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COMETARY HABITATS FOR PRIMITIVE LIFE

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ABSTRACT

Comet Halley studies indicate most of the nucleus is covered by an insulating crust, presumed of pyrolysed organic material. The subcrust is warmed and percolated by gases within 2AU, so provides one habitat for primitive replicating organisms. Cracks and crevices within contaminated ice in the craters provides a habitat for photosynthesising organisms. Subsurface lakes on the Europa model, though insulated by some metres of ice, would require a trigger (perhaps meteorite impact) and energy source (chemical or metabolic energy) to initiate and maintain a suitable habitat on short period comets. Constraints on transfer between comets and other planetary bodies implies that radiation-resistant species with lengthy hibernation potential would be expected.

1. NUCLEUS STRUCTURE AND COMPOSITION

The intensive studies of Halley's comet, particularly the imaging of the nuclear region by the *Giotto* and *Vega* probes, have given a new picture of the comet nucleus. Most of the dust is emitted in jets from active regions of ~1 km scale, presumably entrained in gas escaping from relatively deep, crater-like hollows that enforce directionality /1/. The surface is rough on scales down to 50m or less, corresponding to at least several tens of apparitions with spatially irregular losses of volatile material. Some 80-90% of the surface is comprised of very dark material (3-4% albedo), emitting little if any gas and dust. This picture (Fig. 1) corresponds to the 2-phase model of the nucleus surface advocated by Shul'man /2/ comprising a) vigorously sublimating ices with an admixture of organics and salts, plus b) a relatively dense, stable crust composed of non-volatile grains and relic contaminants.

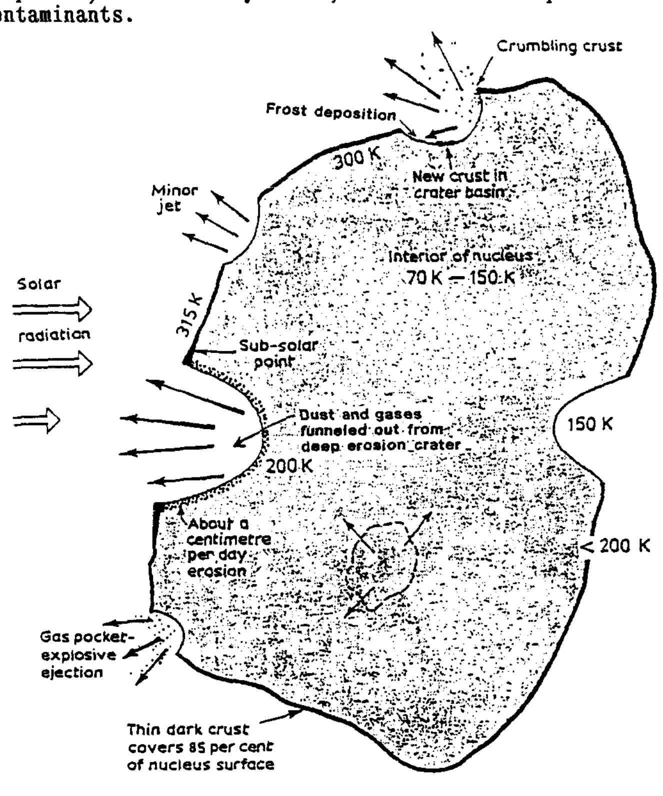

Fig. 1: Two-phase crust model of the comet nucleus, post-Halley.

In view of the chemical composition with highly carbonaceous fraction now known for Halley's comet /3/ and the extreme darkness of the surface, Shul'man's model needs modification /4/ by replacing the loose surface by a cohesive *crust*. The surface material gains cohesion through surface bonds between grains, through components of the percolating gases accreting onto them and through processing of the surface organic material under periodic solar heating (rotation period 2-7 days in comet Halley's case). It was thought /2/ that patches of crust would gradually spread to cover the whole surface; however, lateral conduction of heat from the hotter crust to adjacent ice should give extra sublimation and ensure a sharp division between the phases. Surface evolution is more likely to proceed via new patches of crust accumulating during a cooler period ("winter" season); destruction of weak crust during "summer" may proceed via gas pressure under a near-impermeable crust, via crumbling of undermined edges, or via bombardment by fragments from adjacent gassy regions.

