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A CONTINUING CONTROVERSY: HAS THE COMETARY NUCLEUS BEEN RESOLVED?

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I. COMETARY ACTIVITY AT LARGE HELIOCENTRIC DISTANCES

Barnard (1891) appears to have been the first to recognize the significance of systematic observations of comets at large distances from the sun. His successful tracing of two 1889 comets to heliocentric distances over 5 and even 6 a.u. caused him to notice that some of the short-period comets might be within the reach of the Lick Observatory's 36-inch refractor throughout their entire orbits around the sun. Although it is clear nowadays that the short-period comets would be a good deal fainter at comparable distances than the two nearly parabolic comets referred to by Barnard, his original idea proved basically correct, except for the necessity of using photographic plates. Periodic Comet Encke was probably detected near aphelion during Barnard's lifetime, in September 1913 (Barnard 1914a; Marsden and Sekanina 1974). Undisputed images of the comet just several days off aphelion were obtained in 1972 (Roemer 1972; McCrosky and Shao 1972).

Barnard's emphasis on the observation of distant comets stemmed primarily from his apprehension of the importance of precise positional determinations at large heliocentric distances for orbital studies. This attitude completely prevailed until the mid-20th century, although interest in the physical processes in comets at large distances emerged from time to time, usually in connection with a discovery of a peculiarly behaving comet far from the sun.

A study of the tails of two distant comets by Osterbrock (1958) was a significant step forward, primarily because it showed that the two comets, Baade 1955 VI and

Haro-Chavira 1956 I, behaved in the same way and therefore were not cases of yet other exceptional objects (such as, e.g., P/Schwassmann-Wachmann 1; or, a few years after the two comets, Humason 1962 VIII). Indeed, Roemer (1962), in her excellent paper reviewing the progress in the study of physical processes in comets at large heliocentric distances, pointed out that tails of the type displayed by the two comets observed by Osterbrock are rather common among the distant comets and that these comets have still other characteristic properties. I have recently interpreted Osterbrock's results (Sekanina 1973) to indicate that new comets on the incoming branch of their orbit show definite signs of a surprisingly high activity at distances up to about 15 a.u. or more, and that substances that vaporize from the comets at the required rates at such large distances must be equivalent to or more volatile than solid methane. This information is derived unambiguously from the dynamics of the rather heavy particles – most probably "dirty" icy grains – that constitute the tails and heads of the distant comets and that are also responsible for the comets' pure reflection-type spectra, such as the one observed by Walker (1958) in Comet Baade.

II. LARGE-SCALE PHOTOGRAPHS OF COMETS FAR FROM THE SUN

Independent evidence on the significant activity of many – and not only new – comets at large heliocentric distances comes from large-scale photographs. They show that a number of comets display definite traces of a coma at distances up to 8 a.u.; the image of Comet Stearns 1927 IV (which was by no means a new comet) was still diffuse at a record distance of 11 a.u. (Van Biesbroeck 1933). Furthermore, it is not difficult to demonstrate that the actual solid nucleus is not observed even on plates on which the cometary image looks essentially stellar. In the following, we use the photographic "nuclear" magnitudes by Roemer whenever available, both because they are internally consistent and because they are generally fainter and therefore, it is believed, closer to the brightness of the actual nucleus than are the nuclear magnitudes by any other observer.

As an example of the observed variations in the nuclear magnitudes with heliocentric distance, we have plotted in Fig. 1 the light curves of two new comets of large perihelion distance observed by Roemer (Jeffers 1956; Roemer 1956; Roemer and Lloyd 1966). If the cometary images referred to the solid nucleus, their brightness should, of course, be inversely proportional to the square of the heliocentric distance. Meanwhile, however, at distances r from the sun ranging from 4.6 to 6.1 a.u., Comet Humason 1959 X – described by Roemer as essentially stellar, nearly stellar, or sharply condensed on most plates – basically followed a r^{-4} law. Comet Haro-Chavira 1956 I also fitted a r^{-4} law after perihelion (at distances of 5.6 to 7.8 a.u.), while the preperihelion observations showed the comet to be substantially brighter and suggested that it may have actually started fading intrinsically even before reaching perihelion. The r^{-2} law is also totally incompatible with Roemer's postperihelion nuclear magnitudes for Comets Baade 1955 VI (r^{-3} law between 3.9 and 7.8 a.u.), Wirtanen 1957 VI (r^{-6} for the primary nucleus between 4.6 and 7.3 a.u. and r^{-4} for the secondary nucleus from 4.6 to 6.9 a.u.), and Gehrels 1971 I (r^{-4} between 5.4 and 7.1 a.u.). The first of these three comets was new, the second was most probably new, and the third was positively not new (Marsden and Sekanina 1973).

In a rather surprising contrast to Roemer's nuclear magnitudes, Van Biesbroeck's (1930a, 1933) considerably brighter estimates of the "total" magnitude of the abovementioned Comet Stearns did follow a r^{-2} law except in the immediate neighborhood of

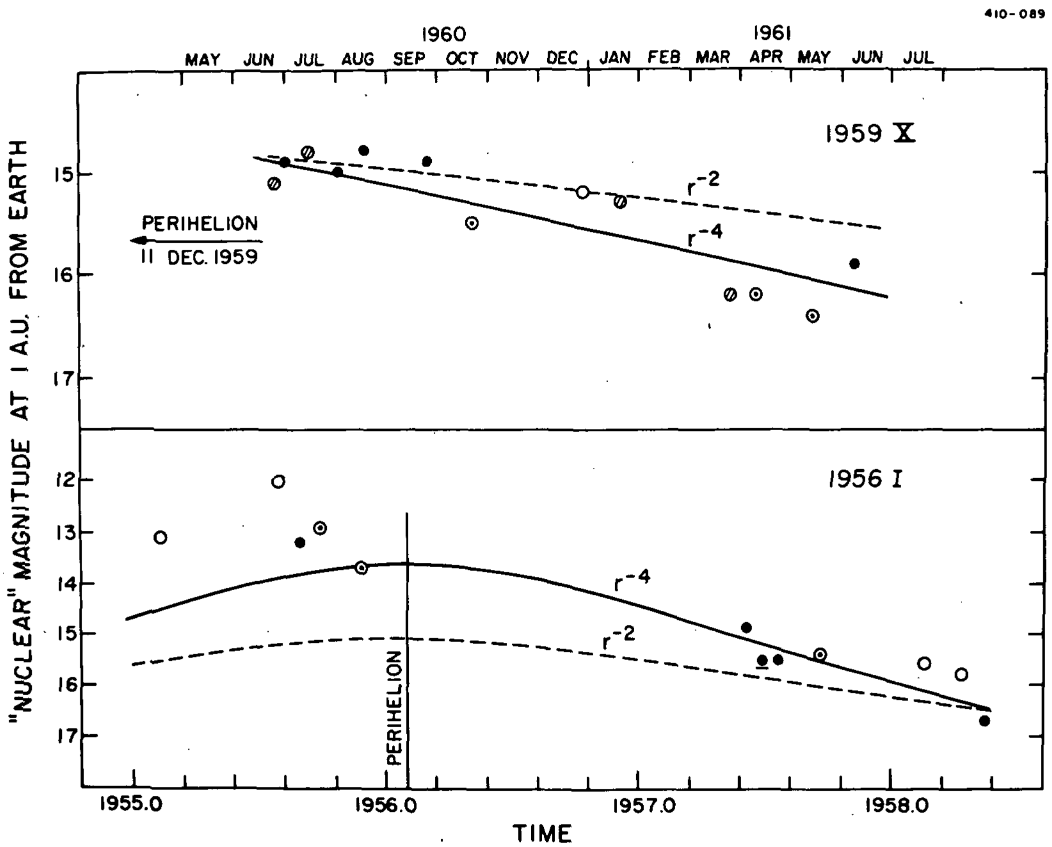

Fig. 1. "Nuclear" magnitudes by Roemer of Comets 1959 X and 1956 I, reduced to a unit geocentric distance, versus time. Observations before 1956 were made with the 36-inch Crossley refractor of the Lick Observatory, and those after 1956, with the 40-inch Ritchey-Chrétien reflector of the Flagstaff Station of the U.S. Naval Observatory. Observations with the 20-inch Carnegie astrograph of the Lick Observatory have not been used here, in order to avoid a possible instrumental effect. The various symbols correspond to Roemer's description of the cometary image on plates: underlined circle – stellar image; solid circles – practically or essentially or nearly stellar image; shaded circles – practically no coma, sharply or strongly condensed image; circled dots – well-condensed or condensed image, nuclear condensation; open circles – other description, usually mentioning the presence of a coma, or no comment on the image.

perihelion (Fig. 2). It appears, therefore, that neither an essentially star-like appearance nor a r^{-2} brightness law alone guarantees that the solid nucleus has actually been resolved.

Recent nuclear magnitude estimates of Comet Kohoutek 1973f by Roemer from her large-scale plates suggest that even the simultaneous presence of a practically stellar image and of the inverse-square power law at large heliocentric distances does not imply the detection of the solid nucleus. Preperihelion photographs of the comet at distances more than 2 a.u. from the sun (Roemer 1973a, b) show the comet to be nearly stellar, and Roemer's nuclear magnitudes fit the inverse-square power law with a precision better than $\pm0\overset{m}{.}2$. Yet a postperihelion plate at 2.5 a.u. from the sun (Roemer 1974) shows that the nucleus is 3 magnitudes fainter intrinsically than it was before perihelion (see Table I for details).

The activity of comets at large heliocentric distances and the associated bias in the reported nuclear magnitudes have a profound effect on the determination of the sizes and reflectivities of cometary nuclei; this problem will be discussed in Sections IV and V.

