1991SSRv...56...93W

STRUCTURAL EVOLUTION OF COMETARY SURFACES

MAX K. WALLIS and N.C. WICKRAMASINGHE
School of Mathematics, University of Wales College of Cardiff, Wales, U.K.

(Received 17 July, 1990)

Abstract. Comets with a high content of organics and light molecules are expected under cosmic radiation to gain a relatively unreactive crust and less volatile material to some ten metres deep. Interstellar dust impacts act to loosen and turn over ≈1 cm of the surface. We discuss how far this accords with observations of cometary dust halos and new versus old comets. Two key material properties have emerged from recent studies. Firstly, the source of cometary volatiles is not *ice* in the sense of material with a single sublimation energy. Secondly, the particulates are not simply mineral dust but include much organic material, some of which undergoes chemical processing and exchanges with the gaseous environment. Consistent with these properties, a coherent crust rather than a mantle of loose grains would build up to cover much of the nucleus of periodic comets. It would consolidate by *cooking* in the solar radiation, especially at peak temperatures around perihelion. There are two disjoint surface phases: one of volatile material, the other the refractory crust, the former deepening into crater-like hollows over successive apparitions. The transition to non-volatile crust is unstable, subject to competing consolidation and disruption processes, and sensitive to seasonal changes. A comet dims and becomes asteroidal as the inert crust extends over the erosion craters, and may only be rejuvenated via collision with a boulder-sized impactor or perturbation of the orbit to smaller perihelion distance.

1. Present State of Knowledge

The results from the GIOTTO mission to comet Halley have vindicated the critics of the dirty snowball model of the cometary nucleus, a model developed from Whipple's (1951) hypothesis of a mixture of 25% mineral dust plus ices or clathrates of methane, ammonia and carbon dioxide. This statement is made by Hughes (1990) except that he used the word *supporters* instead of *critics*. We on the other hand, took the view that the model could be used for comparative purposes, but had numerous difficulties in explaining quantitative observations and the rich variety of cometary behaviour; it now appears misleadingly inflexible and has exhausted all utility as a predictive theory (Wallis 1987).

What has been vindicated by the recent range of spacecraft and astronomical studies is the original Laplacian concept of a comet as a monolithic body of partly volatile material that is evaporating under solar radiation. Results from experiments onboard GIOTTO showed that the fractions of simple gases of methane and ammonia and nitrogen in Halley's comet are very low, if present at all (Krankowsky and Eberhardt, 1990); that the solid particles have substantial carbonaceous components rather than being mineral dust; and that much of the cometary gases are emitted from carbonaceous grains in the coma rather than directly from *ices* of the nucleus (Wallis *et al.*, 1987). Kerogen as a complex organic material with a whole range of chemical binding energies, is a suitable prototype for the composition, rather than an ice or

Space Science Reviews **56**: 93–97, 1991.

clathrate (containing impurity gases) that has a unique binding energy and distinctive sublimation behaviour. Dust particles composed of kerogens, of which polyoxymethylenes (POM) are one component (Van'yysek and Wickramasinghe, 1975), emit carbon monoxide and formaldehyde as extended sources, as were observed in Halley's coma (Krankowsky and Eberhardt, 1990). The comet surface is not pristine material uncovered by evaporative loss, nor does it appear to be covered in loose dust grains (Brin and Mendis, 1979) moved by breezes and under coriolis forces to accumulate in valleys or on polar caps; instead much of the surface is a cohesive, dark, carbonaceous crust, pyrolysed by solar radiation and probably persistent over several cometary orbits. Such a crust may be friable and rupture or erode erratically. It would also evolve seasonally and depend strongly on orientation at perihelion.

From nucleus images (Keller and Thomas, 1989) and from the above arguments, we infer the schematic picture in Fig. 1a of the comet nucleus appropriate to Halley at the spacecraft encounter (0.9 AU). The actively outgassing regions – some 10–15% of the surface in the case of Halley – emit directed *jets* of particulates entrained in the gases. Some condensation may occur initially as the expanding gases become supersaturated (Shulman, 1972; Crifo, 1990), but generally the particulates emit gases, whose photolysis adds energy to accelerate the flow (Shulman, 1972; Wallis, 1974).

