness, calculated as the volume-to-base area ratio of a fitted spherical segment.

[b] Derived from the volume assuming bulk density of 0.4 g/cm^3.

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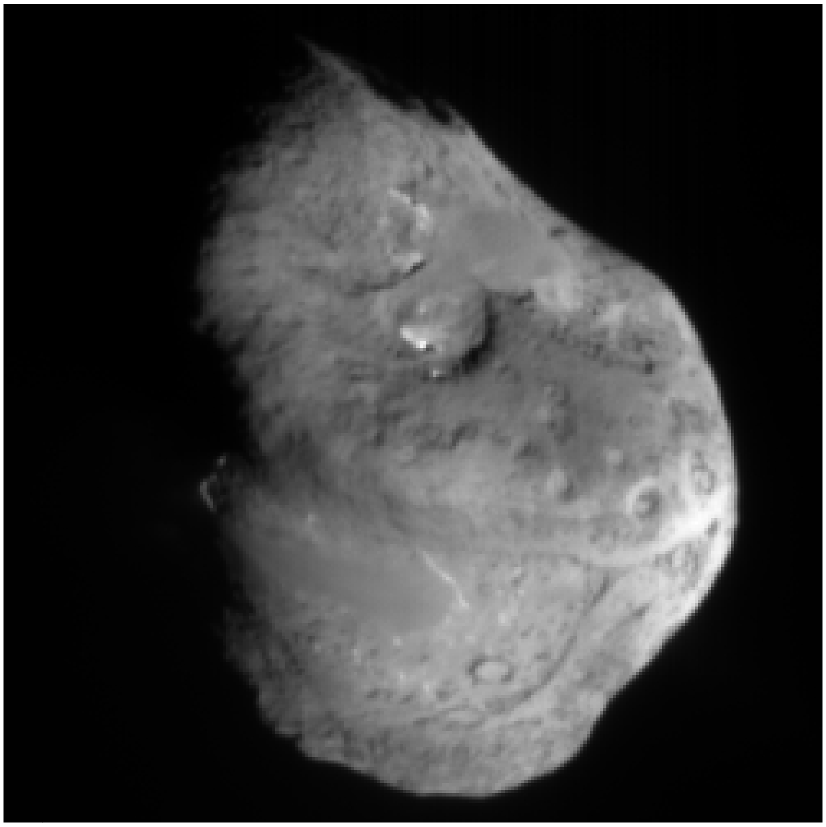

Figure 11. Image of the nucleus of comet 9P/Tempel taken by the impactor's targeting sensor of the Deep Impact probe about 5 minutes before crash on 2005 July 4. The image shows widespread thick layers of terrain bounded by steep scarps. The sun is to the right. From the top to the bottom, the nucleus is about about 7 km in size. (Image credit: NASA/JPL-Caltech/UMD.)

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A fragmentation model, consistent with the conservation-of-orbital-angular-momentum law and incorporating a nongravitational deceleration of a major fragment relative to the principal nucleus of a split comet as a parameter, was developed (Sekanina 1978, 1982) and applied to dozens of comets with multiple nuclei, including comets 73P and C/2001 A2 (Secs. 7.3 and 7.4), to derive the fragments' separation times (for correlations with the onset times of outbursts), separation velocities, and the decelerations. The separation velocities were found to be always very low, ~1 m/s. A major finding was the discovery of a discrepancy for *nearly spherical* fragments between their brightness and the nongravitational deceleration to which they were subjected: their light curves required much lower decelerations, while the computed decelerations implied much fainter objects. The proposed solution to this dilemma was to make each fragment *pancake-shaped* (Sekanina 1982), with its dimensions defined by the size of the parent nucleus as the thickness and the plane-of-fissure diameter of a spherical segment that fits the deceleration. In this scenario, the brightness is determined primarily by the maximum cross-sectional area of the tumbling pancake, whereas the deceleration is determined primarily by its minimum dimension (thickness). A typical deceleration derived for the major (persistent) fragments was 7×10^{-5} the solar gravitational attraction (Sekanina 1982), with the corresponding dimensions and mass shown below in Table 3. In conformity with the prevailing views in the 1980s, I assumed that the pancake-like nuclear fragments were jettisoned pieces of a purged insulating mantle with a spread reservoir of icy material attached to the base. Each pancake's release from the parent nucleus was accomplished by activation of an ice sheet by the penetrating heat wave and presumably assisted by nuclear rotation. However, each pancake's dimensions and mass are independent of its nature.

