THE STUDY OF THE PHYSICS OF COMETARY NUCLEI

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PERIODIC COMET HOLMES

Whipple's paper "Comet P/Holmes, 1892III - A Case of Duplicity?" (see Appendix I) has been edited for publication as CFA Preprint No. 1995 and has been sent to Icarus for formal publication. As reported previously the paper presents strong circumstantial evidence that the two huge outbursts in 1892-93 were the consequence of a grazing encounter with a satellite comet, followed 73 days later by a final, nearly central, impact of the satellite on the major nucleus. This research requires further study to estimate the gravitational stability of the required orbit against separation by solar perturbations. The restricted three-body theory of celestial mechanics cannot yet deal adequately with marginal cases of instability as represented by the suggested binary orbit of P/Holmes. Numerical integration of various orbital configuration is needed to indicate the length of time that a 73-day-period satellite could remain in orbit about the major nucleus in a situation that is eventually unstable. Planning for such numerical simulations is underway, as a final check on the question of duplicity for P/Holmes.

ICES IN THE SOLAR SYSTEM

By invitation Whipple attended an international Advanced Research Workshop on "Ices in the Solar System" at Nice, France, on January 16-20, 1984, sponsored by N.A.T.O. and arranged by Drs. Jurgen Klinger and Daniel Benest. Whipple presented an invited paper entitled "Present Status of the Icy Conglomerate Model". This paper is now in press as CFA Preprint No. 1966 (see Appendix II) and as a contribution in the book to be printed summarizing the conference presentations.
The conference brought together for the first time diverse groups of scientists whose researches involve ices as applied to bodies in the Solar System, excepting largely terrestrial ice meteorology and glaciology except as it is representation of phenomena observed in planets, satellites, comets and rings in the Solar System. Cometary observations and problems were of major interest to the conferees involving a third of the papers presented. These papers and the discussion strengthened the suspected relation between ices in cometary nuclei and their origin as interstellar condensation or equivalents. A major and highly important conclusion at the conference was that much of the ice in comets, or perhaps all of it, has never been heated appreciably from the very low temperatures characteristic of interstellar space. In other words, comets did not condense and aggregate from gases that were heated by the collapse of the primitive solar nebula and then later cooled. Amorphous ices and highly complex hydrocarbon ices appear to constitute a significant fraction of primitive cometary ices, perhaps directly aggregated from instellar dust. Water ice, of course, constitutes the major fraction of cometary ice, but its primitive state may be appreciably amorphous, with considerable cometary activity resulting from the energy release and physical changes induced by the change from amorphous to ordinary ice, caused by solar heating to rather low temperatures.

Whipple found the "Ices" workshop to be perhaps the most productive conference scientifically that he recalls.

**COMET P/KOPFF**

As a member of the Comet Rendezvous Science Working group sponsored by NASA, Whipple presented a discussion of cometary
nuclei at the meeting held at the Jet Propulsion Laboratory on January 11-13, 1984.

Because the Group concluded that Comet P/Kopff is the most desirable target for rendezvous in the middle 1990's, Whipple made a special effort to determine its rotation period and spin axis by the halo method. He could not determine a specific spin period but the copious data indicate a slow rate of spin measured in days. The asymmetrical coma suggested roughly the polar axis of spin, direct spin in 1932 but retrograde spin in 1945 and 1983, consistent with D.K. Yeoman's determinations of an increasing period of nongravitational motion from 1906 to 1946 and a decreasing period from 1945 to 1977. This study is favorable to P/Kopff as mission target because it indicated that the nucleus of P/Kopff contains many active areas and therefore is "young" enough to show the major phenomena of active comets. Measurement of its polar-axis precession and its shape should be most illuminating scientifically. Whipple believes that a definitive study of the observational literature, possibly coupled with new observations at the comet's intermediate return, should provide a clearcut period and the spin axis variation well before the anticipated rendezvous.

COMPLEX

Whipple is a member of the Committee on Planetary and Lunar Exploration (COMPLEX) for the U.S. National Academy's Space Science Board. He served on the Committee at meetings in Sante Fe, New Mexico in July and at the Jet Propulsion Laboratory in December, 1983.

OTHER ACTIVITIES

Whipple acts as a consultant to the Imaging team of the European Space Agency Giotto mission to Halley's comet and as a member of the steering group of the International Halley Watch sponsored by N.A.S.A.
COMET P/HOLMES, 1892 III – A CASE OF DUPLICITY?

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21 pages
4 figures
4 tables
Running head:

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ABSTRACT

The observations of comet P/Holmes 1892III, exhibiting two 8–10 magnitude bursts, have been carefully analyzed. The phenomena are consistent with the grazing encounter of a small satellite with the nucleus on November 4.6, 1892 and the final encounter on January 16.3, 1893. The grazing encounter produced, besides the first great burst, an active area on the nucleus, which was rotating retrograde with a period of 16.3 hr and inclination nearly 180°. After the final encounter, the spin period was essentially unchanged, but two areas became active, separated some 164° in longitude on the nucleus. After the first burst the total magnitude fell less than two magnitudes from November 7 to November 30 (barely naked eye) while the nuclear region remained diffuse or complex, rarely if ever showing a stellar appearance. The fading was much more rapid after the second burst (barely naked eye at maximum) while the nucleus frequently appeared stellar after the first day. It seems reasonable to conclude that the grazing encounter distributed a volume of large chunks in the neighborhood of the nucleus, maintaining activity for weeks. The final encounter activated a new area on the nucleus, the shock and fall back disturbing the area already exposed by the grazing encounter. Several details of this scenario are fitted rather well.
Comet P/Holmes, 1892III —
A Case of Duplicity?

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INTRODUCTION

This first appearance of this short period comet (P = 7.1 y, q = 2.1 AU) was extraordinary, perhaps unique. Certainly a huge burst that occurred near November 5, 1892, made the discovery possibly on November 8. Holmes (1893) reports that the comet had not been visible in the same region less than two weeks before his discovery. Barnard's (1913) description on November 9.2 at Lick Observatory is revealing: "Its appearance was absolutely different from any comet I have ever seen — a perfectly circular and clean cut disk of dense light, almost planetary in outline with a faint, hazy nucleus and a slight condensation some 5 seconds south following the nucleus (brightness = Andromeda Nebula, diameter 260" at 8°0'm P.S.T. and 286" at 9°40'm)." He observed the comet to brighten perceptibly by the next night at which time he saw an outer faint diffused envelope some 12" (800,000 km) in diameter.

Barnard's description carries great weight because he was a superb and experienced observer, having already discovered 15 comets and observed many more. His comments were generally confirmed by many other observers over the world. Interest in the comet flared as the comet burst again to nearly
naked eye brilliance on January 16, 1893, after having faded some 5–6 magnitudes by late December and early January. On subsequent returns P/Holmes has remained extremely faint and inactive. Its maximum absolute brightness by the $\Delta^{-2} r^{-4}$ law was $H_{10} = 0.0$ in 1892; $9.5$ in 1899; and $9.8$ in 1906 (Vsekhvyatskii, 1964). It was lost for 7 apparitions, again to be observed as 1964X, 1972 I and 1979 IV. Kresák (1973) lists $H_{10} = 13.5$ for the 1972 apparition. Thus the comet seems to have flared by some 9–10 magnitudes or 5,000–10,000 times in brightness in 1892 unless the outburst itself reduced its basic activity level. Even had it been somewhat brighter intrinsically the chances for its prior discovery were still small in earlier passages at $q \sim 2.2$ AU.

The second outburst on January 16, 1892, involved a bright stellar image that expanded and faded rapidly, typical of lesser bursts in other comets.