Experiments that sublimate frozen solutions of organics and salts under simulated space conditions /5/ show fractionation into non-volatile particulates and escaping gases. The abundant sub-micron grains of largely organic composition /3/ may form this way, or may exist imprisoned in the ices. If the sublimating mixture percolates through a matrix, the organics and salts would tend to bind and consolidate it. Fragile tree-like structures build up, having the very low albedos observed /6/. At the black body temperature of e.g. T_0 = 335K (at 0.7 AU), the organics undergo some chemical charring. The resulting, more resilient, porous crust should be stable over several returns of the comet (being eroded at the edges or crushed by colliding fragments - see below), so the degree of charring is largely determined by the temperature maximum [$T \sim T_0 q^{-1/2}$ at perihelion distance q, apart from polar and seasonal complexities dependent on inclination of the rotation axis]. A variation of this view sees the organic surface material as transformed by cosmic rays during the lengthy residence time in the Oort cloud /7/, prior to escape of volatiles and thermal processing in the inner solar system.

The composition of the nuclear *ices* is still uncertain. Carbon compounds constitute a substantial fraction of molecular fragments detected in Halley's coma, but CO as a major component seems to be emitted from grains or molecular gas on a 10^4 km scale /8/. H_2CO has a similar distributed source, supporting the idea of formaldehyde polymer component in the grains /9/, but generally more complex kerogen is indicated. Much of Halley's abundant H_2O could be mixed in kerogen and have somewhat weaker attachment energy than crystalline ice, as hypothesised for comet Bowell /10, 11/.

Evidence for aqueous alteration of minerals in meteorites /12/ has long fuelled hypotheses concerning the presence of liquid H_2O within minor solar system bodies. Asteroids orbiting at 2-4 AU could lose 100km thick ice crusts slowly enough to maintain subsurface lakes. Comets being much smaller need thermally insulating snow and an internal heat source to cause melting of their interiors. Rietmeijer /13/ argues that aqueous alteration can take place well below the melting point, in interfacial H_2O layers. In addition to weakening the case for liquid water, this mechanism similarly explains how H_2O is available for bacterial processes at low temperature.

Spectral observations in the infra-red show impressively close similarities between comet Halley's dust component and interstellar material /14/. The 3-4μm feature can be most closely modelled by particulates made of sample biological material /11/, while the 10-12μm feature and indeed the whole range to 30μm corresponds to POM (formaldehyde polymers) plus siliceous material as from diatoms /15/. The infrared spectral resemblance, together with indirect evidence /16/, points to comets being derived from condensed interstellar gas and dust, containing the range of complex C-compounds identified in the gas phase. They should be initially rich in pre-biotic if not biological organics - plentiful feedstock for life-forms. The resemblance could be interpreted more strongly, as evidence that Halley's comet itself contains much bacterially-processed material, and even as adding plausibility to the speculation that micro-organisms actually influence in an organised fashion the physico-chemical evoluation of such a comet /17/. For the present discussion however, we concentrate on purely physical and chemical processes that operate in the potential cometary habitats.

2. COMETARY HABITATS

In addition to the two crustal regimes of Fig. 1 and sub-crustal lakes, we consider (Habitat D below) the post-accretion heated interior /18/.

Habitat A. A carbonaceous crust a few cm thick overlies frozen volatile material (Fig. 2a). Considering for concreteness a comet at 0.9AU (for mean infra-red emissivity 0.85), the temperature has a maximum surface value of ~310K early afternoon, down to order 150K nightside, but varies over 150-200K at some 3cm deep (the depth depending on thermal conductivity and rotation rate; for higher conductivity, the crust is thicker and these temperatures apply lower down). While imprisoned H_2O might even melt, the dark 200-250K zone with interstitial water is conceived as the principal growth layer.

Sublimating nutrients and water vapour diffuse through the crustal matrix for some weeks around perihelion. As the comet recedes, the layer reverts to a deep-frozen state and is stable over several returns to perihelion. This habitat would suit e.g. the species of diatoms that inhabit the base of polar ice, which live heterotrophically on organic material, in symbiotic relationship with bacterial species /19/. It would also suit bacteria such as inhabit cracks in rocks of the antarctic dry valleys.