III. EVAPORATION OF COMETARY NUCLEI

Delsemme (1972) pointed out that the empirical law used by Marsden (1969) for the nongravitational acceleration in the motion of P/Comet Schwassmann-Wachmann 2 strongly resembles the vaporization curve of water snow, derived from the steady-state equation at the cometary surface. Since the vaporization flux is obtained from

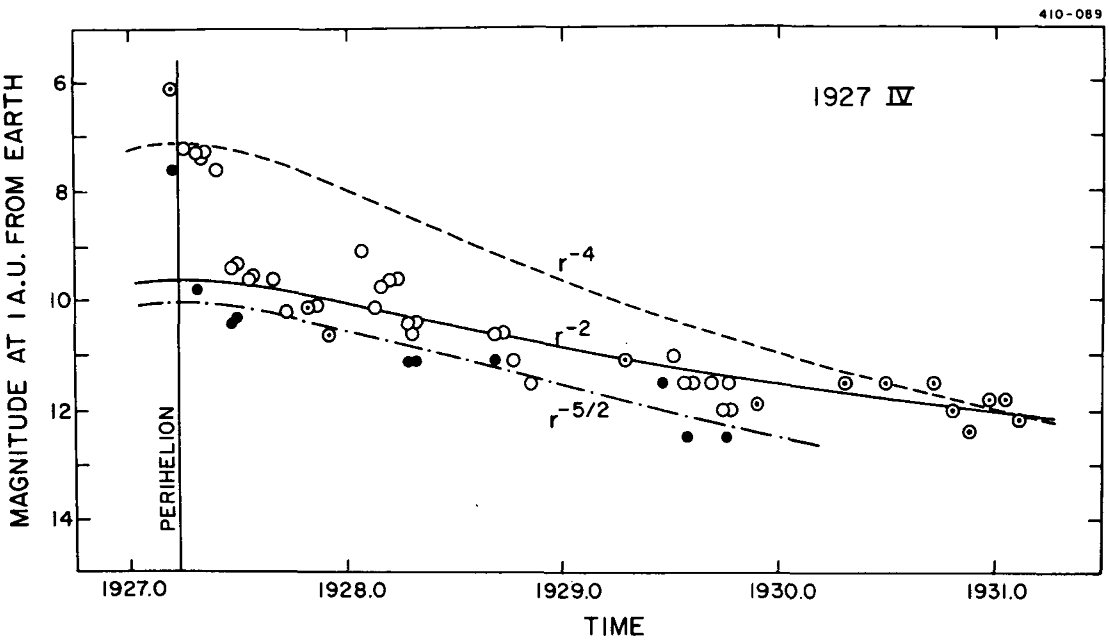

Fig. 2. "Total" and "nuclear" magnitudes of Comet 1927 IV, reduced to a unit geocentric distance, versus time. The observations were made by Van Biesbroeck at the Yerkes Observatory: open circles – total visual magnitudes with the 40-inch refractor; circled dots – total photographic magnitudes with the 24-inch reflector; solid circles – nuclear magnitudes, all visual except for the preperihelion one, which is photographic. The observed nucleus was seldom described as star-like in appearance, and the comet's image was still diffuse in 1931.

Table 1

"Nuclear" magnitudes of Comet Kohoutek 1973*f* (observations by Roemer 1973a, b, 1974).

Date	Location in Orbit	Distance from Sun (a.u.)	Phase Angle	Nuclear Magnitude*			Description
				No phase effect	Lambert phase law	Moon's phase law	
1973 Apr. 4	before perihelion	4.4	12°	10.7	10.7	10.4	nearly stellar condensation in trace of coma
Apr. 28	before perihelion	4.2	14	10.9	10.9	10.6	sharply condensed nucleus
Sept. 29	before perihelion	2.1	13	10.6	10.6	10.3	nearly stellar nuclear condensation
1974 Apr. 26	after perihelion	2.5	14	13.7	13.7	13.4	

*Reduced to unit heliocentric and geocentric distances by the inverse-square power law.

the equation numerically, and since no analytical form is available, we suggested the following empirical formula to fit the variations in the normalized vaporization rate with heliocentric distance r (Marsden et al. 1973):

$$g(r) = \alpha \left(\frac{r}{r_0}\right)^{-m} \left[1 + \left(\frac{r}{r_0}\right)^{n}\right]^{-k} , \qquad (1)$$

where m, n, k, and r_0 are parameters of the vaporization curve and α is the normalizing factor.

Although the above expression was originally intended to fit a particular vaporization curve, a study of a large number of vaporization curves for a rapidly rotating nucleus (constant vaporization flux over the nuclear surface) later revealed remarkable properties of formula (1):

A. The exponents m, n, and k are practically independent of the absorptivity κ of the cometary nucleus for solar radiation, its emissivity ϵ for reradiation, and the latent heat of vaporization L.

B. The scaling distance r_0 (in a.u.) is the following simple function of κ, ϵ, and L:

$$r_0 = 370\ L^{-2} \kappa^{1/2} \epsilon^{-0.56} , \qquad (2)$$

where L is in kcal mole^{-1} (L_{H_2O} is taken equal to 11.4 kcal mole^{-1}).

The above results should be complemented by three additional remarks:

C. Formula (1) also applies to the average vaporization rate from a nonrotating nucleus (with no evaporation from the dark side) if r_0 from equation (2) is multiplied by a factor of $2^{1/2}$, and to the vaporization rate from the subsolar point of the nonrotating nucleus if r_0 is multiplied by a factor of 2.

D. A very important relation has now been found to exist between the fraction of the solar energy absorbed by the nucleus that is spent for snow vaporization (E_{vap}) and the fraction that is reradiated back to space (E_{rad}). Analysis of a large number of vaporization curves indicates that the ratio E_{rad}/E_{vap} is a virtually exclusive function of the rate of variation in the vaporization flux with heliocentric distance, thus depending only on the ratio r/r_0. Inspection of these vaporization curves indicates that the logarithmic gradient w of the vaporization flux Z,

$$w = - \frac{d(\ln Z)}{d(\ln r)} , \tag{3}$$

is related to E_{rad}/E_{vap} by

$$\frac{E_{rad}}{E_{vap}} = 0.604 \, (w - 2)^{1.05} \tag{4}$$

for $w \lesssim 4$, and by

$$\frac{E_{rad}}{E_{vap}} = 0.522 \, (w - 2)[1 + 0.105 \, (w - 2)] \tag{5}$$

for $w \lesssim 8$. This remarkable relationship is actually a logical extension of the physical interpretation of the scaling distance r_0 submitted by Marsden et al. (1973).

E. The logarithmic gradient w calculated from the empirical formula (1) converges to $m + nk$ when $r \gg r_0$, whereas the steady-state equation indicates that for $r \gg r_0$, gradient $w \sim r^{1/2}$ and therefore diverges. Thus it is preferable to replace $g(r)$ at distances substantially exceeding r_0 by

$$h(r) = \beta \exp(-br^{1/2}) \quad , \tag{6}$$

where

$$b = \left(\frac{\ell\sigma\epsilon}{Q\kappa}\right)^{1/4} \left(\frac{L}{R_g}\right) \quad , \tag{7}$$

in which σ is the Stefan-Boltzmann constant, Q is the solar constant, R_g is the universal gas constant, and ℓ equals 4 for the rapidly rotating nucleus and 2 for a nonrotating nucleus. If formula (6) is used in relative terms and in conjunction with formula (1), the normalizing factor β can serve to adjust $h(r)$ so that it matches $g(r)$ at a particular distance $r_1 > r_0$, for which

$$\frac{d}{d(\ln r)} [\ln h(r)]_{r_1} = \frac{d}{d(\ln r)} [\ln g(r)]_{r_1} \quad ; \tag{8}$$

$h(r)$ then replaces $g(r)$ at $r > r_1$, and

$$\beta = g(r_1) \exp(br_1^{1/2}) \quad . \tag{9}$$

If formula (6) is used in absolute terms, β is determined by the vapor pressure of the vaporizing substance.

IV. THE DELSEMME-RUD METHOD

An ingenious method has recently been proposed by Delsemme and Rud (1973) to separate the cross-sectional area S of a cometary nucleus from its Bond albedo A_s for solar radiation. The vaporization cross section $(1 - A_s)S$ has been determined from the production rate of water at relatively small heliocentric distances on the assumption that water snow, the dominant component of cometary snows, controls the vaporization process at the nuclear surface. The vaporization cross section therefore also depends on the latent heat of vaporization of H_2O and on the intensity of the impinging solar energy. In their approach, however, it does not depend on the emissivity of the cometary nucleus for reradiation, because Delsemme and Rud have assumed that the radiative term of the steady-state equation can be neglected at the heliocentric distances under consideration ($\lesssim$ 0.8 a.u.). The photometric cross section A_sS has been established from Roemer's nuclear magnitudes (reduced to unit heliocentric and geocentric distances) and from a carefully discussed relation among the Bond albedo, the geometric albedo, and the phase law of the nucleus. Delsemme and Rud have thus obtained two equations, which can readily be solved for A_s and S:

$$
\begin{aligned}
(1 - A_s)S &= c_1 \quad , \\
A_sS &= c_2 \quad .
\end{aligned}
\tag{10}
$$

Taking into account the systematic bias in the nuclear magnitudes of comets (Section II) and the generally not negligible contribution from E_{rad} (Section III), we can now modify Delsemme and Rud's formulas (10) as follows:

$$\pi\kappa R^2 = c_1 \left(1 + \frac{E_{rad}}{E_{vap}}\right) ,$$

$$\pi(1 - \kappa) R^2 = c_2 \times 10^{-0.4\Delta m} , \qquad (11)$$

where $R = (S/\pi)^{1/2}$ is the effective radius of the solid cometary nucleus, $\kappa = 1 - A_s$ (by definition), and $\Delta m > 0$ is the bias or contamination factor (in magnitudes) giving the difference between the actual magnitude of the nucleus and the nuclear magnitude by Roemer. We note that the E_{rad}/E_{vap} term produces an increase in both the nuclear radius R and the absorptivity κ (and, hence, a decrease in A_s), whereas the Δm factor implies an increase in κ but a decrease in R. We also remark that equation (11) contains four unknowns, κ (or A_s), R (or S), E_{rad}/E_{vap} (or, if a rotation model is specified, the emissivity ϵ, or the Bond albedo A_r, for reradiation), and Δm.

V. COMET BENNETT 1970 II

From a careful analysis of OAO-2 spectrometric and photometric observations of Comet Bennett, Keller and Lillie (1974) have recently concluded that the production rates of hydroxyl and atomic hydrogen are indeed consistent with the assumption that water controls the gas output at heliocentric distances ~1 a.u. They have also derived a production rate of water vapor from the nucleus of Comet Bennett of $(2.9 \pm 1.2) \times 10^{29}$ molecules s^{-1} at 1 a.u. and a variation in the production rate proportional to an inverse 2.3 ± 0.3 power of heliocentric distance between 0.77 and 1.26 a.u.

The new production rate compares very favorably with Delsemme and Rud's (1973) value of 4.4×10^{29} molecules s^{-1} at 0.8 a.u. from the sun, which was based on several investigations of hydrogen production only. At the same heliocentric distance, Keller and Lillie's determination gives 4.8×10^{29} with the $r^{-2.3}$ law and 4.5×10^{29} with the r^{-2} law used by Delsemme and Rud. The $r^{-2.3\pm0.3}$ law implies that $E_{rad}/E_{vap} = 0.17$ [see eq. (4)] with a lower limit of 0.0 and an upper limit of 0.35. Equations (11) now contain three unknowns and can be solved for κ and R with the bias factor as a parameter.

We have retained c_2, determined by Delsemme and Rud with the Lambert phase law, and used Keller and Lillie's results to derive the average value of $\pi\kappa R^2 = 19.3$ km^2, as well as its limits, 9.7 km^2 (for $E_{rad}/E_{vap} = 0$ and H_2O production of 1.7×10^{29} molecules s^{-1} at 1 a.u.) and 31.5 km^2 ($E_{rad}/E_{vap} = 0.35$ and H_2O production of 4.1×10^{29}). The dependence of the solution of equations (11) on Δm is exhibited in Fig. 3. The two corrections to κR^2 suggested by Delsemme and Rud have not been applied here, since they are rather uncertain and do not alter the results significantly. We note, however, that in their sum, they would tend to decrease both R and κ somewhat. [The corrections are, respectively, due to evaporation of volatile substances adsorbed on water snow (which increases c_1) and to the fact that water can be transported away from the nucleus not only by evaporation but also in the form of icy grains (which decreases c_1).]

Figure 3 also compares the solution of equations (11) with Delsemme and Rud's results and with the nuclear size derived by Sekanina and Miller (1973) from the photometric study of the type II tail of Comet Bennett.

