

## IS WATER ICE THE MAJOR DIFFERENCE BETWEEN COMETS AND ASTEROIDS?

A. H. DELSEMME  
*University of Toledo*

*The nature of the volatile phase in comets has never been established from observations. Although water was likely to be its major constituent, evidence was still circumstantial. It is shown here that water evaporation quantitatively explains not only the brightness of the hydrogen and hydroxyl halos observed by the OAO for the two bright comets of 1970, but also, which is much more convincing, it explains their brightness dependence on the heliocentric distance.*

The existence of a volatile phase, whatever it is, seems to be, of course, the major chemical difference between a "normal" cometary nucleus and a standard asteroid. This idea was used by Whipple (1950) to build his icy-conglomerate model, which explained in a qualitative way the nature of the so-called nongravitational forces acting on comet Encke. However, the chemical nature of this icy phase has not yet been positively identified. Therefore, the nongravitational force theory, developed for many comets by Marsden (1968, 1969), suffers from having no physicochemical model able to describe, in particular, the dependence of the acting force on the heliocentric distance.

The only molecule of the icy phase that cannot be reasonably doubted is water. There are many circumstantial reasons that I will not try to review again here. They range from the type of chemical considerations that were so successfully introduced by Urey into the study of the solar system and its origin, up to the recent observations of the hydrogen and hydroxyl halos by the OAO for the two bright comets of 1970 (Blamont, 1970; Code, Houck, and Lillie, 1970), to which I have just learned that we should add comet Encke. Previously, I have shown (Delsemme, 1971) that water evaporation explains the right order of magnitude of the brightnesses of the two halos. The major uncertainty comes from our ignorance of the albedo (or of the radius) of the cometary nucleus concerned. The right order of magnitude is reached if the albedo is between 0.10 and 0.90. It is obvious that when the albedo is larger than that, the energy absorbed diminishes drastically and the ices do not vaporize enough any more.

This shows how such an argument heavily depends on the model adopted. The other arguments for water are of an even more circumstantial nature and could be turned around easily. For instance, OH and H could be described as free radicals from the nucleus, using the ideas independently proposed by Haser (1955) and by Donn and Urey (1956). In this case, Levin's (1943, 1948) ideas on desorption could still be used.

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 about either the early chemical history of the cometary nucleus or the hypothetical parent molecules of the other free radicals observed in the cometary heads.

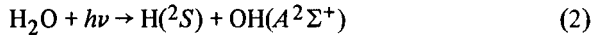
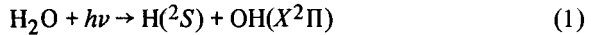
A new quantitative argument for the presence of water can be developed from the observed brightness dependence on the heliocentric distance of the hydrogen and hydroxyl halos. It is based on Code's (1971) observations, in particular of comet 1969g. On the log brightness versus log heliocentric distance diagram, the eight observed points draw a perfectly straight line for OH. For the Lyman- $\alpha$  emission, seven of the nine observed points also draw a straight line. Two points that are 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. In the preprint kindly communicated later by Dr. Code, I find a slope  $n = -5.9 \pm 0.1$ . Because it is almost exactly 6, I propose here that the emission of light by the hydrogen and hydroxyl halos is in each case a three-step process in which each step shows, at least in a first approximation, an inverse square law dependence. The three steps proposed are

- (1) Vaporization of water snows from the cometary nucleus
- (2) Photodissociation of the water molecule into H and OH
- (3) Photoexcitation of H and OH by absorption of the solar continuum

The production rate of  $\text{H}_2\text{O}$  vapor by the first process depends on the total energy flux absorbed by the cometary snows, which varies as the inverse square law if the temperature of the cometary snows does not vary. The correction introduced by the temperature dependence 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 AU. 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 (Delsemme and Miller, 1971). An average value of  $-2.1$  therefore can be used. It remains true for all types 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 (McNesby and Okabe, 1964), giving reactions (1) or (2), respectively:



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 180 and 140 nm than between 140 and 115 nm.

For the third step, H and OH must be distinguished. H 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- $\alpha$  radiation.

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

Provided that 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 provided that the optical depth effects do not vary too much during the range of distances covered, because the global brightness in Lyman- $\alpha$  light (or in OH light) is practically proportional to the production rate of the H atoms (or of the OH radicals) in their excited state, one has

$$B \propto Zf^2 \propto r^{-6.1} \quad r < 1.3 \text{ AU}$$

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  $\text{H}_2\text{O}$  were dissociated by process (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 process (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. On the other hand, the evaporation of water could be used with more confidence to provide a physical meaning in Marsden's formulation of the nongravitational force.

## ACKNOWLEDGMENTS

I thank Dr. Code for an early communication of his results. This work was made possible by grant GP-17712 of the National Science Foundation.

## REFERENCES

- Blamont, J. 1970, Observation de l'Émission d'Hydrogène Atomique de la Comète Bennett. *C. R. Acad. Sci. Paris* **270**, 1581-1584.
- Code, A. D. 1971, Symp. on Recent Observations of Comets, AAS Div. Planet. Sci. (Tallahassee).
- Code, A. D., Houck, T. E., and Lillie, C. F. 1970, Comet Tago-Sato-Kosaka (1961g). Central Bureau Astron. Telegrams, IAU Circ. 2201.
- Delsemme, A. H. 1971, Symp. on Recent Observations of Comets, AAS Div. Planet. Sci. (Tallahassee).
- Delsemme, A. H., and Miller, D. C. 1971, Physico-Chemical Phenomena in Comets. III. The Continuum of Comet Burnham. *Planet. Space Sci.* **9**, in press.
- Donn, B., and Urey, H. C. 1956, On the Mechanism of Comet Outbursts and the Chemical Composition of Comets. *Astrophys. J.* **123**, 339-342.
- Haser, L. 1955, La Conservation des Radicaux Libres à Basse Température et la Structure des Noyaux des Comètes. *C. R. Acad. Sci. Paris* **241**, 742-743.
- Levin, B. F. 1943, *Astron. Zh.* **20**, 37.
- Levin, B. F. 1948, Dependence of the Variation in Brightness of Comets on Their Solar Distance. *Astron. Zh.* **25**, 246.
- McNesby, J. R., and Okabe, H. 1964, Vacuum Ultraviolet Photochemistry. *Advances in Photochemistry* (ed., W. A. Noyes et al.), vol. 3, p. 157. Wiley-Interscience. New York.
- Marsden, B. G. 1968, Comets and Nongravitational Forces I. *Astron. J.* **73**, 367-379.
- Marsden, B. G. 1969, Comets and Nongravitational Forces II. *Astron. J.* **74**, 720-734.
- Whipple, F. 1950, A Comet Model. I. The Acceleration of Comet Encke. *Astrophys. J.* **111**, 375-394.