# Reports

## Comets: Production Mechanisms of Hydroxyl and Hydrogen Halos

Abstract. *The brightness dependence on the heliocentric distance that has been observed for the hydrogen and the hydroxyl halos of comet 1969g can be quantitatively explained by a three-step process: the vaporization of the water snows, the photodissociation of the water molecule into the ground states of hydrogen and hydroxyl, and the photoexcitation of hydrogen and hydroxyl by a fluorescence mechanism.*

Since Whipple's suggestion (*1*) of the icy conglomerate model, the chemical nature of the icy phase of the cometary nucleus has not yet been checked by observations. The only molecule of the icy phase that cannot be reasonably doubted is water, mainly because of the discovery of the hydrogen and hydroxyl halos by the Orbiting Astronomical Observatory and by the Orbiting Geophysical Observatory for the two bright comets of 1970 (*2*). However, the argument is still of a circumstantial nature and is dependent on the model. For instance, our ignorance of the albedo (or of the radius) of the cometary nucleus introduces a major uncertainty. If the albedo is between 0.10 and 0.90, water evaporation can predict the right order of magnitude of the brightness of the two halos. But if the albedo were much larger than 0.90, the solar energy absorbed by the nucleus would diminish drastically and the ices would not vaporize enough. In this case, OH and H could originate as free radicals from the nucleus, to use the ideas independently proposed by Haser and by Donn and Urey (*3*); a desorption process, as described by Levin (*4*), could then explain the physicochemical mechanism for their production.

Of course, the large brightness of the two halos makes these ideas rather unlikely. On the other hand, OH and H could come from one or several other molecules, more complex than water. This cannot be ruled out because we still do not know very much either about the early chemical history of the cometary nucleus or about the hypothetical parent molecules of the other free radicals observed in the cometary heads.

A new quantitative argument can be developed from the observed brightness dependence on the heliocentric distance of the H and OH halos. It is based on Code's observations (*5*) of the intensity of the total flux of each halo, in particular of comet 1969g. On the log brightness versus log heliocentric distance diagram, the eight observed points form a perfectly straight line for OH, between 0.78 and 1.02 A.U. For the Lyman-$\alpha$ emission, seven of the nine observed points also form a straight line. Two points that are much lower than the straight line are explained by Code as a spurious effect that is clearly understood (telluric reabsorption of part of the halo light because of the geometry). The slope for both OH and H is exactly the same. Code mentions a dependence on distance to $-5.8$ power (*5*). However, on his preprint's diagram (*6*), I find a slope $n = -5.9 \pm 0.1$. Since the slope is almost exactly 6, I propose here that the emission of light by the H and OH halos is in each case a three-step process, where each step shows, at least in a first approximation, an inverse square law dependence. The three steps proposed are (i) vaporization of water snows from the cometary nucleus, (ii) photodissociation of the water molecule into H + OH, and (iii) photoexcitation of H and OH by absorption of the solar continuum and fluorescence.

The production rate of $H_2O$ vapor by the first process depends on the total energy flux absorbed by the cometary snows, which varies as the inverse square law. But part of it is radiated away from the nucleus by Stefan's law. The correction introduced by the heat balance on the vaporization rate of the snows gives a slope that is not exactly 2 but remains a constant at heliocentric distances smaller than 1.3 A.U. The slope is between $-2.15$ and $-2.05$ depending on the accepted values for the snow albedos in the visible and in the infrared (*7*). An average value of $-2.1$ can therefore be used. It remains true whatever the type of snow.

The photodissociation described in the second step depends, of course, on the photon flux, which also follows the inverse square law. This photodissociation can be obtained by absorption of the solar flux, either in the first or in the second continuum of water (*8*), which gives the reactions shown in Eqs. 1 and 2, respectively.

$$H_2O + h\nu \rightarrow H(^2S) + OH(X^2\Pi) \quad (1)$$

$$H_2O + h\nu \rightarrow H(^2S) + OH(A^2\Sigma^+) \quad (2)$$

As the two continua overlap, the ratio of the rates of the two processes is not known with accuracy, but the first one must strongly predominate because there is much more energy available in the solar spectrum between 1800 and 1400 Å than there is between 1400 and 1150 Å.

For the third step, H and OH must be distinguished. Hydrogen is produced in the ground state and must therefore absorb a solar photon again, introducing the third dependence on the inverse square law, before emitting Lyman $\alpha$.

The same third step is followed by the OH molecules produced by the first reaction (Eq. 1) in the ground state. But, if they were produced by the second reaction (Eq. 2) in their excited state, they would bypass the third step and radiate the molecular band $A^2\Sigma^+ \rightarrow X^2\Pi$ immediately.

If the heliocentric distance of the comet does not vary too much during the time of flight of the molecules or atoms through the whole coma (which is almost always true), and if the optical depth effects do not vary too much during the range of distances covered, the global brightness in Lyman-$\alpha$ light (or in OH light) is given by

$$B \propto Zf^2 \propto r^{-6.1} \ (r < 1.3 \text{ A.U.})$$

where $Z$ is the production rate of molecules by vaporization, $f$ is the photon flux of the sun, and $r$ is the heliocentric distance. If $H_2O$ were dissociated by the second process (Eq. 2) only, the exponent of $r$ would still be $-6.1$ for H (Lyman $\alpha$) but would be $-4.1$ for OH.