2. Anticipated Knowledge

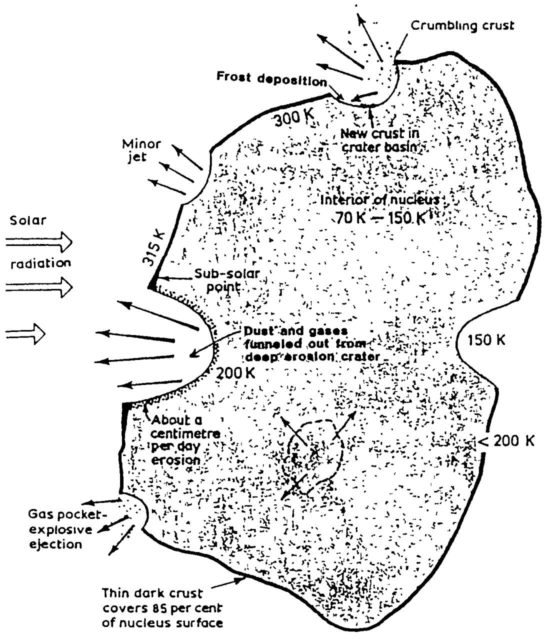
Scientific consensus on the surface composition and structure has yet to emerge, but theoretical modelling combined with results of simulations of postulated material components (Grün, 1991; Klinger, 1991) and refined astronomical observations are advancing our understanding. The CRAF mission will spur on studies as well as offering the prospect of direct data on the comet surface. Let us indicate current ideas on the processing and evolution of the comet.

The active outgassing regions are envisaged (Fig. 1b) as erosion craters of km scale that have deepened via evaporation over several perihelion passages (Wallis, 1986; Colwell and Jakowsky, 1987; Weissman and Stern, 1989). When illuminated, a crater would act as a sun-trap, assisted by *greenhouse* blocking of infra-red radiation by H_2O vapour and aerosol cloud. As the emerging jet is subsonic, its gas expands laterally in breezes towards the nightside (Keller and Thomas, 1989), the larger entrained particulates dropping out as hail (Fig. 1b).

As the depth of Halley's active craters indicates that they persist through several returns on a comet, the fraction of non-volatile pebbles that accumulate in *scree* which blocks evaporation (Fig. 1b) must be small. But eventually such scree plus new crust that persists through perihelion would block off most gas emission. The comet dies through suffocation, as indeed may Halley after a few more returns. But resuscitation and rejuvenation are apparently possible (Kresák, 1987). Perturbation into an orbit closer to the sun may give a surge in subsurface gas pressure that ejects an area of crust to create a new outgassing region. Alternatively, an impact of an interplanetary boulder or large meteoroid could rupture enough of the crust to create a viable active region.

The size necessary for viability is not clear – several metres or tens of metres, initially – but would depend on closeness to subsolar orientation through perihelion passage.

The surface of comets that traverse the solar system for the first time – the parabolic comets from the Oort cloud – appear to outgas uniformly. The failure to fulfil early promise, as the recent comet Austin 1989o, is at least in some cases due to the exhaustion and loss of an accompanying coma of volatile grains. Unlike Halley, these new comets show no significant variation on the few hours rotational time scale, as can be revealed by the IUE finder camera (Feldman *et al.*, 1987). What processes would have conditioned these *pristine* surfaces while in the outer solar system?