The images of 9P/Tempel returned by the *Deep Impact* spacecraft mission (cf. Figure 11) have provided strong evidence of nuclear layering (Thomas *et al.* 2007), which consists of extensive thick units (Table 3) as well as much thinner ones. A "talps" ("splat" spelled backwards) or "layered pile" model was published by Belton *et al.* (2007), who proposed that these layers are primordial and omnipresent on the nuclei of the Jupiter-family comets, even though they are less apparent on 19P/Borrelly and barely discernible on 81P/Wild. Further research should test the veracity of the talps hypothesis. By identifying pancake-shaped fragments as jettisoned layers, one can explain two phenomena that otherwise are difficult to understand: (i) cataclysmic fragmentation (such as for comet C/1999 S4), by all layers breaking loose as free-flying pancakes simultaneously; and (ii) large uncratered plains on the nucleus' surface, by their long-term protection against cosmic bombardment by layers that had been stacked on top of them, but were jettisoned just recently. Truly remarkable is the agreement in Table 3 between the estimated masses of a *typical* thick layer and a *typical* major pancake-shaped nuclear fragment, and also between them on the one hand and the mass of the dust cloud around 17P on the other hand (Sec. 5)! This correspondence suggests that *a thick layer 10^{14} g in mass jettisoned from the surface of 17P into the atmosphere as a major pancake-shaped fragment and disintegrating almost immediately into a cloud of dust* is a conceptual hypothesis for the megaburst that is worth pursuing further. It is noted that — given the sizes of the base areas in Table 3, which occupy between 10 and 35 percent of the comet's hemispheric surface area — the lifted pancake-like layers of terrain are truly extended sources of particulate debris. For example, if centered on a rotation pole, a mass of 6 km^2 would cover the nucleus' surface of comet 17P from latitude 90° down to latitude 40°, and its disintegration upon the lift-off would scatter microscopic ejecta into a wide cone with an apex angle of at least 100°. Such an enormous event, of nearly global proportions on the scale of the nucleus of comet 17P, is in sharp contrast to the local character of flare-ups known to occur episodically on the surface of comet 29P (Sec. 7.1). The signaled propensity for nearly spontaneous crumbling into mostly microscopic-sized particulate debris implies (Sec. 8.5) that the energy needed to pulverize the jettisoned mass was much lower than the energy associated with the dust cloud's expansion.

8.4. Kinetic Energy of the Expanding Cloud of Dust

A crude estimate for the kinetic energy acquired by the dust injected into the coma during the active phase of the megaburst can be obtained from the injected mass $\mathcal{M}_{\rm dust}$ and the expansion velocity $v_{\rm exp}$, both derived in Sec. 5:

$$E_{\rm exp} = \frac{1}{2}\mathcal{M}_{\rm dust} v_{\rm exp}^2 \approx 1.25 \times 10^{23} {\rm erg}. \tag{8}$$

By sheer coincidence, this number is on the same order of magnitude as the explosive energy of the Tunguska object (e.g., Ivanov 1963, Ben-Menahem 1975) and virtually identical with its new revised estimate (Boslough and Crawford 2008). However, the result (equation 8) is in fact an upper limit to the true kinetic energy of the expanding mass of dust in the atmosphere of 17P, because only a fraction of the injected particles reached the envelope of the cloud.

A more rigorous approach must use the dust-particle size-distribution function $f(h)dh$ from Sec. 5 and a size-dependent particle velocity $v(h)$, in which case the kinetic energy is

$$E_{\rm dust} = \frac{1}{2} \int_{h_{\rm min}}^{h_{\rm max}} \mu(h) v^2(h) f(h) dh, \tag{9}$$

where $\mu(h) = \frac{1}{6}\pi\rho_{\rm dust} h^3$ is the mass of a particle of diameter h and $v(h)$ is the terminal velocity acquired by this particle during its injection into the coma. Using a hydrodynamical approach to gas-dust interaction in cometary atmospheres, Probstein (1968) was the first to show that terminal velocities for tiny, microscopic dust that rapidly accommodates to the ambient gas flow are nearly independent of particle size, converging to a particular limiting value that is a function of the dust-to-gas mass ratio in the comet's head, whereas large dust is accelerated to lower terminal velocities that vary with $1/\sqrt{h}$. Both boundary conditions are satisfied by a simple law

$$v(h) = \frac{v_0}{1 + b\sqrt{h}}, \tag{10}$$

where v_0 and b are the coefficients that depend on the dust-to-gas mass ratio. The observed expansion velocity is obviously the terminal velocity of the smallest grains in the cloud,

$$v_{\rm exp} = \frac{v_0}{1 + b\sqrt{h_{\rm min}}}. \tag{11}$$

Inserting expressions 3 and 10 into equation 9, one again finds the result to be practically independent of the maximum particle diameter, $h_{\rm max}$, when $k > 4$. The kinetic energy is equal to

$$E_{\rm dust} = \frac{1}{12} n_0 \pi \rho_{\rm dust} v_0^2 \int_{h_{\rm min}}^{\infty} \frac{h^{3-k}}{\left(1+b\sqrt{h}\right)^2} dh. \tag{12}$$