Habitat B. The crust-free ices of the active crater areas sublimate at 190-200K under solar illumination (Fig. 2b), frosting over as they move into evening shadows /20/. If composed of loose sub-micron grains, such a "snowy" surface appears quite dark with incident light being scattered primarily forwards and reaching depths of 1 cm or more. The temperature of 193K above which molecular layers of H_2O flow over the surfaces of grains /13/, is perhaps critical for some life-forms. On rotating ice-ball models at e.g. 1 AU, the surface temperature exceeds 193K for 30-40% of the day-night cycle /21/. The class of diatoms that dwell between newly-fallen snow and polar pack-ice provide an example of micro-organisms that can act photosynthetically under such conditions /19/. The available time is, however, strongly restrictive as sublimation rates are around 1 cm per day. They would need to reproduce and spread rapidly to deeper layers. Larger crevices and fissures over 10 cm scale, penetrated by low levels of scattered light, would provide more time for biological development. During the 20 or 70 hours of comet Halley's "daylight", many doublings of a bacterial population could occur, with reversion to a dormant condition during the night.

Habitat C. Refrozen ice (Fig. 2c), as hypothesised for Jupiter's satellite Europa /22/ provides an alternative explanation for the crater interiors appearing dark /1/. Even 10-30 cm of surface bubbly ice does not prevent penetration and absorption of visible light. The photosynthetically important wavelengths penetrate clear ice to some 10-30m, while the infra-red is blanketted. This causes a *greenhouse* effect that prolongs the life of sub-surface lakes, though heating via the tidal, electrical or radiogenic processes of Europa /22/ are absent. As argued for European seas, photosynthesis could occur at low light levels, $\lesssim$ 5% for algae and 1% for diatoms (such as inhabit the antarctic sea-ice interface). The latter can switch to low levels of heterotrophic metabolism during darkness.

Habitat D. Following accretion in the early solar system, comets could have developed vapour/liquid interiors (Fig. 2d) due to heat generated by decay of the radionuclide ^{26}Al. This would happen for a snowball-like nucleus with 10-50% mineral fraction only if it is large, over 4-6 km radius /18/; since Halley's comet nucleus has turned out large and dark, an upward revision of comet sizes is implied, which may put a large fraction of comets into this category. The vapour interior lasts for 1-10 million yr, quite adequate for biological speciation. Supply of chemical energy is a strong limiting factor with only the original interstellar nutrients and radiogenic products available as sources. Heterotrophic bacteria and diatoms as for habitat A are suited to this environment. Once the radioactive heat source dies away, the life-forms would be imprisoned in a state of deep freeze, only to be released after 10^7 or 10^8 yrs following substantial sublimation or disintegration of the comet.

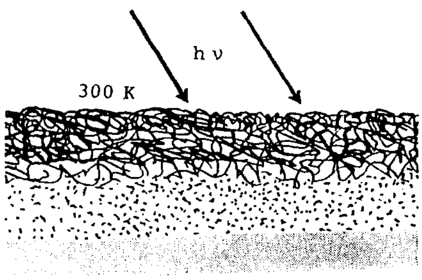

Fig. 2a Sub-crust, between 'ice' and the porous 'cooked' protective crust.