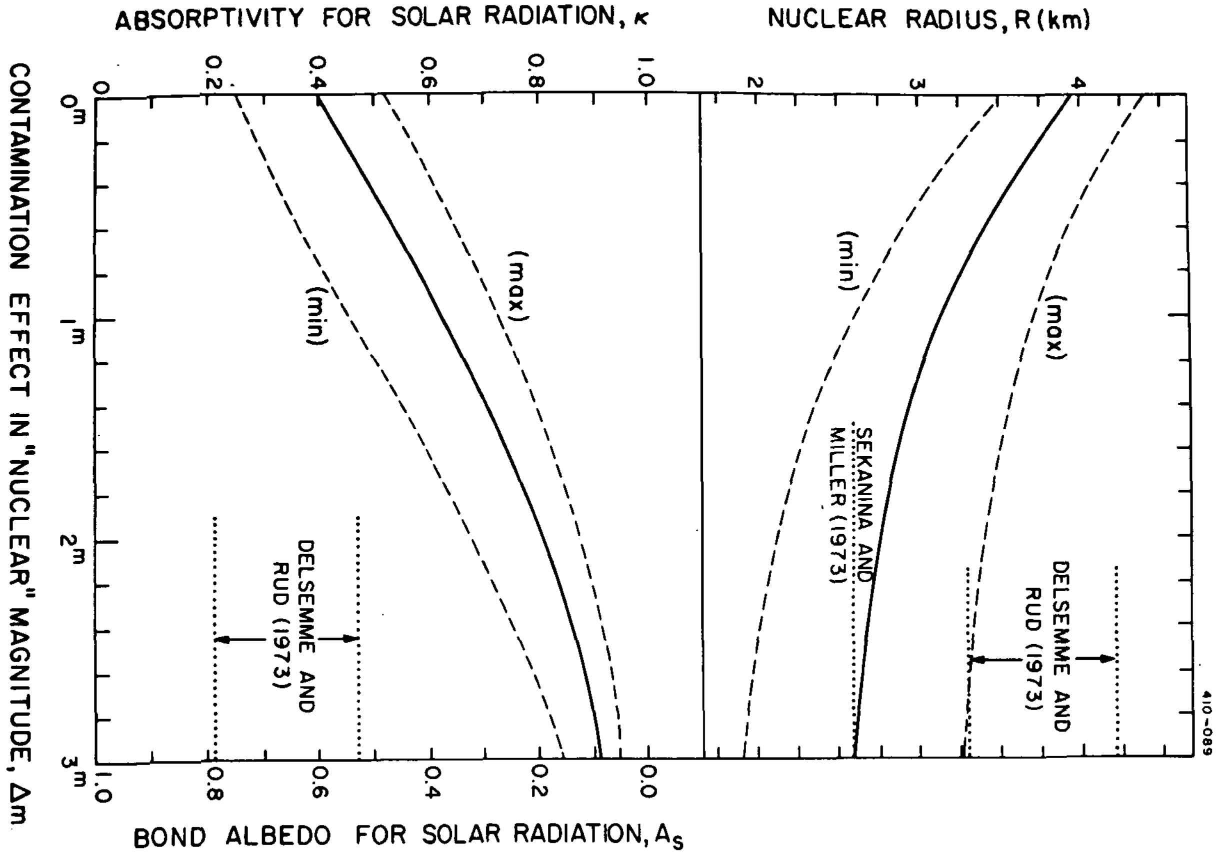

Fig. 3. Comet Bennett 1970 II. Nuclear radius (top) and surface absorptivity and Bond albedo for solar radiation (bottom) versus the contamination effect in the nuclear magnitude Δm (i.e., the difference between the magnitude of the actual nucleus and the observed nuclear magnitude). The dashed curves give the upper and lower limits. The results by Delsemme and Rud (1973) and by Sekanina and Miller (1973) are shown for comparison.

The high albedo A_s, deduced by Delsemme and Rud, appears to be incompatible with Whipple's (1950) "dirty-snowball" model of the cometary nucleus in general and with the high contents of dust observed in Comet Bennett in particular. It came as a surprise even to the authors themselves. And Keller and Lillie (1974) comment that their results would be more consistent with a lower albedo and that Delsemme and Rud may have underestimated the effect of dust.

While this controversy may lead to other interpretations in the future, once production rates of water are known for a greater number of comets, the present discussion of equations (11) indicates that in the case of Comet Bennett, we can bring A_s from over 0.6 down to 0.1 or 0.2 if we accept that the brightness of the actual solid nucleus is some 2 to 3 magnitudes below the level measured by Roemer's nuclear magnitudes. At the same time, allowance for this effect also cuts the nuclear radius from nearly 4 km down to less than 3 km and thus brings it into considerably better agreement with the Sekanina-Miller determination. We note that this determination implies an H_2O production rate, which, according to Keller and Lillie, is in excellent agreement with the OAO observations.

The possibility of a 2- to 3-magnitude bias in Roemer's nuclear magnitudes cannot, in general, be excluded in light of the results of Section II. To be more specific, we list in Table II the nuclear magnitudes of Comet Bennett. The last three entries, used by Delsemme and Rud to calculate A_sS, are indeed very consistent with the inverse square law of light reflection. So is, however – at least when the Lambert phase law is applied – the first entry, which is affected by a significant contribution from the coma. This appears to remind us of Van Biesbroeck's observational series of Comet Stearns (Fig. 2).

Table II
"Nuclear" magnitudes of Comet Bennett 1970 II (postperihelion observations by Roemer; see Marsden 1971, 1972a).

Date	Distance from Sun (a.u.)	Phase Angle	Nuclear Magnitude* No phase effect	Lambert phase law	Moon's phase law	Description
1970 June 1	1.6	29°	12.5	12.4	11.7	not clear photometric resolution from coma
July 2	2.0	23	12.0	11.9	11.4	central condensation embedded in coma
July 27	2.4	22	11.8	11.7	11.2	sharply condensed
Sept. 26	3.2	18	12.6	12.5	12.1	rather sharp, faint coma
Nov. 25	3.9	14	12.5	12.5	12.2	sharp, nearly stellar, trace of coma
1971 Jan. 20	4.5	13	12.4	12.4	12.1	well condensed, possibly trace of coma

*Reduced to unit heliocentric and geocentric distances by the inverse-square power law.

The Lambert phase law is probably a more realistic approximation than is the moon's phase law even for a dust-rich surface of an icy-conglomerate nucleus. Nevertheless, we point out that because the moon's law would imply a lower c_2 in equations (11), its effect would be identical with that of an additional Δm correction: Compared to the figures resulting from the Lambert law, the nuclear size would go down, whereas absorptivity κ would go up (and, hence, A_s down).

All the above considerations are independent of the adopted model of nuclear rotation. The emissivity of the nucleus for reradiation could be calculated only if the nuclear spin were known. For two adopted models, the rapidly rotating nucleus and the nonrotating nucleus, the emissivity ϵ is plotted versus Δm in Fig. 4. It turns out that ϵ is almost completely indeterminate, mainly because E_{rad} is very poorly known. (Note that $E_{rad} = 0$ is equivalent to $\epsilon = 0$.)

Comet Tago-Sato-Kosaka 1969 IX, also studied by Delsemme and Rud, has not been included here. The production rate of water for this comet has been assessed from the number density of OH, which itself is only an order-of-magnitude estimate (Code 1971). We therefore feel that $(1 - A_s)S$ is not known sufficiently well to justify the type of study explored in the case of Comet Bennett. It seems, however, that the law of variation in H_2O production with heliocentric distance, $r^{-2.9\pm0.2}$, may be reasonably well established for Comet Tago-Sato-Kosaka from the relative OH densities (Delsemme 1973). Then the ratio E_{rad}/E_{vap} near 0.9 a.u. from the sun comes out to be as high as 0.54 ± 0.12, which restricts the absorptivity for solar radiation to $\kappa \lesssim 0.6$ for a rapidly rotating nucleus ($A_s \gtrsim 0.4$) and to $\kappa \lesssim 0.3$ for a nonrotating nucleus ($A_s \gtrsim 0.7$). It also implies that emissivity ϵ must be near unity ($A_r \simeq 0$).

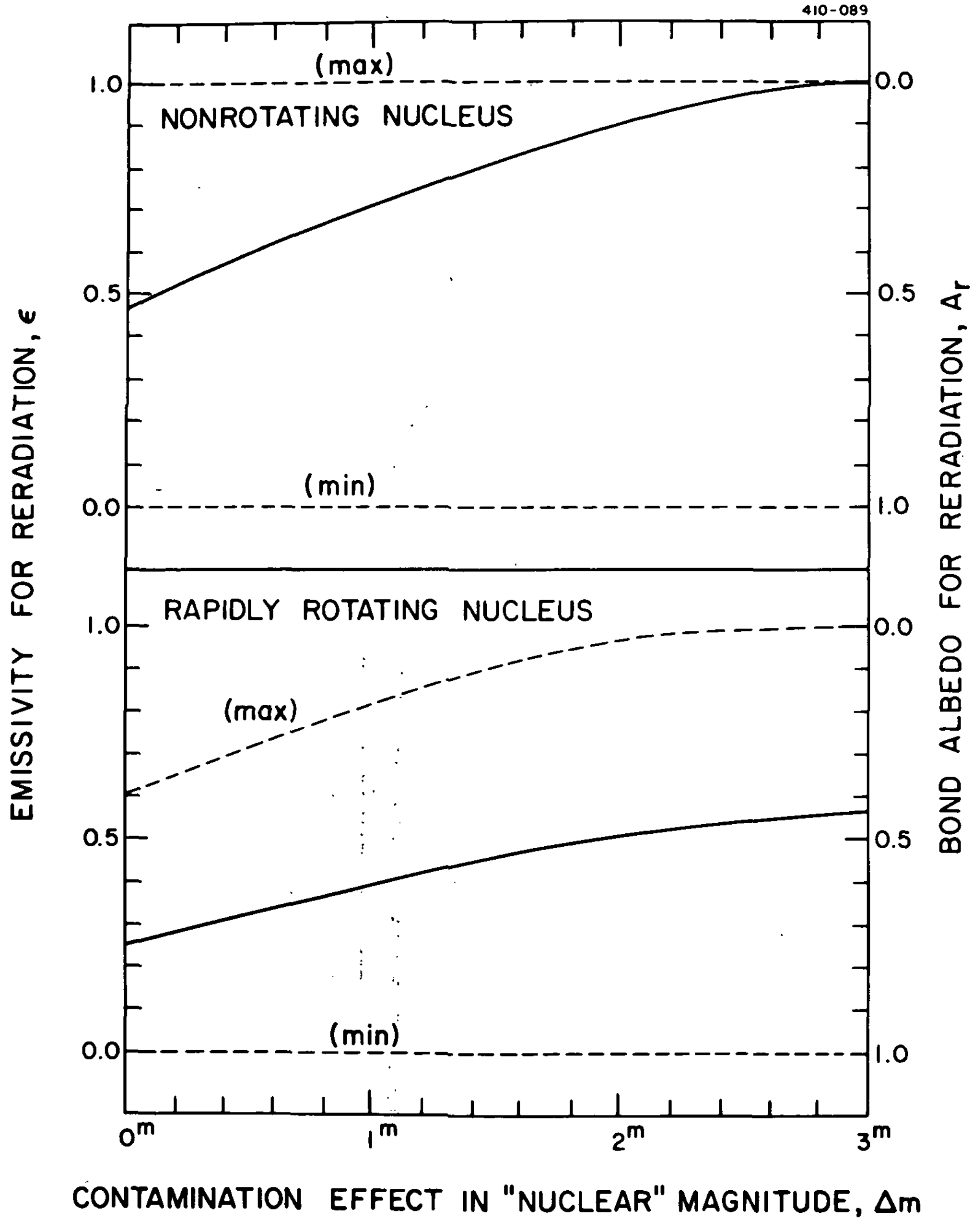

Fig. 4. Comet Bennett 1970 II. The surface emissivity and Bond albedo for reradiation from the nucleus versus the contamination effect in the nuclear magnitude Δm, on the assumption of a nonrotating nucleus (top) and a rapidly rotating nucleus (bottom). The probable upper and lower limits (dashed curves) indicate that the emissivity is, in either case, virtually entirely indeterminate.