The light curve of P/Holmes in 1892–3 has been derived in Fig. 1 and 2 with data from many observers without corrections except for reduction to

$$H_{10} = \text{Magnitude (Obs.)} - 5 \log (\Delta r^2)$$  \hspace{1cm} (1)

The two bursts have been synchronized at November 5 and January 16 to make an easy comparison between them. The total magnitude estimates are plotted in Fig. 1 and those of the nucleus in Fig. 2.

The photometric observations made by Wendell (1899) with a 60 arcsec aperture are included only for January 19 and 21, 1893. On other dates his
observations fall in the never-never land between total and nuclear magnitudes. Barnard's very careful observations during the first burst are identified in Fig. 1 as probably representing the most reliable measures. The deduced values by Vsekhsvyatskii (1964) and his quoted values from Holetschek (deleting a February value) are also identified.

In Fig. 1 it is clear that the first outburst peaked more than a magnitude brighter than the second. The first burst was also much more prolonged. On November 30.2, Updegraff at Columbia, Mo. (1892) saw the comet as barely naked eye, equivalent to H = +1, indicating a brightness loss of not much more than 1 magnitude in 3 weeks. A comparable loss occurred in less than a week for the second burst. The comet must have faded extremely rapidly in early December, caused largely by the final fading of the huge outer shell, which had grown to a diameter of ~3,300,000 km, observed by Renz at Pulkova (1893) on November 23.7. During the second burst the largest coma diameter was ~1,250,000 km observed by Wilson (1893) at the Goodsell Observatory on February 17.0.

The major difference in the nuclei between the two bursts is evident in Fig. 2. The nucleus was rarely compact or even seen in the first event while a stellar nucleus was frequently seen during the second. The significance is self evident, viz. the light of the first burst came primarily from material dispersed to great distances from the nucleus whereas the light and the activity in the second burst centered close to the physical nucleus, the latter corresponding more to an average cometary burst.
Spectra in the blue and visible by several observers at both bursts showed only a continuum, with possibly a trace of the green band near 5170 Å seen by Campbell (1893), Keeler (1893), and at South Kensington (1893). Kammermann (1893), Konkoly (1893) and Vogel (1893) saw only continuum. It seems likely that in both cases the comet detritus was highly dusty and that the particles from the first burst were larger than those from the second. This theory is supported by numerous observations that in the second burst the nucleus and inner coma were yellowish or reddish and the outer coma tail bluish. Color was rarely noted during the first. The coma turned white near January 20.0 according to Lovett (1893), confirmed by Weiss (1893) on January 20.8. Tail development was minimal during both bursts but more noticeable in the second.

THE NOVEMBER 1893 BURST, PHYSICAL ANALYSIS

Orlov (1940), from Barnard's measures of coma diameters, sets the first burst of P/Holmes at 1892, November 5.5 UT, this date being here corrected by +8h because he used Greenwich rather than Pacific time for Barnard's observations. He plots two explosions concurrently, one at an expansion velocity of 0.95 km s⁻¹ and the other at 0.42 km s⁻¹. The latter corresponds to \( v = 0.65 r^{-0.5} \) km s⁻¹ following the Delsemme (1982) formulation of fine dust expansion carried by water vapor as

\[ v = 0.580 r^{-0.5} \text{ km s}^{-1} \]  

(2)

Although the comet's solar distance of 2.39 AU at the time is near the limit of \( H_2O \) activity by solar radiation, the nature of the burst on a presumably old comet suggests strongly that \( H_2O \) could be the prime mover. On this
assumption then, Table I is compiled from coma diameter measures made before November 2, and those of the inner coma made later. The observers in Tables I, II and IV are identified in a footnote to Table I along with their locations.

A stellar nucleus first appeared some two weeks after the outburst, observed by Wagner (1893). The search for a spin period of the nucleus follows the author's (1982) procedure except that Eq. (2) is used for the expansion velocity instead of $0.535 \, r^{-0.6} \, \text{km s}^{-1}$. Each observed date (Col. 2 in Table I) is corrected by $\Delta t$ (Col. 5) calculated by dividing the measured coma diameter (Col. 3) by double the expansion velocity of Eq. (2) in arcsec per day (Col. 4) to derive the Zero Date (ZD, Col. 7). The assumption is made that the ZD represents the time at which an active area on the rotation nucleus is oriented so as to initiate a minor burst. The time spacings of the ZD's are searched to determine the spin period of the nucleus.

For the interval from November 19 to December 15, an excellent solution for the period, $P$, is $16^{h}26^{m}0$. The standard deviation, $\sigma$, in time for a single observation (Col. 8) is $\pm 0.076$ or $\sim 4$ arcsec, and $P/\sigma = 9.0$. Extrapolation of the spin to near the time of the major burst gives ZD = November 4.87. The three measures (12-inch refractor) by Barnard and the one by Hahn (1893) give a mean result consistent with others of ZD = November 4.63, about a quarter of a day earlier than that derived from the spin period.

Completely at variance with this determination of the major burst on November 4.63 are Holmes' discovery coma diameter of 5', and that by
Barnard of 12' on November 10 (36-inch refractor). If the burst actually occurred on November 4.63, the radial expansion velocities determined by these coma diameters become 0.74 and 0.77 km s\(^{-1}\), respectively, consistent with Orlov's conclusion but much larger than is typical for comets at \(r = 2.3\) AU from the Sun. There is no reason to expect a large error in Holmes' first observation nor Barnard's "very diffused faint envelope 12' ± in diameter surrounding the comet." Remnants of this faint outer envelope probably remained to be observed by Renz (1893) on November 23.7, as a nearly circular faint disk of 30' diameter. Near this date other observers were measuring the diameter in the range 14' to 20', consistent with the major expansion velocity of Eq. (2). Even on January 14, Lovett (1893) observed an outer diameter of \(\sim 25'\), or \(2.5 \times 10^6\) km, testifying to the persistence of the debris ejected 70 days previously.

The outer envelope, however, remains a mystery. The consistency of the expansion velocities from Holmes' and Barnard's observations tends to preclude acceptance of an earlier burst, for which there is no independent evidence. The expansion velocity is too high for typical dust carried by C, N, O radicals and too low for H or \(\text{H}_2\). Actually the velocity is near that of the terminal velocity of \(\text{H}_2\text{O}\) atoms at 200 K (Delsemme, 1982), 0.860 km s\(^{-1}\). Could some of the finer dust have been carried to a velocity so near that of the molecules?

**THE JANUARY 1893 BURST, PHYSICAL ANALYSIS**

On January 15.08 Hough (1893), at the Dearborn Observatory, saw the comet as a "weak nebula." On January 16.7 Palisa (1893) at Wien was surprised
to find it had brightened to a "yellow fixed star" of diameter 20", confirmed by many observers, next by Kobold (1893) at Strassburg on January 16.87 as of 8.4 magnitude and diameter 41". On January 17.24 Barnard (1913) at Lick Observatory actually watched a starlike nucleus develop while the comet brightened. Table II contains all the diameter measurements through January 1893. Wilson (1893) last saw the comet on April 4.1, but the diameter measures after January were too large (~3'-5') and too uncertain for spin determinations. Table II retains the format of Table I, except that two active areas, IIA and IIB, could be identified (Col. 7 with residuals in Col. 8).

Solutions for the periods and phases of the two active areas, IIA and B, are shown in Table III along with those for the November burst, I. The justification for the admission of two active areas can be seen in Fig. 3, which shows the phase distribution of the January observations with respect to IIA. A second peak centered at phase 0.45 (on January 22) follows IIA by 165° on the nucleus, clearly present in the figure. Table III also lists solutions for the early series combined with the IIA series (I + IIA) and the IIB series, (I + IIB).