After integration, one has

$$\begin{aligned} E_{\rm dust} &= \mathcal{M}_{\rm dust} v_0^2 (k-4) \left(b\sqrt{h_{\rm min}}\right)^{2k-8} B_{\left(1+b\sqrt{h_{\rm min}}\right)^{-1}}(2k-6, 8-2k) \\ &= E_{\rm exp}(2k-8)\Theta^{6-2k}(1-\Theta)^{2k-8} B_\Theta(2k-6, 8-2k), \end{aligned} \tag{13}$$

where for $0 < z < 1$

$$B_z(x,y) = \int_0^z t^{x-1}(1-t)^{y-1} dt \tag{14}$$

is the incomplete beta function and

$$\Theta = \frac{1}{1+b\sqrt{h_{\rm min}}} = \frac{v_{\rm exp}}{v_0} \tag{15}$$

is a dimensionless expansion-velocity coefficient. The correction factor $E_{\rm dust}/E_{\rm exp}$ depends only on the product of b and $h_{\rm min}$, but not on either of them individually. If $h_{\rm mean}$ is the diameter of a mean particle whose terminal velocity is exactly one-half the limiting velocity v_0, the coefficient b is

$$b = \frac{1}{\sqrt{h_{\rm mean}}}, \tag{16}$$

with v_0 then derived from Eq. (11). Taking, crudely, $h_{\rm mean} \approx \sqrt{h_{\rm min} h_{\rm max}}$, $h_{\rm min} \approx 0.1$ micron, and $h_{\rm max} \approx 2$ cm, one finds $b \approx 15$ cm$^{-1/2}$ and $\Theta \approx 0.955$. Keeping b constant but relaxing $h_{\rm min}$ to cover a range of particle diameters, say, from 0.02 to 0.5 micron (Figure 5), one gets Θ in the range of 0.90 to 0.98.

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Table 4. Correction factors $E_{\rm dust}/E_{\rm exp}$ for the kinetic energy of dust injected into the coma of 17P during the megaburst.

Power index, k	Dimensionless expansion-velocity coefficient Θ				
	0.90	0.92	0.94	0.96	0.98
4.02	0.066	0.072	0.080	0.092	*0.114*
4.05	0.155	0.168	0.186	*0.212*	0.257
4.10	0.278	0.300	*0.329*	0.370	0.438
4.20	0.459	*0.489*	0.528	0.581	0.663
4.40	*0.665*	0.698	0.737	0.786	0.854

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The correction factor $E_{\rm dust}/E_{\rm exp}$ is listed in Table 4 as a function of Θ and the power index k. For a constant injected mass of dust, Figure 5 shows that the minimum particle diameter and the power index are tightly correlated. For $\mathcal{M}_{\rm dust} = 10^{14}$ g, the correction factors for the relevant combinations of k and Θ are shown along the diagonal of Table 4 by slanted-type font. To avoid the dust-particle diameters much smaller than 0.1 micron (because of the absence of Rayleigh-type scattering) and the size-distribution functions that are too steep ($h^{-k}dh$, with k slightly exceeding 4, is already substantially steeper than the usual h^{-3} to $h^{-3.5}dh$), the preferred case in Table 4 is $k = 4.05$, $\Theta = 0.96$, which yields

$$E_{\rm dust} \simeq 0.2 E_{\rm exp} \simeq 2.5 \times 10^{22} {\rm erg}. \tag{17}$$

For comparison, the average solar-radiation energy impinging on an area Π (in km^2) of the nucleus' surface of comet 17P during a single revolution about the sun is

$$E_{\Re}(\Pi) = \frac{1}{4} S_0 \Pi \int_{(P_{\Re})} \frac{1}{r^2} dt = 1.078 \times 10^{23} p_{\Re}^{-1/2} \Pi, \tag{18}$$

where S_0 is the solar constant, $S_0 = 1.180 \times 10^{21}$ erg/km^2/day, r is the heliocentric distance, t is time, and $p_{\mathfrak{R}}$ and $P_{\mathfrak{R}}$ are, respectively, the orbital parameter (in AU) and the orbital period during the revolution $\mathfrak{R}$. The factor $\frac{1}{4}$ accounts for an effect of the comet's rotation, as the nucleus' cross-sectional area is one quarter of the total surface area.