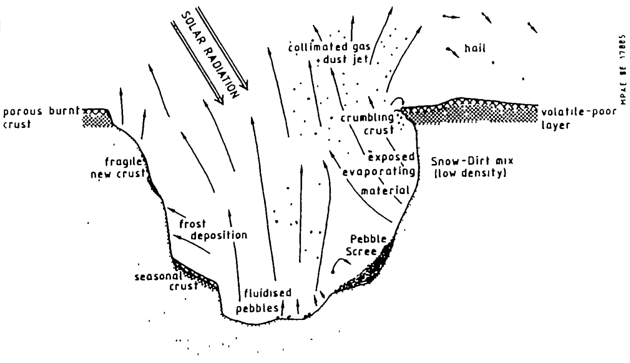


Fig. 1a. (left) Schematic of Halley's nucleus (Wallis, 1986) showing largely inert surface of pyrolized kerogen forming the dark crust plus a major outgassing region, as a crater formed by erosive evaporation that tends to collimate gas and dust emission in a sunwards jet.

Fig. 1b. (right) Details of hypothetical structure in an active outgassing region – an erosion crater acting as a sun trap. Dimension is about 1 km.

UV photons affect only a 1 μm skin, solar flare protons of tens of keV energies can penetrate just to 1 mm, so only cosmic rays can affect the surface to 1 m or deeper. Recent studies (e.g. Draganic and Draganic, 1984; Johnson *et al.*, 1987) indicate that cosmic irradiation of porous organic–ice mixtures induces a polymerised crust and migration of volatiles to seal the interior. A layer some 10 m deep is significantly transformed over the solar system lifetime, though minor effects may extend as deep as 100 m.

Passing stars and occasional supernovae warm the outer layers (Stern and Shull, 1988): Type 1 supernovae would have heated surfaces to 50–60 K, the heat penetrating about 1.0 m and mobilizing volatiles such as CO and CH_4. A luminous O-star passing the solar system at 1 pc distant, heats comets to 20 K, but there is only 1% probability that one has approached to 0.1 pc to produce 60 K surface temperature, with a heat wave penetrating tens of metres that dominates over the supernova effects.

Material impacts have been shown important by Stern (1986, 1988, 1990). Accretion of interstellar gas is outweighed by interstellar dust impacts, which being at hypervelocity (20–30 km/s) cause loss of many times the impactor mass along with devolatilization and polymerisation of neighbouring material. Taking structural energy equivalent to the sublimation energy of ice 2000 J/g or 2 km/s speed, and allowing for 50% of the energy going to vapour speeds, some 50–120 times the impactor mass may be lost (not 5000 times taken by Stern). This means around 1 cm of the surface would be eroded through solar system history. More important seems to be *gardening* of the surface under low speed impacts of small debris in the Oort cloud (Stern, 1988). Depending on debris parameter assumptions, the cometary surface may have been turned over several times to a depth of 0.5–5 m.

The conclusion would be that *gardening* produced a loose regolith which to some extent, particularly for comets ejected to the distant Oort cloud at $(10-50)\cdot 10^3$ AU, then gained some coherence via supernovae warming and interstellar dust impacts. Much of the regolith probably remains loose, as new comets generally arrive with a halo of mm or smaller grains, generating copious quantities of gas, e.g. comets Bowell and Cernis out at 5 AU (Hoyle *et al.*, 1985).

3. Major Outstanding Questions

Supposing the emerging cometary model outlined in section 2 is broadly confirmed via theoretical modelling and via simulation studies (Grün, 1991; Klinger, 1991), major questions will still remain to be solved:

- How dormant are fully-crusted comets and how frequently resuscitated or rejuvenated?
- What mechanisms keep them active at large distances? Halley is still active at 12 AU, comet Bowell produced a coma out to at least 13.5 AU.
- Was there early radiogenic heating via ^{26}Al decay, leading to interior melting and a hollow centre in the case of larger comets (Wallis, 1980; Prialnik *et al.*, 1987)?
- Do giant comets like Chiron (100 km size) break up to produce comet families (Kreutz sun-grazers, proto-Encke) and dominate the interplanetary *debris*?
- Are the complex organic *kerogen* components original to the proto-cometary dust or are they transformed *in situ*?
- Are there prebiotic or biotic components in the organics?

