Asteroids, Comets, Meteors 1991, pp. 325–328
Lunar and Planetary Institute, Houston, 1992

A NEW MEASUREMENT OF THERMAL CONDUCTIVITY OF AMORPHOUS ICE AND ITS IMPLICATIONS FOR THE THERMAL EVOLUTION OF COMETS

A. Kouchi(1), J. M. Greenberg(1), T. Yamamoto(2), T. Mukai(3), and Z. F. Xing(1)

(1) Laboratory Astrophysics, University of Leiden, 2300RA Leiden, The Netherlands
(2) Institute of Space and Astronautical Science, Yoshinodai, Sagamihara, Kanagawa 229, Japan
(3) Department of Earth Sciences, Kobe University, Nada, Kobe 657, Japan

ABSTRACT

Very slowly deposited amorphous ice has a thermal conductivity about four orders of magnitude or more smaller than hitherto estimated. Using the exceedingly low value of the thermal conductivity of comets deduced from the properties of amorphous ice leads to the expectation that internal heating of comets is negligible below the outer several tens of centimeters.

INTRODUCTION

Although the importance of knowing the thermal conductivity, κ, of vapor-deposited amorphous ice ($a\text{-}H_2O$) for predicting the thermal evolution of comets has been widely recognized (e.g., Klinger, 1980; Espinasse et al., 1991 and references therein), there has been no direct measurement available. Therefore, most of the discussions on comet evolution have been based on a theoretical estimation of κ by Klinger(1980). On the basis of our new experimental results and a reanalysis of data found in literature, we have arrived at a new estimate of the κ for $a\text{-}H_2O$ (Kouchi et al., 1991). We discuss the thermal evolution of comet using the new value of κ.

MEASUREMENT OF THERMAL CONDUCTIVITY

Kouchi et al.(1991) investigated the thermal diffusion in ice thin film during deposition, and gave the following relation:

$$h=(T_h-T_s)\bar{\kappa}/[(1-\bar{A})\sigma T_R^4-\bar{\epsilon}\sigma T_h^4+VL] \qquad (1)$$

where h is the thickness of ice film, T_h, T_s and T_R the temperature of the surface of ice film, that of a substrate and that of the ambient radiation field, respectively, $\bar{A}$ the Planck averaged albedo of the sample at temperature T_R, $\bar{\epsilon}$ the Planck averaged emissivity at temperature T_h, σ the Stefan-Boltzmann constant, V the deposition rate, L the heat of deposition per unit volume, and

$$\bar{\kappa} \equiv (T_h - T_s)^{-1} \int_{T_s}^{T_h} \kappa(T)\,dT,$$

the mean thermal conductivity between T_s and T_h. If we obtain the whole set of data: T_s, T_h, T_R, h and V, we can calculate the $\bar{\kappa}$ of a-H_2O using eq. (1). However, it is very difficult or almost impossible to measure the surface temperature T_h because the thickness of a-H_2O is very small compared to the size of the thermometer (e.g., thermocouples), and because the thermal conductivity of a-H_2O is smaller than that of any known thermometer.

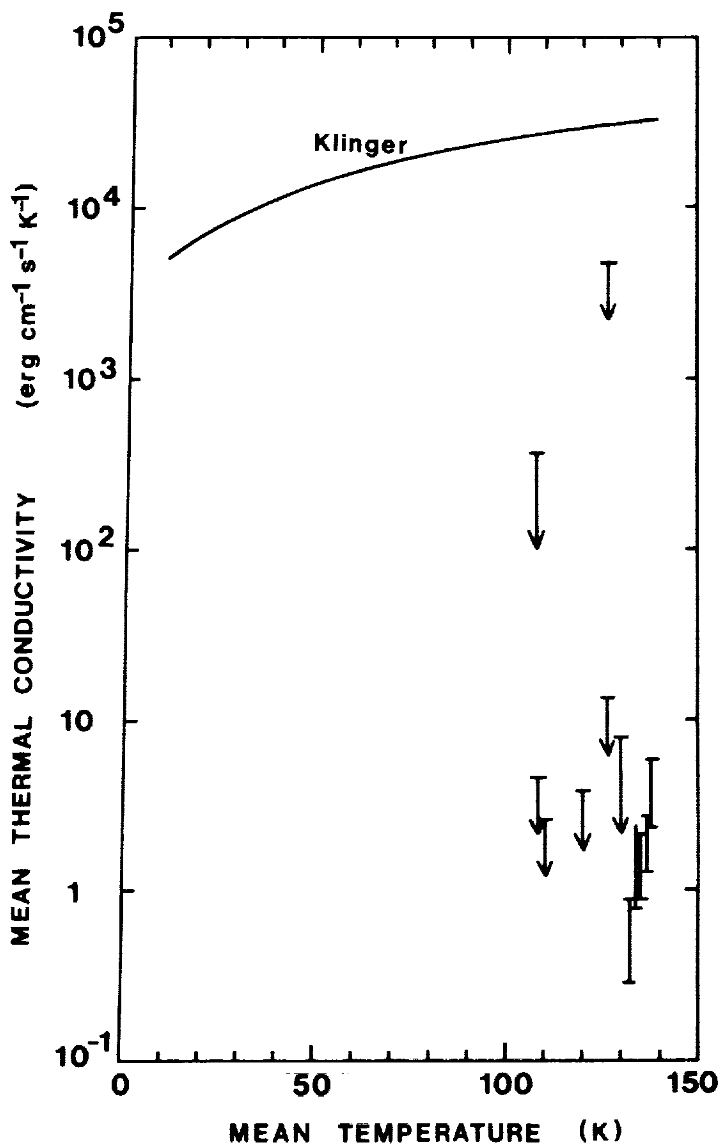

Fig.1 Mean thermal conductivities of amorphous ice obtained by Kouchi et al. (1991) and that estimated by Klinger (1980).

