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Rotation of Cometary Nuclei [and Discussion]

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Rotation of cometary nuclei

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Asymmetric comas and repetitive appearances of structures in the heads and tails of comets are used to infer nuclei rotation periods. However, periodic behaviour of optically-thick expanding comas or of ion plasma production may contribute spurious results. The spin periods of comets are longer than those of asteroids, ranging generally over 10–100 h and above probable limits for gravitational escape. The periods show a flatter distribution, which may reflect an accretional rather than collisional-fragmentation history. Arguments for spin-up with age due to sublimating gases are weak; the converse is possible and spin-down due to preferential escape of particles from equatorial regions appears likely.

1. Determination of rotation parameters

That the cometary comas are often strongly structured was known to ancient observers and depicted in drawings of the 'great' comets of the nineteenth century. While their sketches of emissions emerging from the very nucleus may have been influenced by their theories of comets as irregular sources of material, it has proved possible to trace structures on modern photographs as close to the centre as the resolution scale (Rahe *et al.* 1969). Recently, computer enhancement techniques applied to 1910 pictures of comet Halley – generally considered unstructured with a relatively diffuse coma – have resulted in remarkable views of rays, jets and envelopes (Larson & Sekanina 1983). Thus, the Mt Wilson pictures on four successive days in 1910 show a fan structure inclined to the solar direction and possibly initiating a spiral envelope. With analogies from other comets, the authors could identify this fan as arising from an 'active' zone of the nucleus rotating with a period of about a day and turning on when it reached its maximum temperature just past the sub-solar position.

Comet Pons-Winnecke came the closest to the Earth (in 1924) of any comet this century until last year, and allowed one to see (Sekanina 1981) that the jet or fan-like structure appears to extend to a few hundred kilometres from the centre of light, becoming more concentrated closer in to the nucleus (figure 1). The brightness of this and other comets has been put down to relatively small active areas whose emissivity is sensitive to the solar illumination: they can erupt each rotation for a time but as the comet proceeds round its orbit and the 'season' changes (assuming the rotation axis is inclined to the orbital plane), some stop erupting while other active areas may start up. Unfortunately, as figure 2 illustrates, successive orbits of a comet often do not show similar light curves. A tendency to be brighter consistently before or after perihelion is apparent, but the detailed structure of the light curve as in the 1951 and 1962 apparitions of comet Tuttle-Giacobini-Kresak in figure 2 does not repeat. The two outbursts in 1973 were a particularly impressive example of more complex intrinsic mechanisms, due perhaps to an unstable insulating dust layer being blown off.

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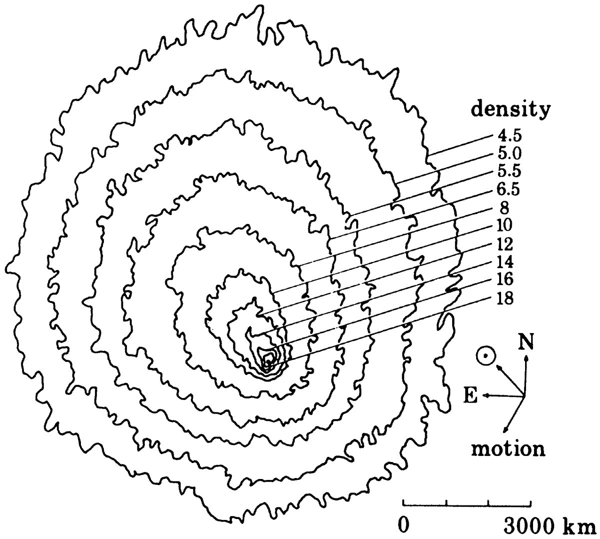

Figure 1. Isophotes of the inner coma of comet Pons-Winnecke on 26 June 1927 (from Sekanina 1981). The Sun's direction is NE as indicated, coinciding with the elongation of the inner isophotes, whereas the outer isophotes point more northerly. The nucleus is inferred to have a strong active region and to rotate clockwise.

