COMET HALLEY'S REMOTE OUTBURST

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Last year's spectacular outburst of Halley's comet — brightening by 300 times due to a 10^5 km coma of particles — was not expected by conventional cometary experts. Explanations based on an asteroid collision, or a solar flare, or ice phase change are unconvincing. Flooding of a cometary crater, resulting from the freezing of an interior lake that cracks the surface ice *via* expansion forces, plausibly produces the observed coma of ice particles.

The problem of explaining an outburst at 14·3 AU is that Halley is thought to be hard frozen snow or ice, with a sunlit surface as cold as 70 K. The outburst created a coma of particles, observed first in mid-February of 1991, which expanded in size while decreasing in central brightness by mid-March, implying outward speeds of some 20–40 m s^{-1}.

The estimated 10^8 kg of material[1] implies at least 20 GJ of energy, far too much to be delivered by solar flares. Collisions with an asteroid, supposed to give 100 times more mass mainly in larger fragments[2], are relatively improbable. Moreover, an impact at around 10 km s^{-1} would eject most material at well over 100 m s^{-1}, for which there was no evidence. If, alternatively, the energy source is internal, what could be the driver gas? Carbon monoxide (CO) is one of the few gases volatile at 70K and is therefore frequently proposed, but why should it be released 5 years after Comet Halley's perihelion passage?

One explanation given credibility[3] is Klinger's suggestion[4] that energy released by a change in ice phase liberates gas from a pocket of compressed CO. A phase change from amorphous to crystalline ice, occurring at 140 K, is supposed to take place some metres below the comet surface, triggered by a thermal wave initiated from heating near perihelion[5]. The phase change supposedly cracks open the ice and releases CO from its pressurized state. However, the whole amorphous-ice theory remains speculative. A high transformation energy (60–70 kJ kg^{-1}) is unverified; relatively pure H_2O is required for crystallization, yet Halley's gases comprised substantial non-H_2O components — over 20 per cent of organic molecules plus similar mass in solid particles in very fine sizes (down to about 10 nm).

The duration of a release generated by changing ice phase is uncertain, since there is positive feedback (heat release warms up neighbouring ice, stimulating further phase change), but modelling[5] indicates a time-scale of weeks, if not months. However, it is inferred from the anisotropy of the coma that Halley's outburst lasted less than half a rotation period (2 or 7 days).

Perhaps because they are locked into the psychology of a snowball comet of low density, cometary pundits have ignored the simpler and more powerful phase change of H_2O freezing within an interior reservoir, suggested years ago by Fred Hoyle[6]. Prior to Halley's spectacular outburst, we[7] proposed the inward freezing of subsurface lakes as the source of activity far from the Sun of both Halley and of Neptune's satellite Triton. The 9 per cent increase in volume when water freezes forces the surface to crack open. Small particles and vapour would be released, with most vapour freezing quickly onto grains, as for Triton's geyser emissions. In more-violent episodes, water would gush out and fill a crater basin.

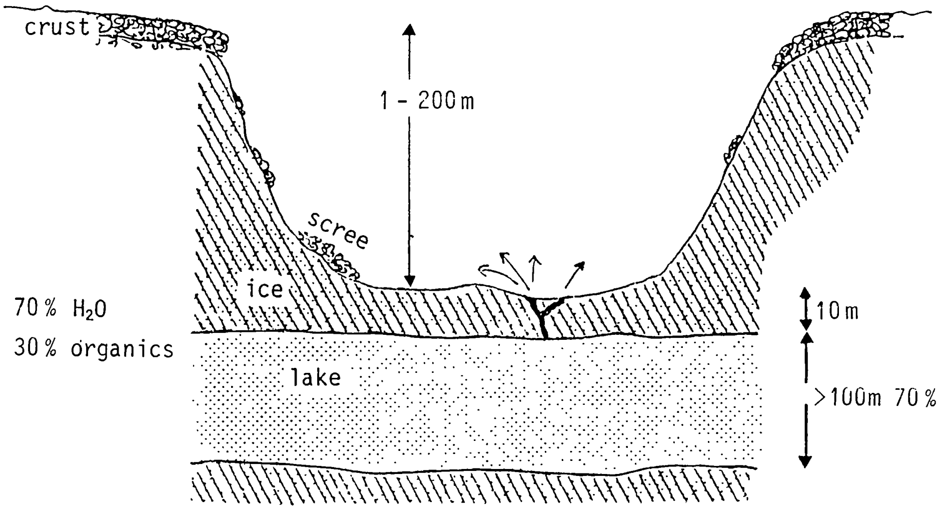

FIG. 1

Sketch of an active comet basin with exposed volatile material, devoid of the old coherent crust that covers 90 per cent of the surface. Patches of temporary crust and scree (from old crust fragments and non-volatile inclusions) are shown. The basin's base is of ice, covering an interior lake.