A major question concerns the time of the actual outburst. Eight diameter measures clearly fix an active area burst on January 16.31 within 0.03 of the IIA solution. Six early observations given in Table IV, however, are discordant on the basis of the expansion velocity of Eq. (2) used for the determination of ZD's. Orlov (1940) concluded that the burst occurred on January 17.40 UT with two expansion velocities of 2.06 and 0.38 km s$^{-1}$.
The six deviant measures in Table IV tend to support, in principle, Orlov's conclusion. Of special interest are Barnard's diameter measures. Two, made with the 12-inch refractor, on January 17.177 and 17.243, of 29'.'4 and 32'.'4 with ZD, respectively, of January 16.35 and 16.33, are listed in the main part of Table II, consistent with the initial IIA burst of January 16.31. His three measures with the 36-inch refractor made less than an hour later on January 17.271, 17.280 and 17.301 are 44'.'0, 47'.'2 and 46'.'7, respectively. If the Eq. (2) velocity is correct, these 36-inch observations indicate a burst 0.3 earlier than the 12-inch observations or else they represent an outer nebulosity similar in character to the one observed in November. If so, and if the major burst occurred on January 16.31, the six deviant observations in Table IV lead, respectively, to expansion velocities of 0.73, 0.83, 0.46, 0.46, 0.47 and 0.53 km s\(^{-1}\). Note that they show a tendency to decrease with time, the mean being 0.58 km s\(^{-1}\). At \(r = 2.64\) AU, Eq. (2) gives an expansion velocity of only 0.36 km s\(^{-1}\). The evidence thus supports, in principle at least, Orlov's conclusion of an anomalous high-velocity expansion accompanying both bursts. The weaker anomalous burst in January then dissipated more rapidly, in less than 1 week instead of 3 weeks for the November burst.

Active area I seemed to have persisted through the January burst. Note in Table III that the continuance of active area I as in IIB gives a better solution than if it were IIA. Since IIA is by far the stronger candidate for the primary January burst because it agrees within 0.03, we seem to be justified in drawing the conclusion that active area I was reactivated by the violence of the IIA burst, possibly with a small shift (of \(\sim 0.08\) or \(\sim 40^\circ\) in longitude) in its position on the nucleus.
None of the evidence of Table III suggests a measurable change in spin period induced by the January burst. All the derived periods lie remarkably well within the reasonably expected error range of their determinations.

INTERLUDE

A photograph of the Andromeda Nebula area by Schooling (1892) on 1892 October 18.865 showed a nebulous object that he first thought was a prediscoveory image of P/Holmes. Kreutz (1893), however, showed that the position deviated from the ephemeris by $\Delta \alpha = -2^m32^s3$ and $\Delta \delta = +19'49"$. The position angle from the ephemeris position was $124^\circ$, close to position angles of the tail of P/Holmes observed later. It seemed possible to me that the image was indeed some relic of a still earlier burst of the comet.

Barnard (1913) photographed P/Holmes on November 11.16 and noted an irregular nebulous mass some 48' southeast from the center of the comet and 39' in diameter. The detached image appeared to be connected with P/Holmes. Again the position angle was displaced more or less in the antisolar direction from the comet. A.R. Klemola, at my request, very kindly found the original plate, sent me prints and measured the positions of two features. His accompanying letter concerning the reality of the image warned "with strong reservations on my part."

Considerable effort was expanded in attempting to link these questionable observations with P/Holmes. A computing program was coded to reduce the
observations to the plane of the comet orbit so that the two positions would
determine an orbit. A number of trials were made with various nongravitational
(NG) forces radially from the Sun and various starting points and times of
P/Holmes itself. I could find no date of separation coupled with any value of
NG force that would fit either observation if it lay in the orbit plane.
Conclusion: neither observation represents an earlier breakup or burst of
P/Holmes. This conclusion is supported by the fact that no comet was reported
during the previous months in the relevant part of the sky in the general direc-
tion of the Andromeda nebula, favorably placed for observation.

WAS P/HOLMES ORIGINALLY DOUBLE?

Corrigan of St. Paul, Minnesota (1893) early explained the first burst
as a collision of asteroids. The second burst extinguished his idea because of
the minute probability that two such collisions for the same body could be
spaced by only 73 days. I have shown (Whipple, 1983) that a comet with a small
satellite might produce exactly this type of double burst. Differential NG
forces between the primary and secondary nuclei could increase their mutual
orbital eccentricity with no secular change to be expected theoretically in their
orbital semimajor axis. The first encounter would be grazing as the pericomet
distance slowly decreased. If the satellite nucleus survived the grazing
encounter it might well be expected to exhibit a markedly increased NG
force that would produce a nearly central collision at the next pericomet
passage. A third encounter and burst would be highly unlikely.
Let us now study the geometrical circumstances of the P/Holmes' bursts to see whether they are consistent with the encounter scenario. In the previous section we have seen that the evidence for an earlier burst appears not to be valid. Thus further study is justified.

The direction of the spin axis of the primary nucleus and the direction of the relative orbital motion are essential factors in the problem. The circumstances are favorable for an encounter when the orbital plane of the system lies fairly close to the heliocentric orbit and the major axis lies roughly perpendicular to the solar direction. Fig. 4a depicts the situation for a prograde system motion in which the NG acceleration for the satellite exceeds that for the major nucleus. The mirror image about the solar direction applies for a retrograde system. Under the circumstances of Fig. 4a, the differential NG perturbations confine the semimajor axis to an orientation generally perpendicular to the Sun while the eccentricity increases and the pericomet distance decreases.

The rotation axis of the primary nucleus is not well determined from the asymmetries in the coma, but all such asymmetries observed tend to be in position angles within a few degrees of the antisolar direction. The geometry, with the comet generally in opposition to the Sun and the Earth lying south of the orbit lead to the conclusion that the rotation is retrograde, with the spin pole not greatly distant from the orbital polar direction. A typical spin period of 16 hours suggests that the lag angle is appreciable, perhaps the order of 20° -40° at a solar distance exceeding 2 AU. Thus the lack of strong asymmetries in the coma with respect to the antisolar direction is not surprising.
We have seen that the first burst of P/Holmes probably occurred near November 4.63, in a possible range from November 4.38 to 4.76. Active area I extrapolates back to November 4.87. We should expect the active area to represent the region on the nucleus disturbed by the assumed encounter. The encounter appears then to have occurred \( \sim 0.24 \) or \( \sim 126^\circ \) in longitude before the active area reached \( \sim 36^\circ \) longitude on the nucleus after the Meridian passage. This assumes that the encounter took place near daybreak at grazing incidence. The uncertainty in the actual time of the first burst leaves ample room for an uncertainty of several degrees in longitude for the location of the consequent active area.

Reference to Fig. 4a shows that the satellite should have been in a prograde orbit about the primary nucleus to fit this geometry.

With this requirement in mind let us look to the circumstances of the second burst. Active area II\( \text{B} \) appears to be only slightly displaced from active area I, as indicated by the superiority of the I and II\( \text{B} \) solution over that of I and IIA in Table III. If the second burst (IIA) occurred on January 16.31 and active area II\( \text{B} \) brightened on January 16.565, the interval between them was \( \sim 0.25 \) or \( \sim 134^\circ \) in longitude. Because the phase of active area IIA and the second burst appear nearly to coincide, the encounter could have taken place in the afternoon on the nucleus not far from subsequent minor bursts on successive rotations with a reasonable lag angle. The violence of the encounter could well have shaken up the area of the first encounter, probably a conspicuous crater by that time. Also we may justly assume that most of the cometary surface was inactive, covered with a thick meteoroidal mantle. The larger pieces ejected
by the second impact could have disturbed the thin mantle over the original impact, active area I, and this reactivated it as active area IIIB. This scenario is consistent within the accuracy of the various determinations involved as sketched in Fig. 4a, b.