Table III lists the nuclear magnitudes of Comet Tago-Sato-Kosaka reported by Roemer. When the Lambert phase law is applied, the observations suggest that the brightness of the nuclear condensation varies more slowly with heliocentric distance than required by the law of reflection. The last two entries, used by Delsemme and Rud to compute $A_s S$, are $0\overset{m}{.}6$ brighter than the first entry, which corresponds to 1.1 a.u. from the sun.

VI. ACTIVITY OF SHORT-PERIOD COMETS AT LARGE HELIOCENTRIC DISTANCES

Uncritical identification of the actual brightness of a solid cometary nucleus with nuclear magnitude can cause a severe misinterpretation of the evolution of short-period comets.

Kresák (1973) recently proposed a classification for nuclei of short-period comets, relying heavily on two basic models I recently formulated (Sekanina 1969, 1971, 1972a). The two, a core-mantle model and a coreless one, were postulated in order to interpret physically the systematic long-term variations in the magnitude of the nongravitational effects, which were established for a number of short-period comets by Marsden and his collaborators (for an updated table of nongravitational parameters, see Marsden et al. 1973).

Kresák found evidence that the nuclei of periodic comets captured by Jupiter from orbits well beyond 3 a.u. fade appreciably during a few revolutions after capture; he concluded that the fading is due to a decrease in the nuclear albedo and is associated

Table III

"Nuclear" magnitudes of Comet Tago-Sato-Kosaka 1969 IX (postperihelion observations by Roemer; see Marsden 1971).

Date	Distance from Sun (a.u.)	Phase Angle	Nuclear Magnitude*			Description
			No phase effect	Lambert phase law	Moon's phase law	
1970 Feb. 3	1.1	69°	15.0	14.3	13.1	condensed
Feb. 13	1.3	52	15.4 pv	15.0 pv	14.0 pv	well condensed
Mar. 7	1.6	37	14.3	14.1	13.3	nearly stellar
Apr. 6	2.1	26	13.8	13.7	13.1	sharply condensed, but not stellar
May 4	2.5	19	13.8	13.7	13.3	small, sharply condensed

*Reduced to unit heliocentric and geocentric distances by the inverse-square power law.

with the rapid removal of a thin envelope of high-reflectivity icy grains covering the massive core of dark meteoric material.

We point out that this hypothesis strongly contradicts the dynamical evidence based on a study of the nongravitational effects. P/Brooks 2, the most outstanding case in Kresák's Fig. 5 (showing a fading parameter), leads the population of short-period comets sorted by the magnitude of the nongravitational effects (see Table I of Marsden et al. 1973). Its mass loss inferred from the dynamical results comes out so very large that only the direct surface evaporation of the comet's snows – the most effective mechanism of gas production – gives theoretical mass-loss rates at least moderately consistent with the well-established observational data. A nucleus with the icy mantle just removed, such as Kresák suggested for P/Brooks 2 and similar comets, cannot supply the required production of gas, because a substantial portion of the solar radiation absorbed by the nucleus should be spent on heating the surface-insulating layer of meteoric material before any evaporation could commence. And even then, the production of gas, which would have to proceed by diffusion through the porous matrix, would barely be able to exert any detectable nongravitational effect at distances near or beyond 2 a.u.

The above reasoning also applies to P/Schwassmann-Wachmann 2, which Kresák does not classify as a recent incomer on account of Belyaev's (1967) orbital calculations suggesting that this comet was around before 1735. Marsden (1966, 1973a) does not, however, find any substantial changes in the comet's motion for at least 2 1/2 centuries before its capture in 1926. It appears, therefore, that no definite conclusion can be reached about the comet's orbital history by running its motion so long into the past.

The contradiction between the photometric and the dynamical lines of evidence, which makes Kresák's interpretation totally unacceptable, can be readily removed when the brightness data he gathered on short-period comets at large heliocentric distances are not referred to the solid nucleus. This possibility is strengthened by a rather striking resemblance between the observed fading of the recently captured short-period comets and that of the new comets. However, since a "new" short-period comet of the P/Brooks 2 type must have moved in orbits with perihelia between 3 and 6 a.u. for a rather extensive period of time in the past, it should have lost virtually all the highly volatile substances (e.g., carbon monoxide or methane) from its outer layer a long time ago. However, such a comet may have retained some supplies of moderately or subnormally volatile materials (with latent heat of vaporization in excess of, say, 6000 to 8000 cal mole^{-1} but below water snow's 11000 cal mole^{-1}), which thus were "enriching" the surface mixture dominated presumably by water snow. After the comet's capture by Jupiter into an orbit of smaller perihelion distance ($q < 3$ a.u.), appreciable amounts of the "enriching" components should start evaporating from the nucleus along with, for the first time, water snow. Stimulated by the evaporating gases, a rather bright icy-grain halo should develop at larger heliocentric distances during the first revolutions in the new, short-period orbit. The halo must rapidly subside at smaller distances from the sun, since the vaporization lifetime of icy grains there drops drastically (Delsemme and Miller 1971; Sekanina 1973).

In the particular case of P/Brooks 2, the observed effect may have been enhanced by the comet's splitting shortly before its discovery, whereby extensive areas of the nuclear interior, potentially rich in highly volatile substances, might have added dramatically to the total momentum of the escaping gas and thus to the extent and brightness of the halo.

Since high vaporization rates point to large nongravitational forces, and since the progressive depletion of the more volatile components of the snow mixture implies, in addition to the gradual subsidence in the brightness and extension of the halo, a progressive decrease in the nongravitational effects in the motion of such a "new" short-period comet during the revolutions just after the capture, the presented interpretation explains, at least qualitatively, the dynamical behavior of such a comet, along with its photometric behavior.

The vaporization curve (vaporization flux versus heliocentric distance) of the "enriched" mixture should differ from that of water snow (unless the latter controls the mixture, as in the case of solid hydrates). Since the variation in the nongravitational forces in the motions of P/Brooks 2 and P/Schwassmann-Wachmann 2 has been found essentially consistent with the vaporization law of water snow (Marsden et al. 1973), yet another interpretation may exist. The alternative is based on the premise that dirty snow should evaporate more rapidly than pure snow of the same chemical composition, simply because the impurities of dark meteoric material would lower the effective surface reflectivity and thus increase the absorbing power of the nucleus for solar radiation (Marsden et al. 1973). If most fine dust is essentially confined to a narrow outer layer of the nucleus, the surface reflectivity should increase when the layer is removed by evaporation, and the vaporization flux should drop accordingly. Note that this mechanism implies a less conspicuous halo at large distances from the sun than did the enriched-mixture model, which could account for the absence of the initial peak in the extreme distance of P/Schwassmann-Wachmann 2 in Kresák's Fig. 5. In conjunction with the high observed level of the nongravitational effects, this mechanism also implies a distinctly smaller size of the cometary nucleus. In any case,

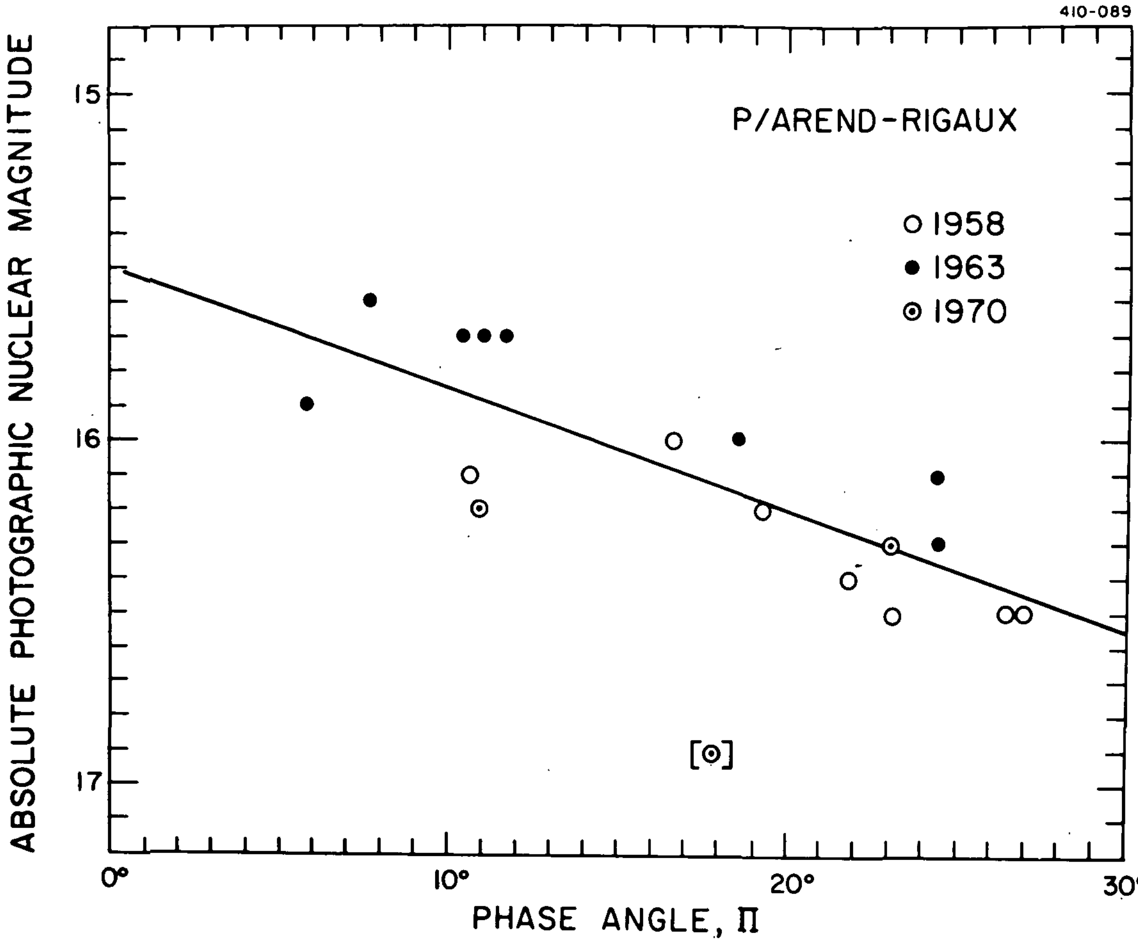

Fig. 5. Phase effect in the absolute brightness of P/Arend-Rigaux. Magnitude estimates of the stellar image of the comet were made by Roemer and reduced here to unit heliocentric and geocentric distances by using the standard inverse-square power law. In 1958, the observations were made after perihelion, and in 1963 and 1970, before perihelion. The solid line is the least-squares fit $15\overset{m}{.}50 + 0\overset{m}{.}035\Pi$. The bracketed observation, inconsistent with the fit (and not included in the solution), is the 1970 recovery observation.

however, either version fits the observed behavior of the new incomers to the short-period comets considerably better than does the interpretation based on albedo variations.