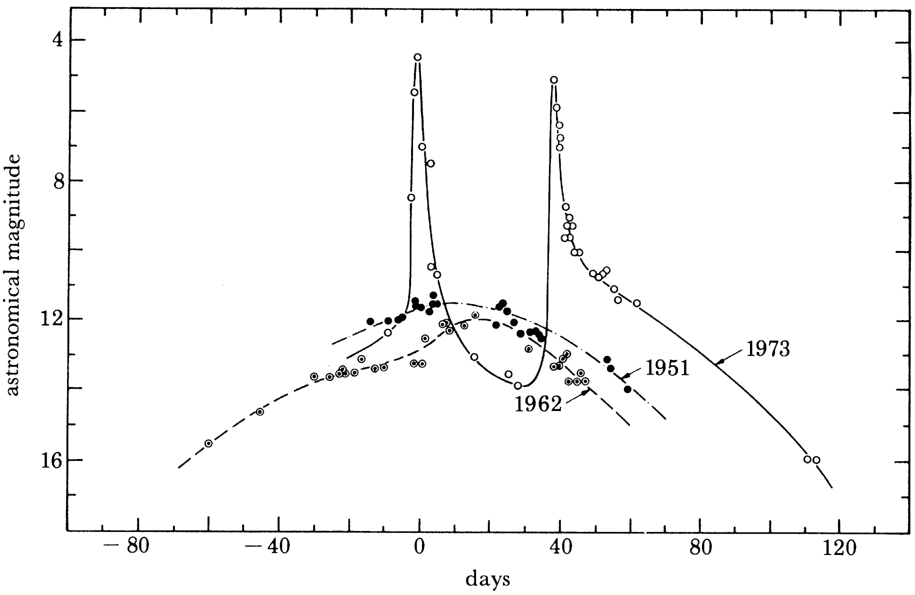

Figure 2. Light curves for comet Tuttle–Giacobini–Kresák on its 1951 (●), 1962 (⊙) and 1973 (○) apparitions. The ordinate is expressed in astronomical magnitudes reduced to 1AU from Earth, and the abscissa in days from the date of perihelion.

Methods for inferring rotation rates assume that fluctuations in brightness and structural features are not smaller examples of the eruptions of figure 2. Recurrent halos are a readily-recognized feature: Whipple has supplemented halo observations with a mass of records of variable coma sizes to infer repetition rates extending over months. As recently reviewed (Whipple 1982), comet Burnham 1960 II is a good example with over 30 observations covering some 200 halo production cycles. The data given on this comet also reveal sources of uncertainty: that there were disparate observers, that only a fraction of the supposed halos were actually observed (two halos may even be reported simultaneously with intermediate ones missing, as on 30 January 1960), and that the interval between observations is often several times the period (17 h in the case of comet Burnham). As the observations extend over a large part of the comet orbit, Whipple finds it necessary to assume a particular variation of halo expansion speed with heliocentric r (measured in astronomical units): $v = r^{0.6} \times 0.535$ km/s. However, this has no physical basis and Bobrovnikov's data on which this mean variation was based have never been published.

Certain comets (e.g. Morehouse 1908 III; Humason 1962 VIII) have shown distinct plasma envelopes continuing into ion tails, and observers may not distinguish these from halos; these as well as periodic solar changes cause some confusion and probably some spurious determinations. The method applied to the exceptionally close comet IRAS–Araki–Alcock 1983 (preliminary unpublished result of Whipple) did not agree with the sole determination by radar. But generally, the halo method appears successful, giving results consistent with the few examples of sunward fans (Sekanina 1981) and the inferred precession of comet Encke (Whipple & Sekanina 1979). Comet P/Schwassmann–Wachmann-1 has been intensively studied to find a 120 h period and infer slowly-migrating active areas (Whipple 1980); however, the direct observation of a range of halo speeds (ten to a few hundred metres per second (Weigert 1959)) renders the analysis uncertain.

The bare nucleus of certain comets may have been observed, the brightness showing an asteroidal-like phase change (e.g. P/Neujmin-1 shown by Degewij & Tedesco 1982), but no systematic variations caused by rotation have been extracted. Photo-electric photometry of the central condensation of comet P/d'Arrest gave a 15% double-humped fluctuation repeating in 5 h over three observation nights (Fay & Wisniewski 1978). Other observations claimed to indicate rotation include: spiralling dust jets from comet Bennett 1970 II; dust streamers in the tail of comet West 1976 VI; the 'wagging' plasma tail of comet Burnham 1960 II. For these phenomena, the rotation explanation is, however, rather uncertain (Sekanina 1981).