During the current revolution about the sun, the entire surface of the nucleus, 34.2 km^2, receives an energy of 2.15 $\times$ 10^{24} erg from the sun. Because of the planetary perturbations, the orbit of 17P varies from return to return, and so does the total amount of impinging solar energy. However, these variations are very small. During the revolution centered on the 1892 return, for example, when the perihelion distance was 2.14 AU (compared to the current value of 2.05 AU), the comet received 2.12×10^{24} erg from the sun, assuming the same nuclear surface area; at the 1964 return, the perihelion distance was 2.35 AU and the energy received during that revolution was still 2.05×10^{24} erg. During the entire period of time between the 1892-1893 explosive events and the 2007 megaburst, the total energy impinging from the sun on the nucleus of comet 17P/Holmes was 3.4×10^{25} erg, nearly 1400 times the kinetic energy of dust injected into the atmosphere during the megaburst. Almost all of this received solar energy was reradiated back into space as thermal radiation if the nucleus' surface was kept at an orbit-averaged blackbody temperature of 148 K. The balance of the energy was used to sublimate water and other ices and to transfer heat into the nucleus' interior. For comparison, a black-body temperatures are 195°K at perihelion of 17P and 178°K at a heliocentric distance of the megaburst; the temperatures of water ice on the nucleus' surface at the subsolar point are 194°K and 191°K, respectively, at the two distances; and the corresponding nuclear surface-averaged temperatures of water ice are 180°K and 173°K.

8.5. Amorphous-to-Cubic Ice Phase Transition and Water Production

The very high kinetic energy of the megaburst of 17P requires an internal energy source. While there has been a number of mechanisms suggested over the years (for reviews, see e.g., Hughes 1990, 1991), I focus on the amorphous-to-cubic water ice-phase transition as a mechanism that appears to be consistent with, and favored by, the range of temperatures listed at the end of Sec. 8.4, as is apparent from the following.

First proposed as a potential source for triggering comet outbursts by Patashnick *et al.* (1974), the amorphous-to-cubic ice transition is strongly exothermic, with an energy-release rate per unit mass of $(dE/d\mathcal{M})_{\rm trans} = 24$ cal/g or 1.0×10^9 erg/g. The amount of information on amorphous water ice has recently grown exponentially, and it is impossible to present even an abridged overview of the results. From the astrophysical standpoint, the complexities of the water-ice transitions are apparent from laboratory work by Jenniskens and Blake (1994, 1996), who investigated the evolution, during warm-up, of vapor-deposited amorphous ice at a temperature of 15°K and an extremely low pressure of $\sim 10^{-7}$ torr. They confirmed the previously reported formation of high-density amorphous ice (1.17 g/cm^3), which persisted until 38°K. At the temperatures between 38°K and 68°K, a transition took place to low-density amorphous ice (0.94 g/cm^3), whose further heating caused its structure to change when the temperature reached 122°K to 136°K, depending on the experimental conditions. The crystallization began between 142°K and 160°K, and the formation of cubic ice, of the same density, eventually slowed down between 158°K and 170°K. A fraction of low-density amorphous ice did not crystallize, forming instead "restrained" amorphous ice that coexisted with cubic ice in a mix up to at least 178°K. At higher temperatures, at and above 213°K, both cubic ice and any traces of "restrained" amorphous ice got transformed into hexagonal ice. Jenniskens and Blake concluded that, in practice, the quoted temperatures must also depend on impurities such as dust inclusions, which in the amorphous-ice transition regime can assist the formation of more-complex organic molecules. Jenniskens and Blake speculated that the comets presumably originating in the so-called "Kuiper" (or Whipple) transneptunian belt (which presumably include 17P) should contain high-density amorphous ice, and that "restrained" amorphous ice could account for anomalous gas retention to warm up impure ices to temperatures in excess of 150°K.