The nuclear sizes derived by Kresák (1973) and listed in his Table II must be considered totally incorrect, because of his misinterpretation of the nuclear magnitudes and also since, judging from his figures, he mistakenly used the Bond albedo instead of the geometric albedo in his photometric formula for the nuclear radius (the intended kind of albedo is not specified in the paper).

VII. P/AREND-RIGAUX AND P/NEUJMIN 1. PHASE EFFECT IN THE BRIGHTNESS OF A COMETARY NUCLEUS

Marsden (1968, 1969) called attention to two short-period comets whose motions appear to be completely free from nongravitational effects: P/Arend-Rigaux and P/Neujmin 1. He pointed out that the two are usually entirely stellar in appearance and that they are strong candidates for a type of objects that are presumably in transition from comet to asteroid.

P/Arend-Rigaux was systematically observed by Roemer at its three most recent apparitions (Roemer 1965; Roemer and Lloyd 1966; Marsden 1971). The comet was virtually always perfectly stellar. Its brightness is known to follow closely the inverse-square power law and to show a well-pronounced asteroidal-type phase effect (Marsden 1973a). My least-squares solution, based on 17 observations by Roemer in the range of phase angles from 6° to 27° (Fig. 5), gives a value of $15\overset{m}{.}50 \pm 0\overset{m}{.}12$ for the opposition photographic magnitude of the comet, reduced to 1 a.u. from the sun and 1 a.u. from the earth. The phase term can be written in the form $B\Pi$, where Π is the phase angle in degrees and $B = +0\overset{m}{.}035 \pm 0\overset{m}{.}006$. The mean residual is $\pm 0\overset{m}{.}18$, and the phase curve is symmetrical with respect to perihelion. Only the 1970 recovery observation fails to fit the phase law, being $0\overset{m}{.}8$ too faint. Understandably, no opposition effect can be detected in Fig. 5; in the light curves of most asteroids, the opposition effect does not show up at phase angles exceeding 5° even when high-sensitive photoelectric techniques are used.

We conclude that considerable evidence supports the view that the nucleus of P/Arend-Rigaux has actually been detected, which indicates that the nuclei of defunct or almost defunct comets can be photographically resolved. The above photometric data suggest that the nucleus of P/Arend-Rigaux is about 2 km in radius if its geometric albedo is assumed to be near 0.1.

P/Neujmin 1 was not observed by Roemer. However, during its discovery apparition in 1913, the comet was observed extensively and a search in the literature has revealed fine sets of visual-magnitude estimates obtained by three of the most experienced observers of that time (Barnard 1915; Graff 1914; Van Biesbroeck 1914). In September 1913, the comet was consistently reported to display very slight traces of a coma and/or a tail "attached" to a stellar nucleus (see, e.g., Barnard 1914b); later, the comet was perfectly stellar (Barnard 1915). However, occasional fluctuations in the brightness of the nucleus were noticed in September and October (Banachiewicz 1914; Graff 1914). The brightness estimates of the nucleus reduced with the inverse-square power law show a rather large scatter in September. In its "quiescent" phase, the brightness of the comet's nucleus follows the inverse-square power law closely and shows phase variations similar to those experienced by P/Arend-Rigaux (Fig. 6).

In 1931, P/Neujmin 1 was perfectly stellar, and a series of photographic magnitudes by Van Biesbroeck (1933) suggests a phase effect virtually identical with the one established from the 1913 observations. In 1948 and 1966, the comet was poorly observed. Van Biesbroeck (1950) secured a few plates at Yerkes and McDonald on which the comet's image was not quite stellar. The magnitude derived from the 1948 Yerkes plates, made with the same telescope as in 1931, is perfectly consistent with the 1931 phase curve, whereas the magnitudes from 1948 McDonald plates and from two of Pereyra's (1966) plates exposed during the comet's next return (stellar images) are only fairly consistent with the curve. Four more plates were obtained in a 10-day span at Boyden Observatory in 1966 (Andrews 1966). They show the comet diffuse, yet generally fainter than the above photographic observations would indicate (three of them would cluster at $\Pi = 9°$, absolute magnitude $13\overset{m}{.}5$ in Fig. 6; the fourth is 1 magnitude brighter and would fit the curve within $0\overset{m}{.}1$).

Least-squares solutions to the linear phase law, $A + B\Pi$, forced through the sets of magnitude estimates of Fig. 6, have given, respectively, the following values for the opposition magnitude A, reduced to unit heliocentric and geocentric distances, and the phase coefficient B (mag per degree): $11\overset{m}{.}42 \pm 0\overset{m}{.}12$, $+0.032 \pm 0.006$ (Barnard's visual magnitudes in 1913); $11\overset{m}{.}84 \pm 0\overset{m}{.}12$, $+0.027 \pm 0.008$ (Van Biesbroeck, visual, 1913); $12\overset{m}{.}16 \pm 0\overset{m}{.}14$, $+0.055 \pm 0.019$ (Graff, visual, 1913; B very uncertain because of a small range in Π); and $12\overset{m}{.}52 \pm 0\overset{m}{.}18$, $+0.034 \pm 0.013$ (Van Biesbroeck, photographic, 1931). The mean residuals ranged from $\pm 0\overset{m}{.}11$ to $\pm 0\overset{m}{.}18$. While the

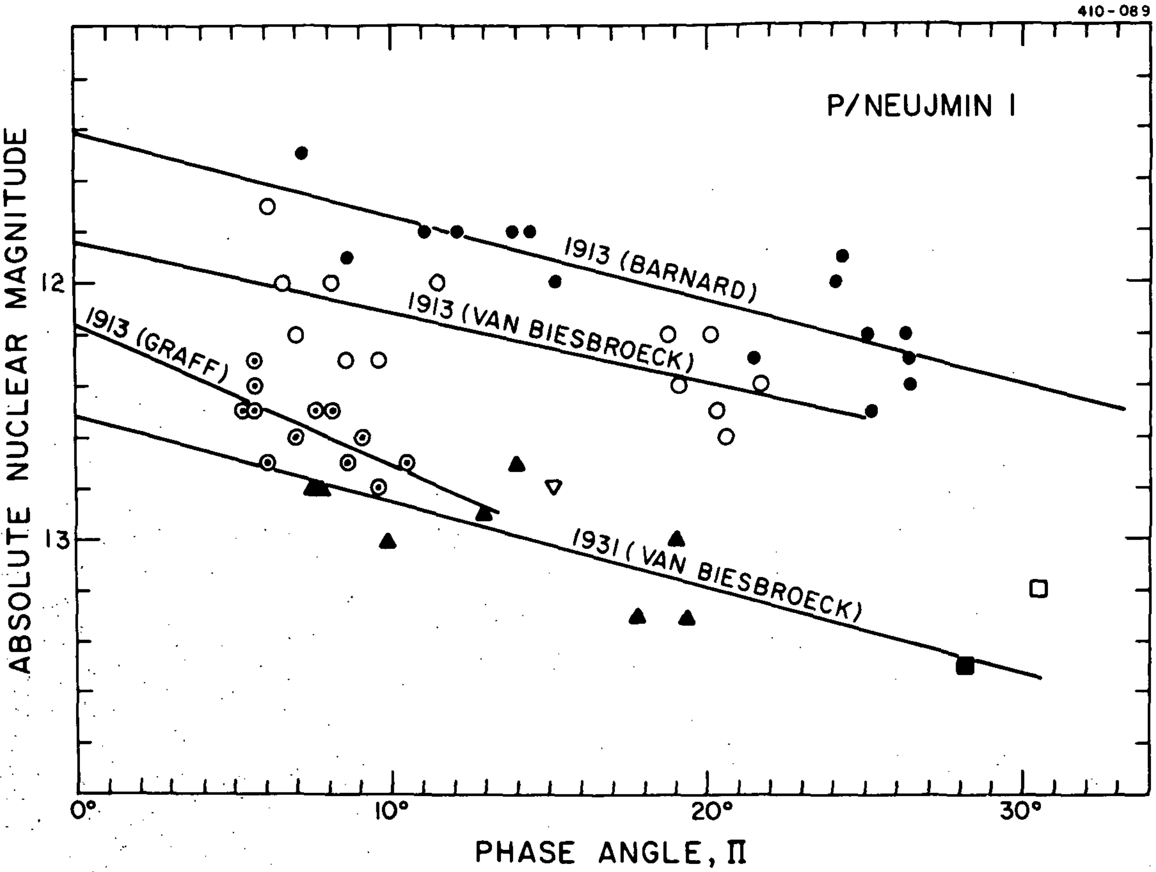

Fig. 6. Phase effect in the absolute (cf. caption to Fig. 5) brightness of P/Neujmin 1. Visual-magnitude estimates of the comet in its "quiescent" phase in 1913 come from Barnard (solid circles), Van Biesbroeck (open circles), and Graff (circled dots). Photographic magnitudes plotted were obtained by Van Biesbroeck with the 24-inch reflector of the Yerkes Observatory in 1931 (solid triangles), and with the 82-inch reflector of the McDonald Observatory (open square) and the 24-inch (solid square) in 1948, and by Pereyra with the 60-inch reflector at Bosque Alegre, Argentina, in 1966 (open triangle). The straight lines are the least-squares fits of the linear phase law forced through the sets of data. The 1913 and 1931 observations were made after perihelion, and the 1948 and 1966 ones, before perihelion.

discrepancies in the zero point among the three observers in 1913 apparently reflect the differences in their photometric scales, the discrepancy between the 1913 (visual) and the later (photographic) observations must, by and large, be due to the color index of the comet.

Analyzing Barnard's and his own 1913 magnitude estimates of P/Neujmin 1, Van Biesbroeck (1930b) did not consider the phase effect and concluded that the brightness of the comet varied in proportion to r^{-5}. However, his 1931 photographic magnitudes show practically no dependence on heliocentric distance when the phase effect is neglected (Fig. 7). This is so because in 1913 the comet, while receding from the sun, was moving away from opposition over most of the period of observation, whereas in 1931 it was moving toward opposition. Thus, the phase effect accelerated the comet's fading in 1913 but offset it in 1931. This peculiar coincidence of circumstances demonstrates the intricacy encountered when an attempt is made to interpret a comet's light curve.