If the period of the system was 73\,d as measured by the separation of the two bursts, the semimajor axis, a, of the orbit was $65.4 \rho^{1/3} R_c$ where $\rho$ is the density of the major nucleus and $R_c$ its spherical radius, the secondary nucleus being assumed relatively small. For $\rho = 1.3 \text{ g cm}^{-3}$ $a$ becomes 71.7 $R_c$. The degree of stability of such an orbit against differential solar perturbations requires further inquiry.

Any precedents for the assumption of double comets remain vague. Van Flandern's (1981) suggestion that they are the source of split comets cannot be supported for several cases in which the splitting is accompanied by outbursts (see Sekanina, 1982). Separation by solar perturbations would be completely nonviolent. Whipple (1977) concluded that the statistical evidence for comet (orbital) groups was unfounded but that there seemed to be an excess of comet pairs beyond expectation. Kresak (1982) found no statistical evidence for either groups or pairs. On the other hand, multiplicity is frequent for both stellar and planetary bodies. The reality of double or multiple comets must rest purely on phenomenological grounds until direct or radar observations of the nuclei answer the question.
DISCUSSIONS AND CONCLUSIONS

The evidence that the two great outbursts of P/Holmes in 1892 were the result of a satellite nucleus first striking the primary nucleus in grazing incidence and finally colliding with it 73 days later is summarized as follows:

1) The magnitudes of the two outbursts are unrivaled except for P/Schwassman-Wachmann 1 with repetitive outbursts and by P/Tuttle-Giacobini-Kresák in 1973. Hence the phenomena are extremely rare.

2) The faintness and fading of the comet on subsequent returns and the lack of other observed bursts suggest a "dying" comet for which the 1892 outbursts were unique.

3) The first burst on November 5, 1892, was unique insofar as general appearance and persistance are concerned while the second on January 16, 1893, was extremely unusual. The loosening of a relatively large amount of ice and dust in a grazing impact and a lesser release at the final impact of a much reduced satellite is consistent with the double-comet hypothesis.

4) The scenario of grazing incidence followed by a final impact is theoretically plausible, although the period between is somewhat long for a double-comet orbit to have been stable for many previous perihelion passages of an "old" comet. Further study is planned to determine the degree of stability of such an orbit against solar tidal separation.

5) The active areas are remarkably well defined. Values of $\frac{P}{\sigma_1}$ ~9 as listed in Table III are near the top limit of similar determinations for other comets with well defined spin periods (Whipple, 1983). This indicates that activity on the nucleus was almost entirely confined to two discrete regions,
a single one after the first burst, reactivated by the second burst and a second active area contributed by the second burst. For a basically inactive comet two impacts by a satellite could be expected to produce just such a result.

6) The phase relationships among the postulated impacts and active areas are surprisingly consistent with the double impact scenario, requiring only that the sense of rotation of the primary and that of the pair's orbital motion be opposed.

7) The apparent and probable occurrence in both outbursts of an expanding outer shell or disk at velocities more rapid than the normal expansion rate seems to be unique. It suggests one or both of two possible physical processes that might be the result of impact, a) release of intrinsic explosive activity of exotic ices by a compressive temperature rise or b) the crushing effect that releases a considerable quantity of unusually fine dust to be carried away near the velocity of H₂O gas.

The above arguments supporting the double impact hypothesis are clearly circumstantial. Nevertheless P/Holmes presents such an unusual case that the circumstances should be kept in mind by observers of cometary phenomena, by theorists, and by laboratory experimentors involved with simulations of cometary or interstellar ice formation. The occurrence of double comets, if such exist, might be proven by radar, by space missions to comets or by novel observing techniques.
ACKNOWLEDGMENTS

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REFERENCES

Holmes, E. (1893).


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The identities of the observers and their locations are listed below for Tables 1, 2 and 4.

b Used for determining date of the burst.
Table II

Diameters P/Holmes January 1893

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<th>ZD d</th>
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E.B. | E.E. Barnard, Mt. Hamilton
---|---
TWB | T.W. Backhouse, Sunderland
JBC | J.B. Coit, Washington
FD | Fr. Deichmuller, Bonn
BvE | B. von Engelhardt, Dresden
AF | A. Freeman, Sittingbourne
EH | E. Holmes, London
FH | F. Hayn, Leipzig
GWB | G.W. Hough, Evanston, IL
FC | F. Cohn, Königsberg
HK | H. Kobold, Strassburg
EL | E. Lamp, Kiel
EOL | E.O. Lovett, Minneapolis
JM | H. Jacoby and J.T. Monell, NY City
FM | F. Millosevich, Rome
KO | K. Oertel, München
CFP | C.F. Pechule, Copenhagen
FP | F. Palisa, Wien
JGP | J.G. Porter, Cincinnati
FRe | F. Renz, Pulkova
FRi | F. Ristenpart, Karlsruhe
RS | R. Schorr, Hamburg
SS | W. Schur and M. Slichtenoth, Göttingen
NOTES TO TABLE II (Cont.)

JFS F. Fr. Schröter, Kristiana
CW C. Wagner, Kremsmünster
EW E. Weiss, Wien
OCW O. Wendell, Cambridge, MA
HCW H. C. Wilson, Minneapolis
Table III
Phases and Periods of Active Areas

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<th>IIB</th>
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FIGURE CAPTIONS

Fig. 1. Total magnitude ($H_{10}$) of P/Holmes.

Fig. 2. Magnitudes ($H_{10}$) of nucleus, P/Holmes.

Fig. 3. Phase vs. active area IIA.

Fig. 4. Suggested configuration of comet nucleus and satellites: a) at first outburst, b) at second outburst.
TOTAL MAGNITUDE ($H_{10}$) OF P/HOLMES
MAGNITUDES ($H_{10}$) OF NUCLEUS, P/HOLMES
PRESENT STATUS OF THE ICY CONGLOMERATE MODEL

Fred L. Whipple
Harvard-Smithsonian Center for Astrophysics

Invited paper

Presented at
NATO Advanced Research Workshop on Ices in the Solar System
Nice, France
January 16–19, 1984

Center for Astrophysics
60 Garden St.
Cambridge, Massachusetts 02138
PRESENT STATUS OF THE Icy CONGLOMERATE MODEL

Fred L. Whipple
Smithsonian Astrophysical Observatory

ABSTRACT

A brief history is presented of the concept that the nucleus of a comet is a discreet body, an icy conglomerate of solar-type materials that would be solid at low temperatures, \(<100\, \text{K}\). A summary describes briefly the observational success of the comet model, both quantitatively and qualitatively. The surprising aspect of the model is its usefulness in spite of its vagueness with regard not only to chemical composition but also to the physical structure of the nucleus, including such basic quantities as dimensions, density and albedo. Some emphasis will be placed on our increasing understanding of the morphology of comet nuclei.

Major attention will be centered on the interplay among the observations, the theory and the laboratory experiments, particularly with regard to the nature of the ices related to comet activity. The interest and progress in this field during the past decade has been most encouraging.
The icy conglomerate model (ICM) of a cometary nucleus (Whipple 1950, 1951, 1955, and 1963) was introduced as a functional concept to make scientific sense of the already diverse and massive store of cometary observations. Laplace (1813) and Hirtz (1889) had earlier suggested that comets were made of ice, but the physics and astronomy of Laplace's day were yet too primitive for a serious development to follow. Both visualized the recondensation of the vapor on the nucleus in the outer portions of the comet orbit, an unsupported concept today. In the 1860's the clearcut identification of some comets as parents of meteor streams provided a cometary model, "the gravel bank," subjectively so appealing that its obvious faults were not considered damming for nearly a century. In 1948 Swings (1948) concluded that solid ices must exist in comets.