The significance of the surface temperatures mentioned at the end of Sec. 8.4 is that they all exceed 160°K at heliocentric distances of up to that of the megaburst and even beyond. Over this arc of the orbit, a small fraction of the total solar energy is diffused as a heat wave into the nucleus, including a porous pancake-shaped layer, whose base is assumed to have previously been warmed up to temperatures exceeding 68°K (high-density to low-density amorphous-ice transition) but not to 160°K. Although the heat wave may retreat a little at larger distances from the sun, it continues to diffuse in during the subsequent orbits. Numerical models (e.g., Prialnik 1992) suggest that cumulatively the front of this heat wave should gradually penetrate, over a number of revolutions, ever deeper into the interior until the icy material at the pancake-shaped layer's base, some 50 meters below the surface, reaches a temperature of $\sim$ 160°K. At that point, the transition from low-density amorphous ice to cubic ice begins, with large amounts of released energy rapidly heating up and sublimating the ice. To test, conservatively, whether this process is numerically feasible, I assume that all volatile material is only water ice, even though there may be 14 percent of carbon monoxide in the emissions (Salyk *et al.* 2007), which would increase the intensity of the process. In a water-only scenario, I first derive the temperature, Υ, reached by the crystallized ice. Writing for $C_{\rm ice}(\Upsilon)$, its specific heat (in erg/g/K) in the range $150°{\rm K} \leq \Upsilon \leq 240°{\rm K}$,

$$C_{\rm ice}(\Upsilon) = 8.68 \times 10^4 \Upsilon - 37.7 \Upsilon^2, \tag{19}$$

the condition determining the post-transition temperature $\Upsilon_{\rm trans}$ of the water-ice reservoir is

$$\int_{\Upsilon_{\rm pre}}^{\Upsilon_{\rm trans}} C_{\rm ice} d\Upsilon = (dE/d\mathcal{M})_{\rm trans} = 10^9, \tag{20}$$

where $\Upsilon_{\rm pre}$ is the temperature at the time the crystallization process sets in. For $\Upsilon_{\rm pre} = 160°$K, the solution to equation 20 is $\Upsilon_{\rm trans} = 226°$K. The sublimation rate of water ice from a unit area at this temperature is 2.4×10^{19} molecules/cm^2/s, more than two orders of magnitude higher than at the temperature of 160°K. Equivalent to the conditions at the subsolar point of a comet at 0.26 AU from the sun and implying a vapor pressure of 5 pascals, the high sublimation rate shows that, in order to satisfy a near-peak water-production rate of 1.2-1.4 $\times$ 10^{30} molecules/s (Combi *et al.* 2007) in Table 5, the emission area required was not more than 5.0-5.8 km^2, in excellent agreement with the estimated base area of the pancake-shaped layer (Table 3).

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Table 5. Reported water production rates for comet 17P after the onset of the megaburst.

Date 2007/08 (UT)	Distance from sun (AU)	Water production rate		Species and line/band observed	Aperture radius (10^3 km)	Observer(s) and reference
		10^{29} mol/s	10^6 g/s			
Oct 25	2.44	12	36	H (Lyman-α)	....	Combi *et al.* (2007)
Oct 27	2.45	14	42	H (Lyman-α)	....	Combi *et al.* (2007)
Oct 29–30	2.46	2.75	8.2	H_2O (2.9 μm hot bands)	....	Salyk *et al.* (2007)
Nov 1	2.47	3.5–5.5	10.4–16.4	OH (0–0)[a]	14.5–120.2	Schleicher (2007)
Nov 16	2.53	7.8	23	H (Lyman-α)	....	Combi *et al.* (2007)
Dec 3–5	2.60	0.23	0.68	OH (0–0)[a]	30.2–125.9	Schleicher (e-mail comm.)
Jan 1	2.72	0.078	0.23	OH (0–0)[a]	56.2	Schleicher (e-mail comm.)

[a] The vectorial model used to derive the water production rate.

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The described process continued with the evacuation, by rapid outgassing, of the space occupied by the icy sheet reservoir. A cave-in of the crumbling pancake of refractory material was prevented by the outflowing water vapor, which, rather remarkably, could lift fragments of up to about 50 meters in diameter into the atmosphere! Since this happens to be just about the thickness of the pancake-shaped layer (Table 3), it is apparent that, at the time of its lift-off from the surface, the body may not as yet have been broken completely into fine dust; rather, the forming cloud of debris may have still included fairly large chunks of material. Their disintegration intensified via in-flight particle fragmentation, a process that begins at the surface but is known to occur almost spontaneously even outside the near-nucleus molecular-drag zone and to lead to complex heterogeneities in the dust coma (e.g., Tuzzolino *et al.* 2004; Clark *et al.* 2004). This evidence is behind the stipulation in Sec. 8.2 that the mass jettisoned from the nucleus' surface into the atmosphere be *exceptionally poorly cemented*. Indeed, the gas pressure of 5 pascals is nearly two orders of magnitude lower than the tensile strength derived for comets by Greenberg *et al.* (1995) and consistent with the results from investigations of split comets. The extraordinary propensity for crumbling suggests that close-up morphology of the cloud of dust expanding from comet 17P — including the boundaries — should be very rugged, unlike the smooth outlines seen on the scale afforded to the terrestrial observers.