2. Rotation statistics and implications

The distribution of cometary rotation periods compiled by Whipple (1982) is shown in figure 3. Compared with unevolved asteroids larger than 100 km (see paper of Dermott & Murray, this symposium; Dermott *et al.* 1984) comets seem to spin more slowly and have a

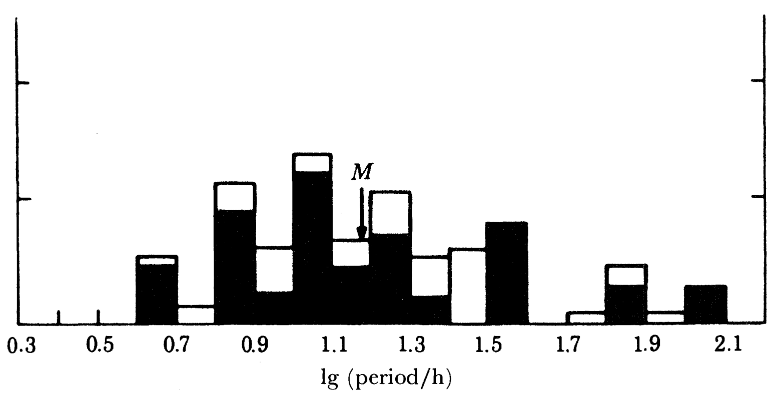

Figure 3. Frequency distribution of 47 cometary periods (weighted sum is 29.7 and weighted median $M = 15$ h) (Whipple 1982); the open rectangles denote less certain determinations.

flatter distribution. The latter property suggests they are not products of collisional break-up (Harris & Burns 1979) but formed through accretion. Though the numbers are rather meagre, there is a suggestion (Whipple 1982) that the larger comets (supposed to correlate with brighter ones in absolute terms) spin slower than the average, again consistent with accretional origin. The small Earth and Mars-crossing asteroids also spin faster (mean diameter 3.3 km, period 5.4 h) than comets so they can only come from dead comets if some spin-up mechanism operates.

The escape of fragments sets a limit on the period of a spherical rotating body

$$P_{crit} = 3.3\ \mathrm{h}/\sqrt{\rho} \quad (\rho \text{ in units of grams per cubic centimetre}). \tag{1}$$

Moreover, structually weak bodies distort into triaxial ellipsoids if their periods become less than about $2P_{crit}$ (Weidenschilling 1981). If $\rho = 1.3\ \mathrm{g/cm^3}$, just four comets out of the 47 (figure 3) have $P < 2\,P_{crit}$ and, in view of the probable spurious results, these cannot be considered significant. On the other hand, if $\rho = 0.4\ \mathrm{g/cm^3}$ appropriate for a self-compacting snowball smaller than 10 km, a further 9 comets have $P_{crit} < P < 2P_{crit}$; thus the stability cut-off may well operate. Self-gravity would give increased ρ for larger snowball comets (Donn 1963), but primordial radiogenic heating may have melted the interior and may have produced a hollow icy centre (Wallis 1979), so the simple formula (1) does not apply and it is better to exclude such exceptionally large comets.

3. Sublimation-induced changes

A rotating snowball of irregular shape, sublimating under the solar radiation, has not yet had its dynamical evolution consistently investigated: some features can be picked out. The first point to note is that most sublimation occurs under fluid rather than free molecular flight conditions. H_2O-ice normal to the solar radiation at 1AU which emits in the region of 10^{17} molecules/$\mathrm{cm^2\,s}$ at speeds corresponding to 180 K has free path lengths of order 1 m (Wallis 1982). The main effect of gas emission predominantly from the sunlit side is a net thrust, and results in deviation from a Keplerian orbit in various well-attested cases. Thermal capacity in the surface layers means that the peak gas emission lags behind the sub-solar point (local mid-day), which gives the thrust a component tangential to the orbit and allows the direction of rotation to be inferred. For quantitative evaluation, the thrust is dimensionally $\beta\int\rho v^2\,\mathrm{dS}$ over the surface; if v is taken as the thermal speed, the numerical factor β cannot be as high as 0.5 (appropriate for collisional effusion), but around 0.1 (to encompass subsonic fluid emission and some flow to the flanks with recondensation (Wallis & Macpherson 1981)). This low value of β is compatible with the larger inferred non-gravitational forces and nucleus sizes only if those comets have low densities of order $0.4\ \mathrm{g/cm^3}$.