The ICM involves a discrete cometary nucleus of radius up to tens of kilometer made of solid compounds primarily of C, N, O and H, conglomerated with a comparable amount of stony materials, expected to approximate a solar mix of the elements that would form solids at low temperatures, probably $<100$ K. Note Table 1 for species observed to date in comets. The noble gases and solid hydrogen should not be present in appreciable quantities because of their high vapor pressures in near vacuum at temperatures even as low as those in interstellar clouds. Some noble gases as well as some atoms and molecules of stony material may be trapped in the ices while most of the stony or meteoroidal material appears as fine dust or "dust Balls" (Opik's term), typical of the fragile low density structures observed as meteors. The observed nature of the stony component of comets will be discussed in a following section.

The basic concept of the ICM involves inactivity of the nucleus at great solar distances coupled with sublimation of the surface ices as the comet approaches the Sun towards perihelion. The nucleus is too small to be resolved optically. The outgoing gases carry with them fine dust and dust balls up to dimensions of even meters very near the Sun. The escaping material forms the dust coma of diameter several tens of thousands of kilometers. Solar radiation pressure drives away the fine dust in highly eccentric orbits to form the curved, generally short dust tails of many comets. The ionized solar wind engages the photo-ionized or charge-transfer ions of the gas to blow them away with acceleration many times the solar gravity to form the great ion tails, sometimes observable for as much as $1$ AU. All the escaping material is lost forever to the comet.

For a rotating nucleus an expected lag in sublimation on the morning side will concentrate the main thrust of the sublimating gases on the afternoon side. As a consequence, the jet reaction of the gas will develop a component of force forward or backwards with respect to the orbital motion about the Sun, depending on whether the rotation is prograde or retrograde, respectively, compared with the orbital motion. The orbital period will
therefore increase or decrease with respect to Newtonian motion. Correspondingly, an oblate nucleus with its pole tilted to its orbital plane will receive a torque causing a precession of the polar axis.

The ICM predicts qualitatively or quantitatively a number of the basic observed characteristics of comets as follows:

a. The longevity of some comets such as P/Encke that has survived hundreds and probably thousands of revolutions about the Sun, losing $-10^6$ tons per revolution. The brightest comets lose $-10^6$ tons of gas per day near perihelion. The void of interplanetary space can provide no source of replenishment for the gases lost from a gravel-bank model (see Kresak, 1981, concerning the estimated lifetimes of comets).

b. The formation of dusty tails and meteor streams from the dust and dust balls ejected by the subliming gas.

c. Survival of several Sun-grazing comets.

d. The non-gravitation (NG) motions now measured for some 42 comets (Marshall, Sekanina, and Yoemans, 1973; Marsden, 1982). About half of the period changes are positive and half negative suggesting a random orientation of spin axes.

e. The large change in the NG motion of P/Encke caused by the precession of its polar axis (Whipple and Sekanina, 1979).


g. The lifetimes (short) of several components of split comets correlated with their radial solar NG motions (Sekanina, 1982a) in the sense that the short-lived components have larger NG accelerations than long lived ones.

h. Dust jets and evidence for discrete active areas on specific spots correlating with spin: periods and axes for P/Schwassmann-Wachmann I (Whipple 1980) and for P/Swift-Tuttle 1862III (Sekanina 1981a).

i. The occurrence of luminosity bursts of one to several magnitudes as the result of some property of cometary ices that is not yet clearly specified. The gravel-bank model does not seem to possess this potential.

j. The periodic recurrence of halos and parabolic envelopes in several comets, indicating a specific spin period for each such comet (Whipple 1982).

k. An acceptable mode of origin, such as the aggregation of ices and dust in the cold outer reaches of the forming planetary system or else within associated interstellar clouds.
1. A number of consistent results from theories based on the ICM, such as asymmetric halos indicating spin axes (Sekanina 1981b), halo expansion velocities (Delsemme 1982), rates of production of sublimating water ice and relative abundances of elements (Delsemme 1977).

Composition of the ICM Ices

In spite of many successful applications of the ICM in clarifying cometary behavior, the basic icy composition remains unhappily vague as well as the physical dimensions, masses, albedos and general morphology. The author's original ICM, following suggestions by Bobrovnikoff (1942) and Wurm (1943), included specifically H₂O ice as the major ice with the thought that CH₄, NH₃, CO₂ and radicals of C, N, O and H might be present. Clearly ices more volatile than H₂O are required to explain vigorous activity at solar distances greater than 5 AU, such as that of P/Schwassmann-Wachmann 1. But what materials?

Delsemme and Swings (1952) pointed out the obvious temperature problem of maintaining solid CH₄ in comets and suggested that, if present, CH₄, NH₃ and possibly other highly volatile ices should appear as solid clathrates, embedded in the H₂O ice or snow. Although the clathrate would solve the problem of containing the highly volatile molecules, it would not explain active sublimation at great solar distances. Hase (1955) suggested that the HO radical might solve this latter problem. Later (1957) he developed a basic theory for the production and lifetimes of daughter species and parent molecules in the coma. To explain bursts in comets, Donn and Urey (1956, 1957) proposed exothermic chemical reactions in comet nuclei involving free radicals.

In the 1960's the theories multiplied to explain the lifetimes and distributions of various species observed in the coma of comets. The serious reader is referred to important summary articles if he wishes to review thoroughly the progress during the last 2 decades on problems of identifying parent molecules and coma structure from spectra and other observation: Swings (1965), Arpigny (1976), Herbig (1976), Keller (1976), Whipple and Houbner (1976), Delsemme (1977, 1982), Houbner et al. (1982) and Wycoff (1982, for a general review of comets).

An early problem concerned the rather short lifetimes of species observed in comets as compared with the laboratory determined lifetimes against primarily photo-ionization and photodissociation by solar radiation. These vary with the observed species typically from a few hours to a few days at 1 AU from the Sun. Houbner and Weigert (1966) suggested an icy grain halo in which the gases would be added more slowly to the coma by sublimation of the grains. Efforts to observe H₂O ice in the near infrared have generally been unsatisfactory although Crib (1982) finds evidence for H₂O icy grains in C/Kohoutek, 1973XII, and Hartmann
and Cruikshank (1983) report the probable detection of H$_2$O ice in P/Schwassmann-Wachmann 1.

For the short-period comets that may have made several dozen to even thousands of perihelion passages, H$_2$O ice appears to be sufficiently volatile to account for most of their average activity. Fig. 1 shows the fit of observed luminosity with model for P/Encke (Period = 3.3 yr.) by Delaunay (1975). His best fit for P/Encke suggests the unreasonable albedo of 0.7 in the visual and a low value of 0.1 in the infrared, probably explained by the surface of the nucleus being mostly covered with meteoroidal debris. His calculations for the idealized vaporization rates for H$_2$O, CO$_2$, CH$_4$, CO and N$_2$ are shown in Fig. 2. The inclusion of up to 15% clathrates has little effect on the H$_2$O curve.

The mean bulk composition in comets by atoms is now fairly well known. Delaunay's (1982) evaluation is shown in Table 2, normalized to Si = 1.0. He bases the gaseous abundances (by number, col. 3) on the production rates determined in several recent bright comets by numerous observers. For the dust (col. 2) he assumes the mass ratio of dust to gas as 0.8, a quantity that is observed to be highly variable from comet to comet and even from day to day for some individual comets (see Donn 1977). For the abundance ratios in the dust Delaunay assumes Mason's (1971) values measured for CI carbonaceous chondrites. This assumption is founded on Millman's (1972, 1977) calculations of the abundance ratios of Na, Mg, Ca and Fe in cometary meteor spectra as similar to those in the Cl chondrites and upon the abundance ratios in the "Brownlee" particles. Brownlee et al. (1977) find that these interplanetary micrometeorites collected in the upper atmosphere have elemental abundances also very similar to the Cl chondrites. For comparison with the cometary values (col. 4) Table 2 lists (col. 5) the "cosmic" abundances for solar-system elements as derived by Cameron (1981).