Also in an effort to understand this extremely low material strength, one should recognize the consequences of the primordial nature of the pancake-shaped layers, as advocated by Belton *et al.* (2007). If the layers are indeed primordial, the transition from high-density to low-density amorphous ice must have taken place some time in the past, leading to the ice reservoir's expansion. If the ice reservoir penetrated into the base of refractory terrain, as it must have, the expansion necessarily involved the pancake-shaped layer as well, which, at least near its bottom, must have been disturbed and severely damaged, lacking structural coherence from then on. In fact, cracks and fissures may with time have spread further into the layer's interior, thus facilitating its eventual disintegration under trivial pressures.

To compare the production rate of water with the injection rate of dust is more difficult, because the relevant production and injection times are not at all well known. An approach I pursue here is in terms of the total amount of water and dust in the atmosphere. For dust, the total mass was estimated in Sec. 5 to be 10^{14} g; for water, a lower limit to its total mass is determined as the product of the lifetime of water molecules and their mass production rate. For any distance r from the sun, the lifetime of water molecules $\tau_{\rm water}(r)$ is the reciprocal of the total photo rate coefficient for destruction of H_2O. For the quiet-sun regime, which is applicable to 2007, Huebner *et al.* (1992) derived a theoretical value, consistent with a number of observations, of

$$\tau_{\rm water}(r) = 0.97r^2, \tag{21}$$

where r is in AU and $\tau_{\rm water}$ in days. Hence, at 2.44 AU, one finds $\tau_{\rm water}$ = 5.8 days. The amount of water in the atmosphere at the time of the peak production rate (Table 5) was thus 7 $\times$ 10^{35} molecules and their mass $\mathcal{M}_{\rm water} \simeq 2 \times 10^{13}$ g, which is a lower limit to the total mass of water molecules in the coma in the immediate aftermath of the megaburst. The resulting estimated dust-to-water mass-production rate ratio is therefore < 5. It is noted that the dust-expansion velocity, equated in Sec. 8.4 with the terminal velocity of the smallest particles (adopted in Sec. 5 to have dimensions near 0.1 micron), can be now calculated from an expression (Sekanina 1981) based on Probstein's (1968) theory to provide another test for the presented model of the megaburst. As the expansion velocity of the dust cloud is a function of the dust-to-gas mass production-rate ratio (which is lower than the dust-to-water mass production-rate ratio), the *lower* limit derived from information gathered in this paper is 0.42 km/s, a satisfactory result.

Two final points: (i) the mass of water molecules in the coma after the megaburst suggests that the energy generated by water-ice crystallization was at least 2×10^{22} erg, an estimate that is close to the kinetic energy of the expanding dust cloud (Sec. 8.4), so that water-to-dust momentum transfer directly contributed to the visually most spectacular attribute of the event; and (ii) comparison of the observed water-production rates in Table 5 shows rather convincingly that, in terms of water release, the activity of the megaburst source was lingering longer than when measured by the rise time (Table 2) of the comet's light curve. When Schleicher's water-production rates are compared with theoretical sublimation rates from a standard emission model, the November 1 and December 3-5 data points imply greatly excessive rates of outgassing (equivalent, respectively, to sublimation areas of 110 km^2 and 15 km^2), while the January 1 data point yields an area of 6 km^2, equal to the estimated base area of the pancake-shaped layer from Table 3. This peculiar trend suggests that, in the aftermath of the megaburst, the crystallization process may have continued for a limited period of time in a newly opened short-lived emission source. This conclusion parallels Whipple's (1984) finding concerning the comet's 1892-1893 outbursts, both of which he found to have been activating (or reactivating) discrete regions on the nucleus' surface.