The observation of the slope $n = -5.9 \pm 0.1$, both for H and OH, seems to point out that the first process (Eq. 1) is overwhelming and, by the same token, confirms for the first time in a more quantitative way the likely presence of water ices or snows in comets and the three-step mechanism of production of OH and H. It seems very difficult to keep a three-step mechanism by using something other than water. Direct desorption of radicals would give a two-step process with $n = -4$ or less. Dissociation of larger molecules would give, by and large, at least one more step for either H or OH. When better observations are known, it is hoped that mechanisms of this type will explain the physical processes and the origin of the other radicals observed in cometary heads.

A. H. Delsemme
*Ritter Astrophysical Research Center, University of Toledo, Toledo, Ohio 43606*

### References and Notes

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## Satellites of the Outer Planets: Thermal Models

Abstract. *Steady-state thermal models for the large satellites of the outer planets strongly indicate that their interiors are currently maintained at temperatures well above the ice-ammonia eutectic temperature by the decay of long-lived radioisotopes of potassium, uranium, and thorium. The present-day steady-state thermal structure of a representative satellite, J IV (Callisto), is shown to be characterized by the presence of a thin icy crust over a deep liquid mantle, with a dense core of hydrous silicates and iron oxides. Some dynamical consequences of this model are briefly discussed.*

It is well established that several large satellites of the outer planets have densities near 2 g cm$^{-3}$, approximating that of a mixture of the rock-forming and ice-forming elements in solar proportions (*1*). Both the available observational data (*2*) and current theories for the origin of the solar system suggest that temperatures at and beyond Jupiter's orbit were low enough to be within the stability field of common ices during the accretionary era. Thus the abundant elements would be found in those chemical compounds that are stable in the presence of a cold, low-pressure gas of solar composition (*3*). Because of the stability of hydrates of ammonia and methane at low temperatures, substantial quantities of these gases may be retained by a condensate formed 50° or more above the condensation temperatures of pure ammonia or methane (*4*).

It is clear that the rate of heat production from the radioactive decay of a solar-proportion mixture of ices and silicates (which is about two-thirds ices by mass) will be much slower than that for a chondritic object, but the possibility of interesting chemical and physical consequences of such mild heating should not be dismissed out of hand. In order to effect large-scale differentiation of the interior of a large satellite such as J IV (Callisto) one need only reach the eutectic temperature in the $NH_3$-$H_2O$ system. The temperature at which the eutectic melt appears is 173°K [by comparison, Callisto's daytime surface temperature, as found by infrared emission measurements, is 160°K (*5*)]. This raises the possibility that the interiors of the Galilean satellites of Jupiter and the larger satellites of the other outer planets may be extensively melted, and hence may have undergone differentiation of the icy and rocky components.

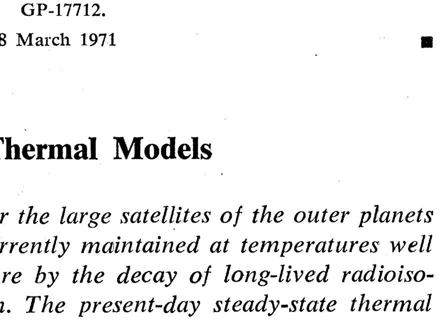

Fig. 1. Approximate present-day interior temperature profiles for Callisto (J IV). The dashed line describes a fictitious object in which melting does not occur, whereas the solid line gives an approximate profile for an object in which the known melting behavior of the $NH_3$-$H_2O$ system is incorporated. A mean surface temperature of 110°K has been used for both models.

I shall describe briefly a steady-state thermal model for J IV in which the present-day heat production by the decay of $^{40}$K, U, and Th is exactly equalled by the net radiative loss from the surface. The heat balance equation for the surface regions is

$$K \frac{\partial T}{\partial Z} = S\rho R$$

where K is the thermal conductivity (*6*), $\partial T/\partial Z$ is the vertical temperature gradient near the surface, $S$ is the present-day rate of heat production, $\rho$ is the density, and $R$ is the radius of the satellite. The present-day value of $S$ for chondritic material is $5 \times 10^{-8}$ erg g$^{-1}$ sec$^{-1}$ (*7*), and thus a solar-proportion mixture of chondritic material with ices, which is three times as massive as the chondritic component, will have $S = 1.7 \times 10^{-8}$ erg g$^{-1}$ sec$^{-1}$. The difference between the central and surface temperatures varies roughly as $R^2$. For a solar-proportion mixture of the rock-forming and ice-forming elements at accretion temperatures above the condensation point of $CH_4$, the condensate is about 54 percent $H_2O$, 15 percent FeO, 13 percent $SiO_2$, 10 percent $NH_3$, and 8 percent MgO (by mass). These major components mixed in the proportions given would give a bulk density at zero pressure of about 1.8 g cm$^{-3}$, in good agreement with the observed density of about 2.0 g cm$^{-3}$ found for J IV.

An instructive but very imprecise calculation of the temperature profile in J IV may be made by using the thermal conductivity of an ice-silicate mixture extrapolated up to temperatures and pressures at which ice I is no longer stable. In such a model no consideration is given to known phase transitions, but the model is instructive in that it shows that the large temperature gradient calculated for J IV (about