Let us consider this in detail. The active emitting regions on Halley are surmised to persist over more than one apparition and to deepen *via* sublimation, while the major inactive part of the surface is protected from sublimation by a non-volatile crust[7]. As imaged by *Giotto*, the active regions were of 1-km-scale radius. We hypothesize that there exists a lake of liquid water below the base of the depression (see Fig. 1) enclosed on all sides by ice. Inward freezing is occurring as Halley recedes from the Sun. The 9 per cent volume expansion causes the surface to crack open and to vent liquid that quickly solidifies. Water vapour sublimates while it cools from 273 K to about 170 K, carrying with it a less volatile organic fraction. We suppose that Halley's latest outburst arose from an abnormally large rupture of this kind, with the liquid flooding over the depressed basin.

The heat loss *via* conduction through ice covering liquid water is calculated as

$$\Phi = \frac{1}{d}\int_{273\,\mathrm{K}}^{T_s} \kappa(\mathrm{T})\,\mathrm{dT} = 567\,d^{-1}\ln(273\ \mathrm{K}\ /\ T_s)\ \mathrm{W\ m^{-2}} \qquad (1)$$

taking the conductivity as $\kappa \propto T^{-1}$ with depth of ice d in metres[8]. With $d = 10$ m, the heat loss is several times 10 W m^{-2}, much greater than mean solar heating of about 1 W m^{-2} at 14·3 AU. Neglecting the latter and equating (1) to the radiative losses, $\varepsilon\sigma T^4$, with the IR emissivity of ice $\varepsilon = 0{\cdot}95$, we find the surface temperature is $T_s = 155$ K and heat loss $\Phi = 32$ W m^{-2}. That heat loss would cause an increase of 0·3-m depth in the ice per month (latent heat plus mean thermal capacity 0·45 MJ kg^{-1}).

For the outburst to emit 2×10^8 kg H_2O vapour, the sublimation energy of 2·2 MJ kg^{-1} is postulated to come from water flooding through a fissure. That can release on freezing and cooling about 0·54 MJ kg^{-1}. Assuming 30–50 per cent loss of heat to the environment (*via* radiation and conductive heating of the 155 K surface), the depth of water required over a basin area of 3×10^6 m^2 is 0·4–0·6 m. Allowing for 30 per cent fraction of organics with no change-of-state energy, the depth of the flood would be 0·5–0·7m, of which 0·07 m is released in vapour and solid grains. Thickening of ice on the lake by 6 to 8 m giving this volume change is achievable within two years starting from 7-m ice cover.

The strength of the emission is conditioned by the rate and duration of freezing, and so by the thickness and thermal conductivity of the overlying material — some 10 m of ice at the base of Halley's crater, covered by snow emitted in earlier, lesser outbursts (as observed in early 1990). The surface of the 0·5-m flood of water of course quickly freezes; the surface material continues to sublimate, drawing on the latent heat of the water below, until the ice freezes through. Computations show that the ice-liquid interface retreats to 0·3 m below the surface in about a day. So the main phase of the outburst lasts this time, the surface temperature dropping to below 205 K and radiative losses being relatively small. While the vapour expands at speeds of a few 100 m s^{-1} the solid organic and mineral particles are only partially coupled to the gas, which explains the 20–40 m s^{-1} speeds for these slower-moving solids.

The last stages of sublimation as T_s drops below 170 K are too weak to lift off the dirt grains, leaving them behind to form a porous crust. This cover on the crater bottom serves as a thermal insulator. Such insulation, together with ice thickened to some 40 m, leads us to calculate[7] that the heat loss rate could be reduced to around 10 W m^{-2}. Over its 70 year timespan away from the inner Solar System, Halley would then lose from its sub-surface lake some 20 GJ m^{-2}, equivalent to a 37-m depth of water transformed to ice. If, alternatively, the chemical or metabolic energy potentially available from the 30 per cent component of organics at 1 MJ kg^{-1} replaces this heat loss, a 25-m depth of material has to be transformed. This seems implausible as such a depth is several times larger than the estimated depth of material sublimating from Halley's active surface per apparition. However, the thermal conductivity of the organic-ice mix is plausibly several times smaller than (the high value) for crystalline ice. So our theory requires such lower conductivity and a lake depth of order 100 m, as is conceivable in the 8 × 8 × 16 km comet.

The origin of interior lakes is one problem with this hypothesis, and their maintenance against complete freezing is another. Liquid water on Triton is perhaps easier to accept, as the satellite shows signs of resurfacing in its distant past, and the deep interior of that Mars-sized body may well contain much liquid H_2O. Halley would, however, need both a trigger to create the initial lake and an interior heat source to maintain liquidity around aphelion passages. The trigger would be the rare hypervelocity boulder impact[2], *e.g.*, a 10-m-sized body impacting at 30–50 km s^{-1} in the inner Solar System. It would have created a huge Halley outburst a millenium ago, and initiated the series of bright but gradually weakening displays[9]. We speculate that continuing primitive biological activity has since then provided a heat source and that nutrients derive from surface material buried in the episodic outbursts. This would constitute a novel 'Gaian' feedback.

References

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