Our interest centers on the abundances ratios of C, N, O and H. The high depletion of H in comets compared to the Sun is, of course, to be expected if comets are the frozen residue from a similar mix of elements. The low H/O ratio rules out the presence of liquid or solid H and, indeed, greatly restricts the possible abundances of CH$_4$, NH$_3$, and the numerous hydrocarbons that appear in the interstellar medium. Consistent with this gross abundance ratio is the conclusion of Huebner et al. (1982) from theirs and other studies of the gas-phase chemistry that "The comet models most consistent with observations indicate that only trace amounts (total amount 2%) of molecules bearing CN, C$_2$, C$_3$ and NH$_3$ can be present in the nucleus." Delaunay notes that C appears to be distinctly underabundant compared to O and N in a solar mix, or in the expected gross interstellar gas and dust.
Cochran (1983) has applied non-equilibrium chemical modeling to a set of spatially and temporally resolved spectra of P/Stephen-Oterma. She concludes that near the nucleus the likely parent for CN is HCN; for OH, H$_2$O and CH$_3$OH; for CH, CH$_4$; for C$_2$, C$_2$H$_2$; and for C$_3$, model dependent, possibly involving grain photolysis. The vaporization rate appears to be controlled by H$_2$O.

The subject of parent molecules is too complicated for adequate review in this summary and so the reader is referred to other relevant papers in this colloquium for explanations and theories.

The Meteoroidal Component of Comets

Our knowledge of the dust and stony or meteoroidal material of very low vapor pressure in comets stems from surprisingly diverse sources:

a. Cometary meteors and meteor streams.

b. Brownlee particles captured in the high atmosphere.

c. Impacts on artificial satellites, space probes and the Moon.

d. Comae, dust tails, and near-nucleus jets, showing solar reflection spectra.

e. Spectra of heavy elements in comets near the Sun.

f. Solar directed tails of a few comets when the Earth passes through the orbit plane.

g. Radar reflections from sizeable particles (centimeters) near the nucleus of the near-Earth Comet IRAS-Araki-Alcock, 1983d.

h. The Zodiacal Light and Gegenschein.

Two important general references with many contributors to dust in the Solar System are Cosmic Dust, edited by J.A.M. McDonnell (1978) and Solid Particles in the Solar System, edited by I. Halliday and B.A. McIntosh (1980).

The observations of impacts in space or on the Moon and observations of the Zodiacal Light and Gegenschein provide information about the orbital distribution and mass content of tiny particles, mostly cometary, in orbits. About detailed composition, little has yet been learned. For relevant reviews see: McDonnell (1978) for space studies; Ashworth (1978) for lunar impact studies; Dohnanyi (1978) for space dynamics of small particles; and Weinberg and Sparrow (1978) for Zodiacal Light and Gegenschein results.

The studies of lunar microcraters summarized by Pechtig (1982) show diameter/depth ratios between 1.0 and 2.7 with two conspicuous peaks at 1.4 and 1.9 and an extension to 2.5. From laboratory data he attributes the highest values to fluffy cometary particles, comprising ≤30 percent of the total by number. This is in accord with the results of Ceplecha and McCrosky (1976) for large fireballs.
Even the polarization properties of the particles in the Zodiacal Light appears as yet not to give clearcut evidence as to their character. The difficulty lies in unknown morphology, probable irregular shapes and probable fluffy structure, all highly variable from particle to particle and not easily susceptible to theoretical or laboratory simulation. That they are chiefly fluffy particles in the 1-100 μm range probably represents much of contemporary opinion.

The lifetimes of zodiacal particles against destruction or escape is relatively short and the source generally thought to be comets, although Delsemme (1976), Röser (1976), Kresák (1980), and Mukai et al. (1983) doubt that the periodic comets can supply the few tens of tons per second (Whipple, 1976) necessary for continuous supply. Such estimates may be increased significantly when the full implications of the large cloud of sizeable particles observed to accompany comet IRAS-Irkut-Alcock (Goldstein et al. 1983; Campbell et al. 1983; and Shapiro et al. 1983) and Comet Bowell, 1980b (Sekanina 1982b; A'Hearn et al. 1983a) are fully interpreted.

From the Super-Schmidt photographic meteors of ~1 g mass, Verniani (1967, 1969) finds a logarithmic mean density of 0.28 g cm⁻³ with some in the 0.01 g cm⁻³ range (specifically the Draconids from P/Giacobini-Zinner). These appear to be almost entirely cometary debris with the interesting possible exception of the Geminids, now associated with the asteroid 1983 TB (Whipple; 1983c, by comparison with Bardwell's elements, 1983) discovered by the Infrared Astronomy Satellite and reported by S. Green (1983) of Leicester. Verniani finds that the mean density of the Geminid meteoroids is ~1.0 g cm⁻³ or more than three times the mean for cometary meteoroids. The Geminid stream, with a perihelion distance of 0.14 AU and aphelion just beyond Mars' orbit, may be asteroidal or, possibly, the asteroid may be a stony comet nucleus. The fluffy or low-density nature of cometary non-volatiles is thus firmly established. However, the analysis of fireball data of the Prairie Network and in Central Europe show that a few stronger and denser bodies appear among them, comparable to weak C1 chondrites (Wetherill and Revelle, 1982).

The most extensive observational source of information about cometary dust lies in the coma and dust tails. The analysis of the kinetics and dust tails by Finson and Probstin (1968a,b)' has been continued by Sekanina (1980, review) and by Saito et al. (1981). Their important results will be summarized in the following pages.

Infrared photometry has developed into an extraordinary powerful tool for analyzing comet dust and larger particles. Coupled with red optical photometry the nearly blackbody radiation from the particles can be separated from that of the scattered
sunlight. Temperature, area, some measure of particle size distribution and information about the scattering nature of the particles can thus be derived with the addition of polarization measures. Ney's (1982) report is the major source of the highly condensed summary that follows. Five bright dusty comets all showed a silicate signature at 10 and 18 μm indicating the presence of small refractory grains of radius < 5 μm in the comae and tails. The anti-tail or sun-ward tail of C/Kohoutek (1973 XII) did not show the silicate signature, thereby indicating nonsilicates or large silicate grains > 30 μm. One (1975 IX) of two comets showing only ion tails gave thermal emissions that could be interpreted as from large grains. The calculated mass loss ratios for H₂O/solids for this comet was 1.2, the smallest among five determinations. The other ratios of H₂O/solids, were 4.2 (1970 II); 9.6 (P/Encke); 9.2 (1973 XII); and 1.6 (1976 VI, C/West that split).

The temperatures of the fine dust exceeded the blackbody temperatures at the observed solar distances by 8% for 1975 IX (ion tail), 26% (1970 II) and 48% (1976 VI) for the fine grained dust, the latter two comets showing fine grained silicate dust. Because the IR radiation is almost exactly equal to the radiation absorbed from the sunlight, the scattered component of which is measured at shorter wavelengths, the albedo of the particles can be calculated from the photometry. For 1973 XII, C/Kohoutek, the albedo of the dust is 0.14 to 0.20 at scattering angles in the range 80° to 135° (See also Crifo, 1982, for other results on the grains of C/Kohoutek).

Forwarding scattering was remarkably strong for C/West indicative of a dirty dielectric grain mixture with dominant size ~1 μm. The ratio of reflected to absorbed energy for five comets is shown in Fig. 3 (Ney, 1982). The albedos of the grains are surprisingly similar among these five comets. During the splitting of C/West, the 10-μm feature was always in evidence, indicating that the interior regions of the broken nucleus produced dust of the same character as the original surface and quite as abundantly.