The gas efflux can affect the rotation. A net thrust vector displaced from the centre of gravity, as expected for an oblate nucleus, induces precession of the axis. This is taken to explain the changing apparent force on comet Encke (Whipple & Sekanina 1979). Hydrodynamic efflux from a rotating snow- or ice-ball would be skewed by tangential pressure gradients, because sublimation will build up gradually through the local morning but cut off sharply in the late afternoon to dusk. This skewing acts to oppose the rotation. Differing sublimation from leading and trailing sides of a valley (the trailing slope sees the sun first and pre-heats the opposite slope causing it to emit more gas) is suggested for spinning-up the nucleus (Whipple 1982). However, the collisional nature of the fluid on the scale of the valley tends to cancel this bias. Recondensation of gas as frost on shaded or weakly-lit surfaces (Wallis & Macpherson 1981) has also to be considered.

While aerosol and small grains are blown away with the escaping gases, the cometary gravity limits the size that can escape from a latitude λ to

$$a < a_{\mathrm{m}}(1-P^2_{\mathrm{crit}}\cos^2\lambda/P^2)^{-1}, \tag{2}$$

where a_{m} is of order 10 mm (Wallis 1982; Houpis & Mendis 1981) and is proportional to the local gas flux. If the rotation axis is not strongly inclined to the orbital plane, a_{m} is much smaller in the polar regions. One is led to expect an accumulation of non-volatile grains and pebbles around the poles, which would choke off the gas production in this region and be relatively stable against seasonal changes. Pebbles released from sublimating ices in mid-latitudes with sizes above a_{m} can move over the surface; Houpis & Mendis (1981) see them as sliding against friction under the action of centrifugal and coriolis forces; a frictionless fluidized bed is probably a more appropriate analogy, but irregularities in the gas production and in local slopes may well dominate and produce complex 'weathering' patterns. Pebbles may collisionally break up into escaping fragments. On the average, however, the centrifugal force causes drifts to lower latitudes where escape is possible for pebbles smaller than $a_{\mathrm{m}}/(1-P^2_{\mathrm{crit}}/P^2)$ by (2). Dynamically, therefore, the drifting particles pick up angular momentum before escaping preferentially from the snowy equatorial regions. They cause the comet to spin-down.

This bias is analogous to the spin-down mechanism for asteroids by angular momentum drain of escaping fragments (Dobrovolskis & Burns 1984), and is common to any mechanisms for particles being ejected against gravity. Whatever the ejection mechanism for comet Schwassmann-Wachmann-1, the spin-down bias should occur there too, and could explain the long 120 h period reported. In summary, it appears that comet spin-down is more likely than spin-up on both observational and theoretical grounds. Explanations of cometary splitting must be found elsewhere, while Earth-crossing asteroids seem unlikely to be dead comets.

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Discussion

W. H. McCrea, F.R.S. (*University of Sussex, Brighton, U.K.*). I should like to ask Dr Wallis whether he considers it now to be established that, as regards rotation, a cometary nucleus behaves as a solid body, and that the core was once fluid.

M. K. Wallis. Yes, to the question of behaving as a solid body, though it is probably fragile in view of the indications of low density and readiness to split up. The postulated melting or vaporization of the centre due to ^{26}Al decay (Irvine *et al.* 1980; Wallis 1980) depends on whether comets accreted within the first million years of the Solar System condensation: presumed to be induced by one or more supernovae. Only the larger comets, of over 10 km radius, would become fluid in the centre, if their mineral component were of similar composition to the Allende meteorite and their conductivity were as low as snow. Freezing would have resulted in a hollow ice-lined core, but the increase in moment of inertia would give rather little slowing of the rotation.

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