VIII. PERIODIC COMET ENCKE

I suggested (Sekanina 1969, 1972a) that the long-term decrease in the magnitude of the nongravitational effects in the motion of P/Encke can be interpreted as an indication of the comet's progressive deactivation but not of its disintegration, and I predicted that the comet should eventually become asteroidal in appearance. Thus, P/Encke is perhaps currently evolving through a phase that might have been experienced in the past by P/Arend-Rigaux and P/Neujmin 1.

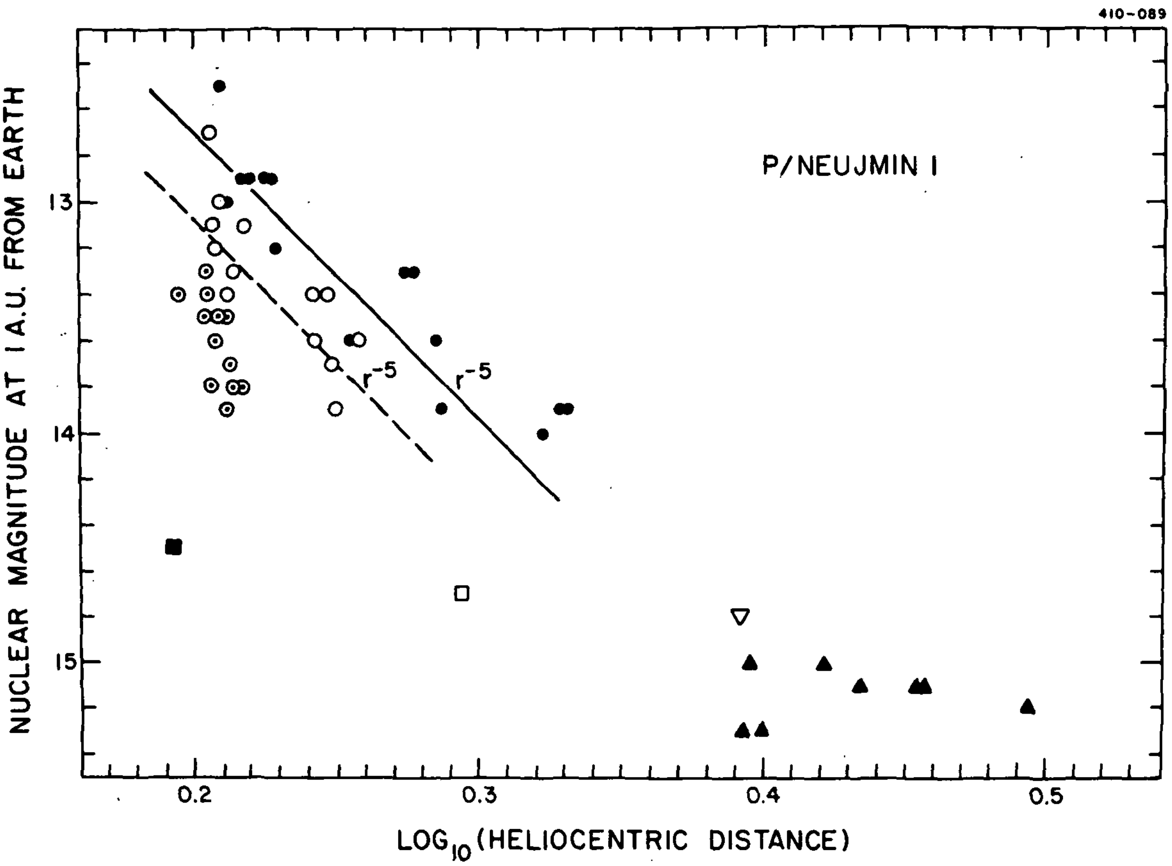

Fig. 7. Phase effect in the magnitudes of P/Neujmin 1 misinterpreted as a variation with heliocentric distance. Observations are the same as those in Fig. 6. Note the fictitious strong ($\sim r^{-5}$) brightness dependence in 1913 (comet receded from the sun and from opposition), as opposed to the equally fictitious brightness independent of heliocentric distance in 1931 (comet receded from the sun but approached opposition). The solid and dashed lines, respectively, are Van Biesbroeck's (1930b) formal fits (ignoring the phase effect) to Barnard's and his own 1913 magnitude estimates.

The deactivation hypothesis is strongly supported by the very low production rate of atomic hydrogen, established for P/Encke by Bertaux et al. (1973) from the OGO-5 observations of the comet's Lyman-alpha emission. Indeed, Delsemme and Rud (1973) concluded that the observed production rate rules out a possibility that water snow could cover the whole surface of the nucleus (or even its significant fraction) and at the same time control the production rate of hydrogen. However, Delsemme and Rud's conclusion depends on Roemer's nuclear magnitude of P/Encke near its aphelion in 1972. We have collected and plotted in Fig. 8 all Roemer's 1957-1974 observations of the comet (Roemer 1965; Roemer and Lloyd 1966; Marsden 1971, 1972a, 1973b, 1974a, b). Although some indication for a phase effect might be present, Fig. 8 does not allow any straightforward conclusion on the character of the phase law or on the brightness of the actual solid nucleus. However, unlike P/Arend-Rigaux, P/Encke seems to be generally fainter after perihelion. On the other hand, it was unusually bright when photographed near the 1972 aphelion.

It is most doubtful that a major part of the scatter in the nuclear brightness of the comet is due to changes in the reflectivity of the nuclear surface. The amplitude of the scatter, about 3 magnitudes, would imply variations in the geometrical albedo of 16:1. Very dark surfaces of the Martian satellites have a geometric albedo of about 0.05 (Masursky et al. 1972). On the other hand, Veverka (1973) concluded that the most probable geometric albedo of a smooth snow-covered object is 0.45 ± 0.1, but he added that large-scale surface roughness would tend to increase it somewhat. Indeed, the (visual) geometric albedo of Europa, the most richly water-frost-covered Galilean satellite (Pilcher et al. 1972), is now believed to be 0.68 (Jones and Morrison 1974). The two values, 0.05 and 0.68, are likely to approximate well the two limits

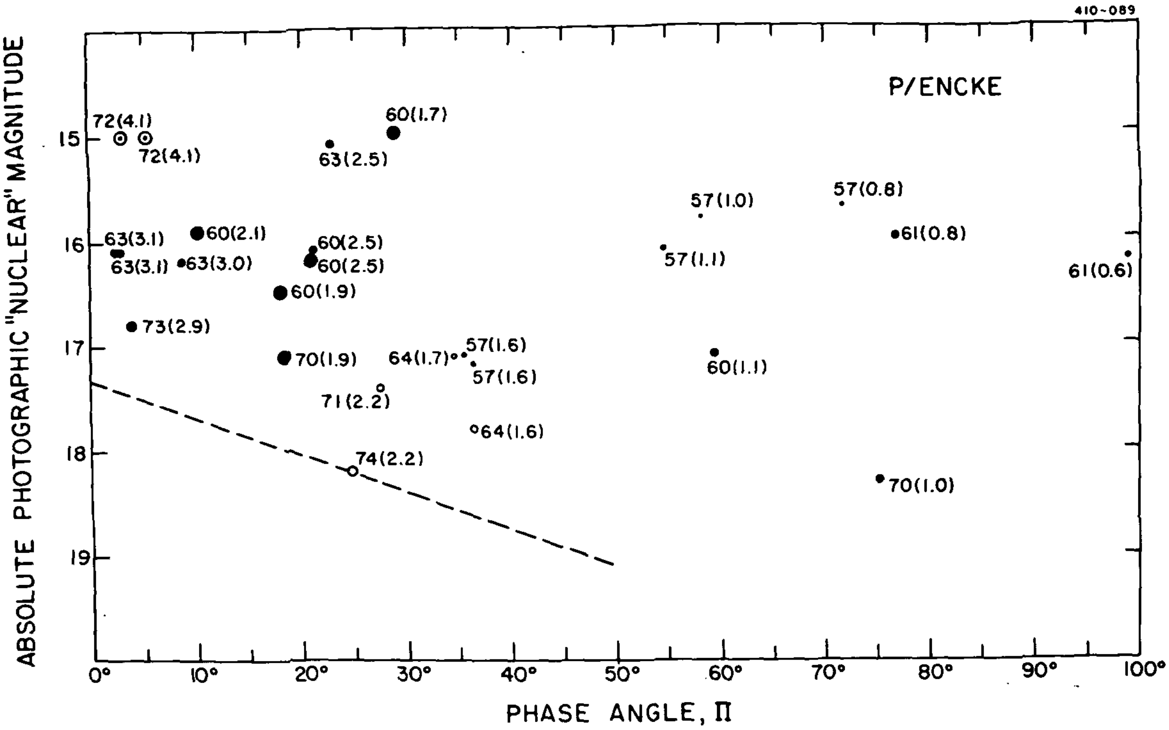

Fig. 8. Roemer's photographic "nuclear" magnitudes of P/Encke, reduced to unit heliocentric and geocentric distances by the inverse-square power law, versus phase angle Π. The size of the circles describes the comet's appearance: The largest ones refer to stellar images, and the smallest, to diffuse images. Solid circles – preperihelion observations; open circles – postperihelion; circled dots – near-aphelion. All postperihelion images were reported by Roemer to be weak. Each entry in the figure is further defined by the year of observation and the heliocentric distance in a.u. (in parentheses). For reference, the phase law established for P/Arend-Rigaux ($B = 0\overset{m}{.}035$ per degree) is plotted to fit the faintest brightness estimate.

for the geometric albedo of small bodies in the solar system. Their ratio gives a magnitude difference of $2\overset{m}{.}8$, matching almost exactly the magnitude amplitude of P/Encke. Naturally, it is most unlikely that the reflectivity of a single object, such as the nucleus of P/Encke, would periodically (once in 3.3 years) vary from one known extreme limit to the other. Consequently, the variations in the size and optical thickness of the icy-grain halo surrounding the nucleus must contribute significantly to the observed scatter.

If, on the other hand, we assume for the moment that the scatter is entirely due to the icy-grain halo, the whole surface of P/Encke should be covered by a snow mixture. Because of the very small nongravitational effects observed (Marsden and Sekanina 1974), such a snow mixture should be dominated and controlled by its least volatile component, i.e., presumably, water snow. In order that an unrealistically high Bond albedo ($\gtrsim 0.9$) be avoided, the comet's vaporization and photometric cross sections should be of the same order of magnitude. With water snow controlling the production rate of hydrogen, the photometric cross section should be about 0.1 km^2 and the comet's radius therefore about 250 m. The corresponding brightness of the nucleus would range between magnitude 18 and 19 (at 1 a.u.). Furthermore, this assumption leads to a relative mass loss of the comet of as much as about 10% per revolution, slightly increasing with time (and to the associated nongravitational effects also increasing somewhat with time). Such a high value of mass loss is difficult to reconcile with the small observed nongravitational effects, unless evaporation from the comet's surface is allowed to be almost perfectly isotropic [the anisotropy factor defined by Sekanina (1969) would barely reach 10^{-3}]. Since the nongravitational effects have been found to decrease with time ever since the 1820s (Marsden and Sekanina

1974), rather than to increase as required by the above assumption, we have to accept further that they are due to a process other than progressive deactivation; systematic motions of the rotation axis of the nucleus (Marsden 1972b; Sekanina 1972b) have so far been the only alternative explanations suggested. But any appreciable effect of this kind requires a fair degree of anisotropy in the vaporization process – which is contrary to the above statement. The well-known asymmetric shape of the comet's head also implies some degree of anisotropy.