Kouchi et al. (1991) observed the structural change of ice films during deposition at T_s=125-130 K using reflection electron diffraction. At thicknesses smaller than h_c, deposition of a-H_2O occurred, while at a thickness larger than h_c, cubic ice (ice I_c) was deposited. This clearly shows that the surface temperature of the ice film at the thickness of h_c corresponds to the temperature of phase transition from a-H_2O to ice I_c, which occurs at around 140 K. Furthermore, this enables us to measure the T_h and, by assuming $\bar{A}$~0, $\bar{\epsilon}$~1 in eq. (1), to determine upper bound of $\bar{\kappa}$ of a-H_2O. Figure 1 shows the $\bar{\kappa}$ of a-H_2O obtained by Kouchi et al. (1991). It is clear that the $\bar{\kappa}$ is at least one to four orders of magnitude smaller than that estimated by Klinger (1980).

HEAT TRANSFER IN A COMET NUCLEUS

Since the cometary nucleus is very porous, the thermal conductivity of the nucleus may be one to two orders of magnitude smaller than that of constituent icy grains. This suggests that the thermal conductivity of the comet nucleus is certainly smaller than 1 erg cm^{-1} s^{-1} K^{-1} and possibly as low as 10^{-2}, a quite shocking result. With such a small value of κ, the major mechanism of heat transfer in the comet nucleus on short time scales may not be only by conduction. However, radiation transport both by visual and infrared and diffusive heat transport by evaporated water molecules are also negligible (Kouchi et al., 1991). The more volatile molecules like CO, CO_2 may be expected to play a more important role in diffusive heat transport than H_2O (Espinasse et al., 1991).

THERMAL EVOLUTION OF COMETS

Greenberg et al. (1991) investigated the pre-history of a new comet: from the protosolar nebula to the Oort cloud, then in the Oort cloud, and from the Oort cloud to the inner solar system. They found that all new comets return to the inner solar system at a temperature lower than their formation temperature in the protosolar nebula and a rough estimate is that it is reduced by about 1/2.

Greenberg et al. (1991) also investigated how little the solar heating affects the interior of a periodic comet. Table 1 shows some typical results for a comet of any size with the initial temperature of 16 K. It appears unlikely that below 25 cm, or even less, the temperature in a periodic comet will rise enough to evaporate CO and will certainly not be enough to evaporate or crystallize water ice.

The conclusion that even periodic comets preserve pristine interstellar matter in cold storage at relatively shallow depth mandates that a greater effort be made to provide the lowest possible return temperature——preferably less than 20 K——than to require probe depth to some meters.

Table 1. Illustrative examples of limitted heat penetration (ΔT) below the surface of a periodic comet nucleus. $\Delta T = T - 16$ K, T_0 is the surface temperature, and $\kappa = 10^{-2}$ erg cm^{-1} s^{-1} K^{-1}.

a) T_0=300 K (~1AU)

	time (yr)					
Δr(cm)	1	3	10	30	100	1000
5	0	7	61	135	197	256
10	0	0	4	43	123	228
20	0	0	0	1	33	176
50	0	0	0	0	0	61
75	0	0	0	0	0	18

b) T_0=130 K (~5AU)

	time (yr)			
Δr(cm)	1	10	100	1000
5	0	25	79	103
10	0	2	49	92
20	0	0	13	71
50	0	0	0	25
75	0	0	0	7

ACKNOWLEDGEMENTS

The authors would like to thank the Netherlands Organization for Scientific Research and the Japan Society for the Promotion of Science for their support. Part of this research was supported by NASA grant(# NGR 33-018-148). One of the authors (T.Y.) acknowledges the support from the University of Tsukuba, Japan. One of the authors (A.K.) was supported by the Yamada Science Foundation, Japan.

REFERENCES

Espinasse S., Klinger J., Ritz C., and Schmitt B. (1991) Modeling of the Thermal Behavior and of the Chemical Differentiation of Cometary Nuclei. Icarus, 92, 350-365.

Greenberg J. M., Yamamoto T., and Xing Z. F. (1991) The Peter Pan of the Solar System:Preservation of Protosolar Nebula Matter in Comets by their Exceedingly Low Thermal Conductivity. submitted to Nature.

Klinger J. (1980) Influence of a Phase Transition of Ice on the Heat and Mass Balance of Comets. Science, 209, 271-272.

Kouchi A., Greenberg J. M., Yamamoto T., and Mukai T. (1991) Extremely Low Thermal Conductivity of Amorphous Ice:Relevance to Comet Evolution. submitted to Ap. J. Lett..