Improving astronomical techniques offer prospect of some advances – observing comets at large distance (cf. second question) and spectral identification of complex molecules and of isotopes (Encrenaz, 1991; Kerridge, 1991). The improving analysis of IDPs (Bradley, 1991; Zinner, 1991) offers valuable clues to the original non-volatile fraction of comets, as well as the evidently inhomogeneous pre-cometary material. The forthcoming CRAF mission to rendezvous with a quiescent comet should tell us a lot about the surface structure. But perhaps the dispatch of an artificial impactor, even a spent spacecraft, to collide with a comet would be the simplest way to reveal its inner structure.

References

Bradley, J.P.: 1991, in E.K. Jessberger (ed.) *Analysis of Samples from Solar System Bodies*, Space Science Reviews, this volume.

Brin, G.D. and Mendis, D.A., 1979, *Astrophys. J.* **229**, 402-408.

Colwell, J.K. and Jakowsky, B.M., 1987, *Icarus*, **72**, 128-134.

Crifo, J.F., 1990, *Icarus*, **84**, 414-446.

Draganic, I.G. and Draganic, Z.D., 1984, *Icarus*, **60**, 464-475.

Encrenaz, Th.: 1991, in E.K. Jessberger (ed.) *Analysis of Samples from Solar System Bodies*, Space Science Reviews, this volume.

Feldman, P.D. *et al.*: 1987, *Astron.Astrophys.*, **187**, 325-328.

Grün, E.: 1991, in E.K. Jessberger (ed.) *Analysis of Samples from Solar System Bodies*, Space Science Reviews, this volume.

Hoyle, F., Wickramasinghe, N.C., and Wallis, M.K., *Earth Moon Planets*, **33**, 179-187

Hughes, D.W., 1990, *Quart J.R. Astron.Soc.*, **39**, 61-94.

Johnson, R.E., Cooper, J.F., Lanzerotti, L.J., and Strazzulla, G., 1987, *Astron. Astrophy.*, **187**, 889-892.

Keller, H.U. and Thomas, N., 1989, *Astron. Astrophys.*, **226**, L19-12.

Kerridge, J.F.: 1991, in E.K. Jessberger (ed.) *Analysis of Samples from Solar System Bodies*, Space Science Reviews, this volume.

Klinger, J.: 1991, in E.K. Jessberger (ed.) *Analysis of Samples from Solar System Bodies*, Space Science Reviews, this volume.

Krankowsky, D. and Eberhardt, P.: 1990 in *Comet Halley 1986, World-Wide Investigations, Results, and Interpretations*. Ellis Horwood Ltd., Chichester, in press.

Kresák, L., 1987, *Astron.Astrophys.*, **187**, 906-908.

Prialnik, D., Bar-Nun, A., and Podolak, M., 1987, *Astrophys.I*, **319**, 993-1002.

Shulman, L.M., 1972, *Dinamika Kometnikh Atmosfer/Neitralni Gaz.*, Ch. 3, Kiev.

Stern, S.A. and Shull, J.M., 1988, *Nature*, **332**, 407-411.

Stern, S.A., 1986, *Icarus*, **68**, 276-283.

Stern, S.A., 1988, *Icarus*, **73**, 499-507.

Stern, S.A., 1990, *Icarus*, **84**, 447-466

Vanysek, V. and Wickramasinghe, N.C., 1975, *Astrophys. Space Sci.*, **33**, L19-28.

Wallis, M.K., 1974, *Mon.Not.R.Astron.Soc.*, **166**, 181-189.

Wallis, M.K., 1980, *Nature*, **284**, 431-433.

Wallis, M.K., 1986, *Comet Nucleus Sample Return, ESA SP-249*, 63-67.

Wallis, M.K., 1987, *Phil. Trans. R. Soc. Lond.*, A **323**, 346-347.

Wallis, M.K., Rabilizirovich, R., and Wickramasinghe, N.C., 1987, *Astron. Astrophys.*,**187**, 801-806.

Weissman, P.R. and Stern, S.A., 1989, Proc. Milpitas Workshop "Analysis of Returned Comet Nucleus Samples", JPL CST Preprint 119.

Zinner, E.: 1991, in E.K. Jessberger (ed.) *Analysis of Samples from Solar System Bodies*, Space Science Reviews, this volume.