We do not find it possible to invalidate the Delsemme-Rud conclusion as to the extent of water-snow cover on P/Encke, even when the unknown radiative term in the vaporization-radiation equilibrium, neglected by Delsemme and Rud, is roughly accounted for.

It appears that a combined effect of the icy-grain halo and reflectivity changes of the comet's surface – the latter associated with the variable extent of the snow cover – is the most acceptable solution to the problem of scatter in the nuclear magnitudes of P/Encke. A particular result of my unpublished calculations of heat- and mass-transfer phenomena in a disperse medium might be of interest in this context. The disperse medium was assumed to be a spherical body composed of a porous matrix of meteoric material with water snow uniformly embedded in it, filling 40% of the whole volume. The object was allowed to move around the sun in the orbit of P/Encke, and temperature and snow-concentration distributions within the object were then calculated as functions of time, starting from the equilibrium conditions at aphelion. The variations in the snow concentration at the surface and at two depths, exhibited in Fig. 9, show completely different patterns. Whereas the subsurface supply of snow decreases very smoothly

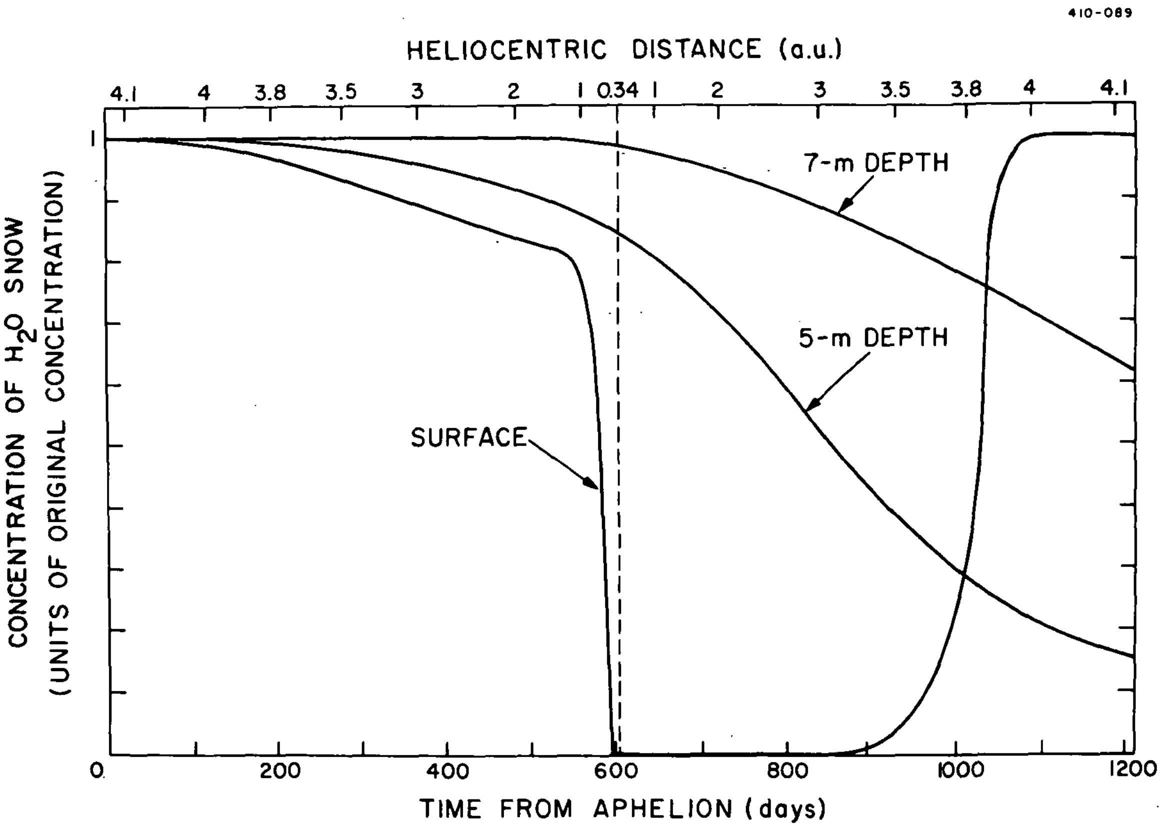

Fig. 9. Calculated mass transfer in a spherical body, moving in the orbit of P/Encke and composed of a porous matrix of meteoric material with water snow initially uniformly embedded: concentration of snow at the surface and at depths of 5 and 7 m as a function of the location in orbit (or of time from aphelion).

throughout the orbit, the surface concentration drops at an almost constant rate as the object approaches the sun until a distance of about 1 a.u. is reached. At that point, the rate of depletion of the surface reservoir starts increasing enormously; the depletion is virtually completed before perihelion. After perihelion, the surface remains practically snow-free until the object has receded to roughly 3 a.u. from the sun. Then, triggered both by temperature inversion (the surface is cooler than the underlying layers, thus facilitating recondensation of transferred vapor) and by a steep gradient in the concentration distribution of snow with depth, the replenishment mechanism restores the initial surface reservoir of snow even before aphelion.

As to the appearance of the object, it would be intrinsically bright near aphelion and on the incoming branch of the orbit because of the high reflectivity of the snow-covered surface and the presence of a small surrounding icy halo. At smaller distances ($\lesssim 1$ a.u.), the decreasing reflectivity of the surface, associated with a progressively diminishing extent of snow cover, is compensated by the increasing activity, so that the object would still look bright but more diffuse. When the surface supply of snow has been essentially depleted (around and after perihelion), the reflectivity will drop sharply (owing to the dark matrix exposed), the activity will cease, and the object will be at its faintest. With the gradual recovery of the snow supply on the surface, the brightness would increase again as the object approaches aphelion. We note that this rough qualitative description of the object's presumed photometric behavior bears a very definite resemblance to the observed appearance of the central condensation of P/Encke, as inferred from the brightness data of Fig. 8.

The described cycle in the object's evolution during one revolution around the sun is restricted only to its surface. The drop, in Fig. 9, in the snow supply beneath the surface by the time the revolution has been completed demonstrates the progressive overall deactivation process, which ultimately leads to the transition of an active comet into an asteroid (Section VII). While P/Encke is, of course, still a live comet, we feel that the available evidence is sufficient to conclude that this comet will inevitably approach the brink of the transition phase in the near future.

IX. FINAL REMARKS AND CONCLUSIONS

There is plenty of evidence that nearly parabolic comets are generally active at large heliocentric distances, where water-vapor pressure is negligibly low. The activity – particularly in the comets arriving from the Oort cloud – is conspicuously asymmetrical relative to perihelion. The substantial fading of nearly parabolic comets after their first passage near the sun, noticed by Oort (1950) from the distribution of "original" semimajor axes of cometary orbits and analyzed more quantitatively by Whipple (1962), is apparently an accumulated effect of the same process that causes the perihelion asymmetry. On an a priori assumption that the influx of new comets is a continuous process, Marsden and Sekanina (1973) have interpreted the fading of distant comets as being due to a rapid depletion of the most volatile substances during the first approach of the comets to the sun.

An important feature of the cometary activity at large heliocentric distances appears to be the formation of a rather dense cloud of presumably large icy grains that circulate in disarray and at very low velocities (lower than the velocity of escape from the comet?) in a circumnuclear space barely more than a few nuclear diameters across. To a terrestrial observer, such a cloud of particles may look essentially stellar, particularly if the space density inside the cloud drops rapidly in the radial direction.

This qualitative interpretation is basically consistent with the observational evidence and suggests that the photometric images of comets far from the sun are contaminated by ejecta much more extensively than has generally been accepted. Thus, the nuclear magnitudes of comets, even at great distances from the sun and when derived from photographs taken with large instruments, give only an upper limit to the size of the solid nucleus. Until Delsemme and Rud (1973) came up with their method of comparing the vaporization cross section of the nucleus with its photometric cross section, no way existed to estimate numerically the contamination effect (i.e., the difference between the magnitude of the solid nucleus and the observed nuclear magnitude), because the surface reflectivity could not be separated from its geometric cross section (Roemer 1966).

The discussion of the Delsemme-Rud method, modified to incorporate the contamination effect as well as the contribution of the radiative term in the vaporization-radiation equilibrium, suggests that in the case of Comet Bennett 1970 II, the nucleus was probably 2 or perhaps even 3 magnitudes fainter than Roemer's nuclear magnitudes. When this effect is taken into account, the Bond albedo of the nucleus of this very dusty comet drops from a suspiciously high value of 0.6 to 0.7 down to a very comforting 0.1 to 0.2, and the size of the nuclear radius decreases from 3.8 to 2.6 or 2.8 km, thus becoming perfectly consistent with an independent determination (Sekanina and Miller 1973).

The formation of a dense cloud of icy grains around the nucleus of Comet Kohoutek 1973f was most probably responsible for the comet's excessive brightness at large heliocentric distances on the preperihelion branch of the orbit, which in turn resulted in the exaggerated brightness predictions for the near-perihelion period. Although the preperihelion nuclear brightness of the comet varied essentially according to the inverse-square power law, and in spite of the comet's nearly stellar appearance, the nuclear brightness after perihelion dropped intrinsically by 3 magnitudes, which implies a physically unacceptable reduction factor of 4 in the nuclear diameter or 16 in the geometric albedo. A moderate geometric albedo of 0.4 would give a nuclear radius of 10 km before perihelion, but only 2.5 km after perihelion. The available data on the production rate of hydrogen (Carruthers et al. 1974; Opal et al. 1974; Traub and Carleton 1974) and hydroxyl (Blamont and Festou 1974; Feldman et al. 1974) are, unfortunately, not easy to interpret, because of an apparently strong perihelion asymmetry and doubts as to whether water was indeed the parent molecule of the two species. Very tentatively, a nuclear radius of some 1 to 3 km can perhaps be inferred.

Uncritical identification of the nuclear magnitudes with the actual brightness of a cometary nucleus can cause a severe misinterpretation of the evolution of the short-period comets. We find it impossible to accept Kresák's (1973) explanation of the rapid fading in the nuclear magnitude of a recently captured short-period comet (of the P/Brooks 2 type) as being due to a decrease in the reflectivity of its nucleus. Instead, attributing the nuclear magnitude to a circumnuclear icy halo, gradually subsiding in brightness during the first revolutions after capture, is clearly preferable, because this interpretation is compatible with the parallel dynamical evidence on the large but rather dramatically decreasing nongravitational effects in the motion.

While the nuclear magnitudes appear to refer generally to a circumnuclear cloud of grains rather than to the nucleus itself, there is little doubt that Roemer's nuclear magnitudes of P/Arend-Rigaux do indeed refer to the solid nucleus of the comet. They satisfy the inverse-square power law, are symmetrical relative to perihelion, and display an asteroidal-type phase effect; furthermore, the comet's appearance is nearly always perfectly stellar, and its motion is free from nongravitational effects. Except for occasional minor flareups, P/Neujmin 1 is the only other comet that also satisfies the above conditions. The two comets appear to be in a transition phase from comet to minor planet (Marsden 1968, 1969).