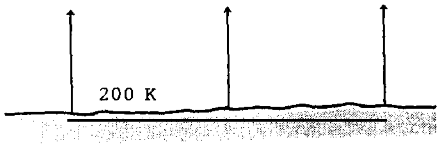

Fig. 2b Sublimating ice/kerogen composite

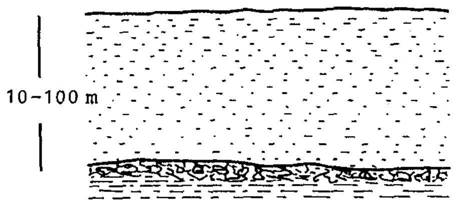

Fig. 2c Subsurface lake interface with ice

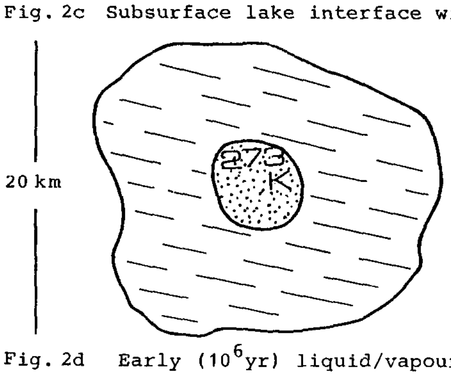

Fig. 2d Early (10^6yr) liquid/vapour interior

A variant on habitat C is conceivable that draws on biochemical heat sources. For the chemical energy released in building large molecules is of order 0.1eV per bond, giving at one bond per 20AMU sufficient energy (500 j/g) to melt ices. In a mixture of frozen lifeforms amid elementary chemicals, a trigger is needed to set off melting in some region enabling biochemical transformations to start and spread with the liquid/vapour region. An impact of a boulder-sized body that burrows into the "snowball" nucleus might provide the appropriate trigger. A representative 100t boulder /23/ impacting at some 35km/s, as typical for asteroidal belt objects on comet Halley, would penetrate several m below the impact crater base in soft material, and with a few % conversion to heat could melt up to 10^4 t. The resultant pool of 20m scale has a cooling time of weeks, quite sufficient for biochemical sources to build up and melt further ice. If chemical nutrients are limited, so that heating is dependent on photosynthesis, the liquid domain is restricted to sub-surface lakes as in habitat C. Since re-freezing to a depth of 40m occurs in about 30 yrs at the orbit of Jupiter /22/, such lakes may not persist over successive apparitions of comet Halley. For short-period comets such as Encke's, photosynthetic biology could keep large lakes liquid, eating deeper into the interior around each perihelion passage as the outer layers sublimate.

3. DISCUSSION

Some comets appear "active" with bursts of gas/dust quite far from the Sun, including comet Halley out to 12 AU. Comet Schwassmann-Wachmann-1 orbiting at 5-7 AU (subsolar surface temperature up to 170K, if dark material: /24/) is the most erratically bursty comet known. The dynamical energy of impacting "boulders" is rather small at the 3-4km/s speed appropriate to this prograde comet /23/, while the favoured explanation as a phase change from amorphous to crystalline ice /24/ depends on the composition being near-pure H_2O. Nevertheless, boulder impacts acting to trigger subsurface chemical or biological activity could lead to pressure build-up and fissure of the surface, releasing a burst of gas and solids. Alternatively, subsurface lakes covered by ~ 10m thick ice (translucent to visible light but opaque to IR - see above) would eject material when the surface fractures on impact of more numerous smaller (1-10t) boulders.

Less speculatively, let's argue from the fact that species of cyanobacteria inhabiting anoxic environments use H_2S rather than H_2O as a source of H /25/. The waste crystalline sulphur reveals itself in S, S_2 and CS (spectral emissions seen by IUE in most comets), the S_2 abundance being surprisingly high at 0.1% of OH or over 10% of S. They could inhabit the surface layers of loose snow and organics, conducting photosynthesis as far out as Jupiter (dayside temperature ~ 150K) or even Saturn (subsolar temperature at 9.5 AU at 130K for a black-body; H_2S freezes at 190K and has significant vapour pressure some 50-70K lower). Species that bind the snow grains in a crust that's blown off episodically by their gaseous products have an evolutionary advantage; fresh layers of organic nutrient are thereby exposed to the weak sunlight and become available to colonisation by photosynthesising micro-organisms. In this connection, we note that S_2 is relatively strong compared to OH in the distant comets Černis and Bowell (at 3.4 AU: /26/).

The migration of species below the comet crust of a visitor to the inner solar system like Halley would ordinarily be slow, so that colonies of species could evolve in particular regions over successive returns. Photosynthetic biological species living in the craters (habitat B) would be spread around by the escaping gas; as gas drag diminishes faster than R^{-2} from the nucleus, cm-sized grains which just lift off against gravity will fall back to the surface under steady outgassing, while others will fall back in the diminishing phase of an outburst. If boulder-induced outbursts occur through the relatively stable crust, the homotrophic species growing within it will also be scattered over the surface, "infecting" large areas with viable biomaterial. Even when such outbursts are absent, evolved crust at the edge of craters will be undermined and crumble into the escaping gas stream (depicted in Fig. 1); fragments just small enough to be dragged off against gravity will fall back onto neighbouring areas. A comet thus processed may resemble a biological time-bomb /17/, ready to produce explosive gas bursts wherever triggering impacts occur.

As habitats for micro-organisms, comets would be not only amplifiers but also distributors of life /17/. Life-forms on them have the advantage of easy transmission between comets. Organisms blown out from sublimating crater material or in the crumbling margins of the crust, would require just a 10μm thick absorptive skin to give protection against the solar UV until possibly picked up by a quiescent comet. Inside comets, the protection of dormant species against X-rays and cosmic rays is of course ensured, so that transfer of viable organisms between stellar systems is quite feasible. Following multiplication of the organisms within comets on their close approach to stars, infection of their interplanetary regions and ultimate pick-up by planets is straightforward.

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