9. Conclusions

Analysis of the light curve, the dust-halo expansion curve, and the images of hydrogen and hydroxyl comae of comet 17P/Holmes provide the bulk of information on the megaburst of 2007, including its onset and evolution, the total mass lost by the comet during the event, and the expansion velocity of the dust cloud. The description in terms of these parameters requires a number of qualifications. By virtue of its nature, the megaburst was not, strictly speaking, a single event but consisted of a sequence of episodes that occurred simultaneously or in rapid succession. Secondary, tertiary, *etc.*, outbursts were hard to resolve because of scatter in both the light curve and the halo-expansion curve. Similarly, the water-production rates derived from observations of H or OH, the water's dissociation products, refer to times that include effects of the water molecules' long destruction lifetimes and are therefore shifted to later dates. Comparison of the brightness with the water-production data suggests that the megaburst's duration was shorter when measured by the injection of dust into the coma than by the lingering outgassing. This is one of the important aspects of the event that remains to be verified.

The megaburst began very much like any outburst, with a precipitous rise of brightness and the appearance of a sharp, stellar nuclear condensation, rapidly expanding into a planet-like disk. However, the light curve's 14-mag amplitude and subsequent plateau persisting in a coma of ever growing dimensions, more than 5 times the sun's size in early January 2008, were unique. There appears to be a problem with the dimensions and magnitudes of the comet that imply its unrealistically low surface brightness. Assuming for high-quality observing conditions a night-sky brightness of visual magnitude 21.0-21.5 per arcsec^2, an area of the sky of about 80 arcmin in diameter, indicated by observations from dark sites for the apparent diameter of 17P in early January, has a total visual magnitude of 2.86 to 3.36. From the reports to the *International Comet Quarterly* of 17 magnitude observations made with naked eye or a very small instrument during January 1-6 that showed the comet to be greater than 70 arcmin in diameter (an average of 80.2 ± 3.8 arcmin), the average magnitude was 3.6 ± 0.3, fainter than the night sky. Unless the reported magnitudes were corrected for the night-sky brightness, it appears that the comet's total brightness was underestimated by at least 0.5 mag and possibly by as much as 1 mag.

Comparison of an assortment of well-documented outbursts with the 2007 megaburst of 17P shows that this event is unrivaled as the most powerful event of this kind on record. I see no need for developing a radically new mechanism in order to explain the enormous magnitude of the explosion, even though I do consider the proposed scenario as tentative because support from detailed heat-diffusion calculations is still missing. Yet, I subscribe to the conceptual hypothesis of a thick, pancake-shaped layer of terrain, like the widespread areas on the nucleus of comet 9P/Tempel seen in the *Deep Impact* spacecraft images, being jettisoned into the atmosphere of comet 17P. Driven by an exothermic reaction caused by the transition of water ice from low-density amorphous phase to cubic phase in an underlying sheet reservoir, the jettisoned pancake of refractory material gave birth to a major fragment, which under more typical circumstances would end up slowly receding from the principal nucleus with a separation velocity of about 1 m/s and a differential nongravitational deceleration on the order of 10^{-5} the sun's gravitational acceleration. An important distinction in the case of comet 17P was that, rather than falling apart gradually, over hundreds of days or longer, this fragment failed to survive its separation from the nucleus and began to crumble precipitously into a cloud of dust immediately upon the lift-off from the surface. It is this behavior that distinguishes 17P from other split comets, a number of Jupiter-family members among them. The hypothesis — fitting all known constraints provided by the observations available at this time — implies that, for a given size of the pancake-shaped layer, the amplitude and peak brightness of the outburst should vary inversely with the residual size of the largest fragment: the smaller its dimensions, the greater amount of microscopic debris and the brighter the outburst. Comet 17P is an extreme case: no sizable fragment but a huge megaburst.

For the nucleus of comet 17P, the megaburst was a nearly global event, affecting a significant fraction of its surface. The expanding cloud of dust had a broad vectorial distribution of velocities, the particles moving away from the nucleus in a wide cone of directions. When viewed from great distance, the flow of debris was lacking the morphology that is associated with collimated ejections of dust from small isolated sources of emission on the nucleus. On smaller scales, however, the motions of particles must have been locally non-uniform, reflecting the stochastic nature of the progressing fragmentation process. The event's unprecedented magnitude challenged observers to make a variety of observations, many of which have not as yet been published. They will eventually constrain this and other models more tightly than they are at this time. The morphological evolution of the coma is an example of the event's features that I left unaddressed.