The rather peculiar behavior of P/Encke is believed to suggest that the extent of the snow cover on the surface of the nucleus varies with the comet's position in orbit. Most of the surface – if not the whole – appears to be snow covered around aphelion and along much of the incoming branch of the orbit, whereas the surface might essentially be rid of snow near perihelion and along a significant portion of the outgoing branch of the orbit. This process is considered to be indicative of the comet's advanced phase of deactivation.

Recent calculations on the motions of the short-period comets and the results discussed in Sections VI to VIII have clear implications for the classification of cometary nuclei. First, we are now positive that the magnitude of the observed non-gravitational effects (and the transverse component, in particular) does not vary straightforwardly in proportion to the relative rate of the loss of mass from the nucleus. Second, an appreciable fraction of the mass lost by a short-period comet during the first several revolutions after capture by Jupiter from a more distant orbit is apparently due to more volatile species than is the mass lost by "old" short-period comets. And third, we now have a very satisfactory correlation between the dynamical and the photometric characteristics of short-period comets at various phases of evolution.

We feel that the evidence for our classifying cometary nuclei into two basic types, described by the core-mantle and coreless (free-ice) models, respectively (Sekanina 1969, 1971, 1972a), has been strengthened by the recent progress. At the same time, the new results allow us to revise the plot, for the two models, of the mass-loss-related nongravitational effect in a comet's motion as a function of time (Fig. 1 of Sekanina 1971). The important change in the revised version (Fig. 10) is the addition of phase I, the early postcapture period, distinguished by a rather steep decrease in the nongravitational activity, as discussed in Section VI. The rest of the presumed evolution has been left virtually unchanged. Phase II, equivalent to phase E in Sekanina (1971), refers to the gradual evaporation of a thick icy envelope surrounding the meteoric matrix in the core of the nucleus. Whereas the coreless model continues to proceed in phase II until complete disintegration by evaporation, the core-mantle model starts a deactivation track (phase III) and ends up with complete depletion of the snow reservoir (phases V and VI). The precise character of evolution in the advanced phases, including the absolute rate of reduction of the nongravitational activity, might depend significantly on perihelion distance.

Obviously, the variations in the nongravitational effects in phases I and IV look very much alike, although they refer to two physically different mechanisms. Our present understanding of the nongravitational forces in short-period comets suggests

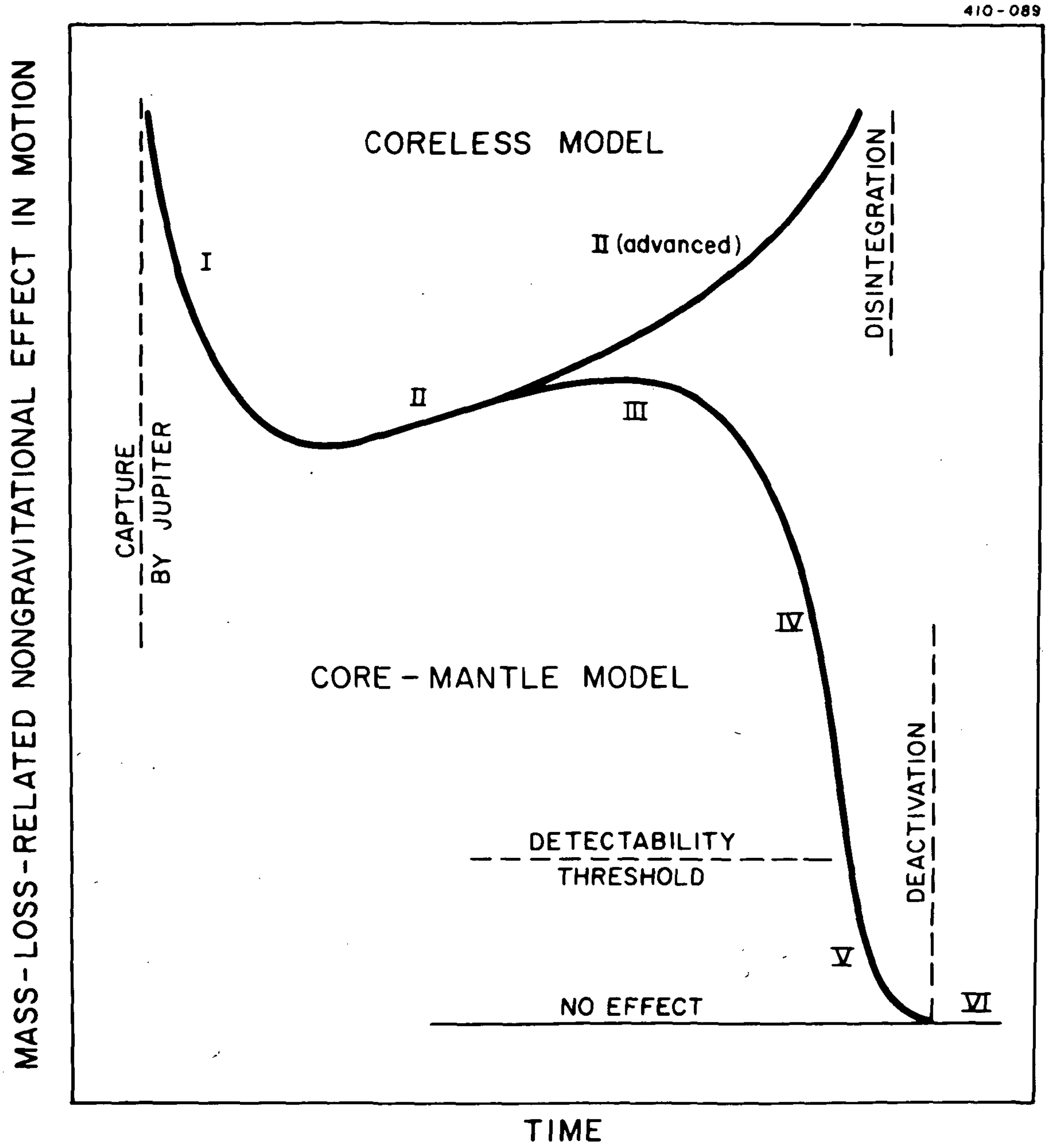

Fig. 10. Theoretical long-term variations in the magnitude of the mass-loss-related nongravitational effects on the motions of short-period comets with coreless and core-mantle nuclei.

the following probable locations in Fig. 10 of some of the well-studied comets: Phase I: P/Schwassmann-Wachmann 2, P/Brooks 2 (advanced?); Phase II: P/Borrelly, P/Tuttle; Phase II (advanced): P/Giacobini-Zinner?; Phase IV: P/Encke; and Phase V: P/Neujmin 1, P/Arend-Rigaux (advanced?).

In spite of all the progress in the physics of comets in recent years, the cometary nucleus still remains very much a mystery. Furthermore, there is little chance that observations from ground-based or even earth-orbiting stations could substantially improve our knowledge of the cometary nucleus. And so, we cannot escape the conclusion that deep-space missions to comets are by far our best hope for the future.

ACKNOWLEDGMENTS

This study could never have been undertaken without the availability of systematic brightness data accumulated through tireless efforts of several observers, primarily Dr. E. Roemer and the late Dr. G. Van Biesbroeck. Dr. B. G. Marsden has contributed informative discussions. This work was supported by grant NSG 7082 from the National Aeronautics and Space Administration.

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DISCUSSION

J. C. Brandt: How do you regenerate the surface without regenerating the intermediate layers of the snow?

Z. Sekanina: The proposed mechanism regenerates snow supplies not only at the surface but also beneath it (though not necessarily in proportion) by transporting vapor via diffusion from deeper layers. This process is stimulated primarily by a decrease in the concentration of snow near the surface resulting from intense surface evaporation around perihelion, and facilitated by the presumably porous structure of the cometary solid material. Furthermore, as the comet approaches aphelion, the surface cools off more rapidly than subsurface layers, thus giving rise to a rather substantial temperature inversion which, in turn, assists the mass transport to the surface and increases the rate of recondensation of water vapor on the surface. On a long-term scale, this mechanism leads to a complete depletion of snow reservoir in the nucleus, thus turning an active comet into a defunct object.

Now, besides, you can show that at large heliocentric distances before the aphelion point is reached, you would have an inversion of temperature. The surface is cooler than the interior, because the heating of the surface for in earlier times before aphelion propogates in a form of heat rate inside and, because the comet in the meantime gets farther away from the sun, there is less energy coming to surface. You can actually, numerically show that at several meters under the surface there is a higher temperature.

In other words, when surface is cooler and there is a transport of vapor to the surface, there is a good chance of condensation on the surface because of the lower temperature.

H. Keller: I have a question concerning the observations of the nucleus at the larger heliocentric distances.

I wonder whether there is a possibility for some systematic effect due to the fact that the geocentric distances, is also increasing when the heliocentric distance is increasing on the comet, an effect which maybe would be similar to the f-ratio effect of instruments. This may be a question for Dr. Roemer, and I would —

E. Roemer: Specifically with respect to P/Encke, some part of the systematic difference between the absolute "nuclear" magnitude derived from preperihelion observation as against that derived from postperihelion observations could easily derive from observational circumstances. Because of the orientation of the inclined orbit, P/Encke goes south very fast after perihelion passage and as a consequence is not observable for the Northern Hemisphere for a number of months, and even then, at very low altitude. Although I normally correct the "nuclear" magnitude estimates for extinction in blue light of 0.3 mag/air mass, that correction likely is inadquate for observation made at very large air mass.

More generally, I prefer to use those "nuclear" magnitudes that refer to a reasonably sharply separated nuclear condensation on an individual basis to form an idea of the limits on the radius of the nucleus defined photometrically. Although the available evidence seems to confirm that use of a $1/\Delta^2$ dependence is appropriate in deriving a "reduced" magnitude, error could arise in use of the "absolute" magnitude for calculation of the radius of the nucleus. The reason is that the unresolved contamination of the "nuclear" magnitude by light from the inner coma will generally be greater when the comet is closer to the sun. A dependence of the brightness on a higher inverse power of the heliocentric distance than the second would be the consequence. It would then become unclear how closely the absolute "nuclear" magnitude might be related to the absolute magnitude that referred only to light reflected from a monolithic nucleus.

Opik suggested some years ago that the geocentric distance dependence of the brightness is better represented by $1/\Delta$ than by $1/\Delta^2$. Meisel (1970 Astron J. 75, 252), as well as a graduate student of mine, Charles Snell, (MS thesis, U Arizona, 1971) have failed to find support for this proposal.

E. Ney: I'd like to make a remark about comet Bradfield.

Between April 7 and 9, to call your attention to it—I mentioned it yesterday in my talk, but I don't think people paid much attention—in two days, this comet changed very abruptly, by three magnitudes at long-wave infrared wave lengths. It just went out; it went down three magnitudes.

In a big diaphragm, Mintler found that it dropped two magnitudes in the visible in a 4-minute diaphragm.

Now, I'm not an experienced comet observer, but I looked at quite a lot of them this year; and I saw at the time the dust went away on Comet Bradfield it certainly changed its appearance. There was a thin coma, but there was a definite stellar image in the center.

I'd like to call your attention to that case, where the dust disappeared. It may be a case to measure a nucleus right.