Campins and Hanner (1982) and Hanner (1983) are making rapid progress in interpreting the IR dust measures in terms of a mixture of hot absorbing grains (such as magnetite) and cold dielectric silicate grains, the latter providing the silicate feature. Such an interpretation seems needed in view of Sekanina and Farrell's (1982) evidence for submicron-sized particles of strongly absorbing and others of essentially dielectric character in the striated tail of C/Markos, 1957 V. The absorbing particles with β lying between 1 and 2 (β = ratio of solar radiation acceleration to solar gravity) require a distribution peak just above 0.1 μm, falling rapidly in number to 0.3 μm. The nearly dielectric particles with β ~ 0.6 appear to be rare near 0.1 μm and increase rapidly in number to 0.3 μm.

In his earlier study of the dust jets near the nucleus of P/Swift-Tuttle, 1862 III, the parent of the Perseid meteor stream,
Sekanina (1981a) found clearcut evidence for jets having dust particles with \( \beta < 0.5 \), dielectric, and other jets that also include absorbing dust with \( \beta > 1.0 \). Saito et al. (1981) point out that the lack of observed values of \( \beta > 2.5 \) excludes the presence in comets of significant numbers of graphite particles in the size range between 0.02 and 0.2 \( \mu \text{m} \).

The physical and chemical character of the refractory material in comets is intimately involved in theories of their mode of origin. The Brownlee (Fig. 4) particles with the electron microscope frequently look like clusters of grapes or of tiny fish eggs (0.1 to 1.0 \( \mu \text{m} \) in size) precisely as one might envision an aggregate of interstellar dust. But, of course, dust formed in the outer reaches of the proto-planetary nebula might give the same appearance. Fraundorf et al. (1982) find that in 57 stratospheric micrometeorites the mean elemental abundances of Na, Mg, Al, S, Ti, Cr, Mn, Fe, and Ni (compared to Si = 1) all match the average Cl chondrite abundances well within a 30% range. The scatter is large, the order of a factor of 2, because the particles are so small, \( \leq 10 \mu \text{m} \), and their components variable enough to bias the measures for any single particle. The major deviant is Ca, underabundant by a fact of 3 or more with about twice the average spread. Fraundorf et al. observe that the Ca deficiency occurs in particles that are often smooth on a scale of microns while particles that are clearly aggregates with high porosity show normal Ca abundances. They suggest that the Ca depletion may be due to mobilization in the parent body.

Three Mg isotopes measured in several stratospheric micrometeorites by Esat et al. (1979) show normal solar-system ratios to an uncertainty of 1% with the exception of only 1 particle. The particles included chondritic aggregates, particles composed of single grains of olivine and pyroxene, and spherules depleted in Fe and enhanced in the more refractory Ca and Al.

The stratospheric micrometeorites are similar to soot in size and optical absorptivity. The aggregates vary greatly in porosity although the submicron components are compact, being mostly composed of amorphous and crystalline silicate materials with Ni bearing iron sulphides and carbonaceous material. Fraundorf et al. note that if the particles are cometary, the above sub-micron components were first assembled and aggregated along with lesser numbers of similar sized or larger monomineralic grains, usually of olivine, enstatite or Ni-bearing iron sulphides. Presumably the voids and surfaces once contained ices. Even though proof of this cometary origin sequence is still elusive, the circumstantial evidence is striking and probably our best foundation, today, for more detailed theories of the formation of comets. Certainly the primitive character of these particles is manifest, as we expect of cometary material.
More Exotic Ices than H₂O in Comets

The conclusion that H₂O ice with or without clathrates is generally satisfactory for even the short-period comets is not acceptable. Comet bursts of 1-3 magnitudes occur in about 3/4 of the light curves of these comets and splitting can also occur in what appear to be rather docile old comets. The classical example is P/Biela, first observed in 1772 with a period of just under 7 years and perihelion distance of 0.72 AU. It was observed again as 1806 I, as 1826 I and as 1832 III, without showing any unusual behavior or brightness changes. But as 1846 II it had split into two components which lasted until 1852 and then disappeared never to be seen again. Their remnants remain as a meteor shower, spectacular in November 1872 (the Andromides), but active regularly and usually weak since 1772. (See Sekanina, 1982 and Hughes, 1975, for thorough accounts of comet splitting and flaring, respectively.)

A number of explanations for comet bursts have been proposed, including the statistically untenable idea of impacts by interplanetary boulders. Hughes finds that the burst distribution curve peaks near the solar distance of 1 AU with no evidence of a bump in the asteroid belt. The collapse of unstable structures on the nucleus, either vertical or cavity ceilings, remains a simple but untestable explanation. All evidence points to an extreme lack of homogeneity in cometary nuclei (Whipple, 1983).

Under very low surface gravity, sublimation could produce bizarre formations. Wasting, slumping or collapse of such irregular features could expose large volumes of ices to sunlight, initiating an outburst. More detailed studies of these processes and their observable consequences are clearly needed.

The core-mantle processes of Mendis and Brin (1977) and Brin and Mendis (1979) deals effectively with the problem of meteoroidal blanketing in the post-perihelion fading of comets and the problem of the removal of the blanket near perihelion. Thus, a maximum of activity and intrinsic brightness, as observed statistically, occurs soon after perihelion. This concept has been elaborated by Horanji et al. (1983) with an added process involving the breakup of friable sponge grains as they are blown away from the surface of the nucleus. Weissman and Kieffer (1981) have included in their theory the effect of opacity and scattering by ejected dust on the thermal properties of the active nucleus.

The magnificent outbursts of P/Schwassmann-Wachmann I at more than 6 AU from the Sun require not only more volatile ices than H₂O but specific mechanisms and morphology both to start and stop them. Whitney (1955) suggested pockets of highly volatile ices such as CH₄ and some storage mechanism for the solar heating between outbursts to build up gas pressure. The identification of CO⁺ emission in the comet both during and between outbursts by
Cochran et al. (1980, 1982) points strongly to CO$_2$ (or CO) as the active ice. Cowan and A'Hearn (1982) base their theory on this premise. They suggest a cut-off mechanism involving accumulation of H$_2$O ice particles (and meteoroidal particles?). The concept of "pockets" with areas the order of square kilometers and thicknesses the order of centimeters strains the imagination. Whipple (1980) suggested a fall-back mechanism of large particles from a small initial active area to break the crust and to expand the active area to an effective size. Cowan and A'Hearn propose that the diurnal temperature variations fracture the surface by differential expansion.

Slow warming to relevant depths over large areas and over intervals of weeks and months seems to be a requirement for preparing the subsurface material to produce the outbursts. The proposals by Patachink et al. (1974, 1977), Klinger (1980, 1981) and Smoluchowski (1981a,b) that amorphous ice may be present in comets and that its transition into the crystalline state may provide an internal source of activity, is most attractive. Discussion of the theory of cometary expectations from amorphous ice is presented by Klinger and Smoluchowski in these reports.

Shulman (1983) doubts the occurrence of amorphous ice in comets on the basis of formation temperatures greater than the 155K transition temperature, contrary to the assumptions of most investigators. He suggests instead the formation of nonequilibrium ion molecular clusters of H$_2$O$^+$ and H$_2$$^+$ induced by the solar wind at > 100 AU from the Sun in its T-Tauri stage.

The suggestion of "Platt" particles in comets will only be mentioned. They are (Platt, 1956), if they exist, the order of 10 Å in dimension and should scatter light of wavelength shorter than some limit, above which they are essentially transparent. See, for example, the discussion by Misconi and Whitlock (1983) for background and references.