As of now (mid-January 2008), there is no sign of a second major outburst, so it appears ever more likely that the history will not be repeated and the pair of outbursts from 1892-1893 will remain unmatched. On the other hand, it was shown in this paper that, in terms of the total mass of dust injected into the atmosphere, the 2007 megaburst was more powerful than the two 1892-1893 outbursts combined. Yet, the remarkable similarity of appearance of comet 17P during the explosive events in 1892-1893 and 2007 strongly suggests that the same mechanism and the same nuclear properties were involved. The lower peak intrinsic brightness implies smaller pancake-shaped fragments in 1892-1893. The lower expansion velocities (Table 2, Figure 3) suggest that the events of 1892-1893 were also less energetic. The pairing of the outbursts is equally inconsequential, as it merely indicates that either the fragment broke up into two while still on the surface, and only a part of it was crumbled and jettisoned immediately, or else that there were two separate fragments with nearly the same thermal history.

It is estimated that comet 17P lost more than 1.5×10^{14} g, or > 2 percent of its mass, in the megaburst and its aftermath. Thus, fewer than 50 events of this magnitude would consume the entire comet. I propose that "peeling off" and jettisoning of pancake-shaped layers of nucleus' terrain, one by is an efficient — perhaps the most efficient — fragmentation process that eventually leads to the comet's demise. The nucleus will disintegrate completely if it is layered throughout its interior, or it will turn into an essentially inert asteroidal object if a nontrivial compact core survives after all layers have been discarded.

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Photometry of Deep-Sky Objects

For explanation of the tabulated data below, see the explanation in the tabulated data on comets in the section following this section. The previous batch of photometry of *ICQ*-recommended deep-sky objects appeared in the Oct. 2007 issue, pp. 130-131. While M31 is not in the *ICQ* list of recommended deep-sky objects (see *ICQ* **20**, 98; **16**, 129; and **26**, 3), data are presented below, including some new determinations of its total magnitude, because of the relevant discussion of the brightness of comet 17P during its in 1892-1893 (see Sekanina's preceding article in this issue). We encourage other regular comet photometrists to contribute both visual and CCD magnitudes of the recommended deep-sky objects.

See also the *ICQ* website: `http://www.cfa.harvard.edu/icq/icqproject.html`.

John Bortle's observation of M31 below was published in 1984 in *Deep Sky* **2**(4), 31; no date was provided, and no reference-star catalogue was provided, though he stated that he used photoelectric-V comparison-star magnitudes.

Descriptive Information, to complement the Tabulated Data (all times UT):

◇ *NGC 224 = M31* ⟹ 2008 Feb. 16.45: unfiltered photometry in bright moonlight, using a rectangular aperture of 3°.06 × 0°.96; `StellaNavigator` ver. 8.1 software used for comp.-star magnitudes; comp. stars have $B-V = +0.51$, $+0.76$, and $+0.82$ [NAG08]. Feb. 28: obs. from elev. 5500 ft; very clear and dark; seven comp. stars used; ranging in mag from 2.1 to 4.6; the bright inner core seen under full moonlight — evidently a week earlier — has total visual mag 4.5; comp. stars β, δ, 51, μ, π, ν, and θ And [OME].

◇ ◇ ◇

Visual Data

NGC 224 = M31

DATE (UT)	N	MM	MAG.	RF	AP.	T	F/	PWR	COMA	DC	TAIL	PA	OBS.
2008 02 28		S	3.4	HV	5.0	N		1					OME
2008 02 28		M	3.9	HV	5.0	N		1					OME
pre-1985		B	4.4		0.0	E		1					BOR

NGC 6712

DATE (UT)	N	MM	MAG.	RF	AP.	T	F/	PWR	COMA	DC	TAIL	PA	OBS.
2007 11 03.79		S	8.7	TI	32	L	5	76	3	2/			MAR02

NGC 6760

DATE (UT)	N	MM	MAG.	RF	AP.	T	F/	PWR	COMA	DC	TAIL	PA	OBS.
2007 11 03.80		S	9.1	TI	32	L	5	76	2	2			MAR02

NGC 6934

DATE (UT)	N	MM	MAG.	RF	AP.	T	F/	PWR	COMA	DC	TAIL	PA	OBS.
2007 11 03.83		M	9.6	TI	32	L	5	76	1.5	4			MAR02

NGC 7078

DATE (UT)	N	MM	MAG.	RF	AP.	T	F/	PWR	COMA	DC	TAIL	PA	OBS.
2007 11 03.84		M	6.8	S	32	L	5	76	4	6			MAR02

◇ ◇ ◇

CCD Data

NGC 224 = M31

DATE (UT)	n	M	MAG.	RF	AP.	T	f/	EXP.	COMA	DC	TAIL	PA	APERTUR	Chp	Sfw	C	P	Cam	OBS.
2008 02 16.45	x	C	3.5	TJ	2.5	A	6	a 30	138				S 3.1 d	K16	SI5	5		MCV	NAG08