The formation and nature of interstellar grains as possible components of comets or as direct processes in comet formation are of prime importance to an understanding of the nature of comets. J.M. Greenberg and his collaborators have made remarkable progress in demonstrating by laboratory experiments, by reference to interstellar matter studies, and by theoretical studies that much of cometary material may well be of interstellar origin or else has been formed in a somewhat similar environment. His review article (Greenberg, 1982) is of vital importance to anyone interested in the nature of cometary nuclei, and provides references to all aspects of this research. Only a brief summary will be made here because the reader should refer to Greenberg's accompanying presentation. The laboratory experiments involve the deposition of H$_2$O, CO, NH$_3$, CH$_4$ etc. on a cold finger at T ~ 10 K while
irradiated with ultraviolet photons. Extremely complex mixtures of molecules and radicals are so produced. They are explosive with accompanying luminescent when heated to ~27 K and to successively higher temperatures. Many of the puzzling aspects of cometary behavior can be explained on Greenberg's model including composition, activity at great solar distances, bursts etc. We have noted earlier the similarity of some of the Brownlee particles to an imagined collection of interstellar dust particles. Yamamoto (1983) has discussed possible condensation processes in the interstellar environment as related to comet formation.

Shulman (1972) proposed that deep space cosmic rays play a significant role in radiation synthesis to alter the chemical composition of the upper meter or so on cometary nuclei and that solar cosmic rays produce near-surface changes that may result in cometary outbursts. Comets that are "new," making their first approach to the Sun after a long residence in the Opik-Oort cloud, appear to be unusually bright at great solar distances, C/Kohoutek, 1973 XII, being a famous example. Marsden et al. (1973) note an excessive number of "new" comets discovered at large perihelion distances, indicating that they are perhaps ~2 mag. brighter on the first approach than on later returns.

Whipple (1977) supported the idea that cosmic rays in the Opik-Ooort cloud are responsible for significant chemical effects in the outer meters of such comets to produce the unusual temporary activity of new comets. Donn (1976) suggested that cosmic rays would produce complex hydrocarbons by polymerization to darken the outer layers. Laboratory experiments by Moore et al. (1983) involved irradiation of thin ice films at T ~ 20 K by 1 ~ MeV protons from a van de Graaff accelerator. The ice mixtures included H₂O, NH₃, CH₄, N₂, C₃H₈, CO and CO₂. New molecules were synthesized in all the solid-phase mixtures. The irradiated mixture contains reactive species exhibiting thermoluminescence and pressure enhancements during warming and also an ~1% nonvolatile residue of complex carbon compounds appreciably darkened. Moore et al. expect exothermic activity to begin on "new" comets at solar distances >100 AU when the surface temperature rises to 20-32 K. The strang particle cloud about C/Bowell, 1980b, suggests that "new" comets may indeed become active at large solar distances (Sekanina 1982b, A'Hearn et al. 1983a). Other exothermic activity could occur on warming to 100 < T < 150 K at 2 < r < 5 AU. The laboratory irradiation matched that from cosmic rays in deep space over 4.6 x 10⁹ years to a depth of more than 1 m in compact ices.

Evidence is strong, although not definitive, that faint P/Holmes 1892 III experienced two outbursts of 6ᵐ or more separated by 72 days as the consequence of an encounter with a companion satellite followed by final impact (whipple, 1983 and in preparation). Peculiar to both these outbursts is further evidence for unusually rapidly expanding faint halos with about twice
the velocity of the observed normal very bright halos, noted first by Orlov (1940). If these impacts initiated actual explosions the second high-velocity halos could have resulted from gas (and dust?) ejected at about the velocity of sound for the prevalent molecules. The velocities involved are: for the first outburst, Nov. 5, 1892, 0.38 and 0.76 km s^{-1}, at r = 2.3 AU; and for the second on Jan. 16, 1893, 0.36 and 0.58 km s^{-1}, at r = 2.6 AU. The question is whether the impact of a satellite nucleus of ~100 meters in dimension impacting at a velocity of only a few meters per second could, by compression, initiate an explosion in a buried mixture of exotic ices?

Concluding Comments

It appears that the icy conglomerate model of comets is alive and well as a basic concept. Most of the details of cometary morphology and composition remain to be determined beyond the clear indications that H\textsubscript{2}O ice is a major constituent and that comet nuclei contain a sizeable fraction of very fine particles much as one would expect to be aggregated either in the outer reaches of the protosolar nebula or in associated interstellar clouds. Exotic ices must certainly be present, some that probably provide exothermic reactions when warmed to rather low temperatures. Space missions to comets, specifically rendezvous missions, are clearly required to answer many of the basic questions. Laboratory studies of ices at very low temperatures and in various radiation environments are also vital to progress in understanding the nature of comets. Continued observations of comets with both classical and novel techniques remain, as ever, vital to this progress. The end result will be a great leap forward in our understanding of how the Solar System originated and, possibly, how life on Earth could arise.

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Note added in press: C.B. Cosmovici and S. Ortolani (IAU Circ. No. 3915 Feb. 10, 1984) find with the Asiago 1.82 m telescope for Comet IRAS-Araki-Alcock (1983d) on 1983 May 9.9 lines of the new molecules HCO and H\textsubscript{2}S\textsuperscript{+}, identified by G. Herzberg. They strongly suspect the presence of H\textsubscript{2}CO, DCO and NH\textsubscript{4}. 

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REFERENCES


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**Table I**

Species Observed in Comets.

<table>
<thead>
<tr>
<th>Species (Near Sun)</th>
<th>Species (Tail)</th>
<th>Species (Dust)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H, C, C₂, C₁₂, C₁₃, C₃</td>
<td>H₂, OH, H₂O, S, S₂</td>
<td>Silicates, mostly dielectrics</td>
</tr>
<tr>
<td>CH, CN, CO, CS, HCN, CH₂CN, NH, NH₂, NH₃</td>
<td>CO⁺, CO₂⁻, N₂⁺, OH⁻, H₂O⁺, Ca⁺</td>
<td></td>
</tr>
</tbody>
</table>
Table 2

Atomic Abundances* in Bright Comets.

<table>
<thead>
<tr>
<th>Element</th>
<th>Dust No.</th>
<th>Gas No.</th>
<th>Total No.</th>
<th>Cosmic No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2.00</td>
<td>22.30</td>
<td>24.30</td>
<td>26,600.00</td>
</tr>
<tr>
<td>C</td>
<td>0.70</td>
<td>3.00</td>
<td>3.73</td>
<td>11.70</td>
</tr>
<tr>
<td>N</td>
<td>0.65</td>
<td>1.46</td>
<td>2.11</td>
<td>2.31</td>
</tr>
<tr>
<td>O</td>
<td>7.50</td>
<td>14.80</td>
<td>22.30</td>
<td>18.40</td>
</tr>
<tr>
<td>S</td>
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<td>0.05</td>
<td>0.55</td>
<td>0.50</td>
</tr>
<tr>
<td>Mg</td>
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<td>-</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>Si</td>
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<td>-</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Fe</td>
<td>0.90</td>
<td>-</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Ni + Cr</td>
<td>0.06</td>
<td>-</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Total No.</td>
<td>13.77</td>
<td>41.64</td>
<td>55.41</td>
<td>-</td>
</tr>
<tr>
<td>Total Mass</td>
<td>254.5</td>
<td>318.3</td>
<td>572.8</td>
<td>-</td>
</tr>
<tr>
<td>Mass Percent</td>
<td>44.4</td>
<td>55.6</td>
<td>100.0</td>
<td>-</td>
</tr>
</tbody>
</table>

*By number, normalized to Si = 1.00 after Delsemme (1982).

FIGURE CAPTIONS

Fig. 1. Production rate vs. solar distance for P/Encke (after Delsemme).

Fig. 2. Production rates for H$_2$O, CO$_2$, CH$_4$, CO and N$_2$ vs. solar distance (after Delsemme).

Fig. 3. Ratio of reflected to absorbed flux vs. scattering angle at coma, i.e. Earth-Sun angle (after Ney).

Fig. 4. Extraterrestrial particle (courtesy D.E. Brownlee).
Fig. 3

SCATTERING ANGLE

scatter curve

\( (\lambda F)_{\text{max VIS}} / (\lambda F)_{\text{max IR}} \)