DEUTERIUM ABUNDANCE IN COMETS: A CLUE TO THE HISTORY OF THE OUTER SOLAR SYSTEM. T. V. Ruzmaikina, Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721.

Abstract. An idea is suggested that the comparative study of D/H abundance in short- vs. long-period comets can help to verify the hypothesis that long-period comets were formed much closer to the Sun than short-period comets, which are believed to have formed beyond the region of the Kuiper belt.

Current point of view on the origin of comets. Comets provide sample return missions from the outskirts of the solar system to its inner part. Therefore they make it possible to study the composition and physical properties of the bodies that spent most of their lifetime far beyond the planetary system and preserved the least-altered material since the origin of the solar system. Therefore the comets provide an opportunity to study the history of the outer regions of the solar system. It is believed now that comets occupy the region from beyond Neptune's orbit to about 200,000 AU. The inner region of the cometary cloud is called the Kuiper belt, the outer is the Oort cloud after astronomers suggested their existence. The distribution of the orbits of short-period comets and direct observations [1] assume that the orbits of Kuiper belt objects have relatively small inclinations, i.e., that they are concentrated in the disk. An isotropic distribution of long-period comets is close to spherical.

Different mechanisms were suggested for the origin of long- and short-period comets. It is believed that short-period comets originated *in situ*, beyond the planetary system, but that long-period comets were formed as planetesimals in the region of giant planets, and then ejected onto highly elongated orbits and that then evolved to large perihelion distances as a result of random stellar perturbations [2–4].

The possiblity of checking this hypothesis has been afforded by high-precision measurements of the isotopic composition of comet ices, particularly the deuterium-to-hydrogen (D/H) ratio in comet water ice, during the flyby of comet Halley in 1986. It is known that the D/H ratio in the giant planets increases with increasing heliocentric distance. Therefore, measuring the D/H ratio in a comet can provide information as to what distance from the Sun the comet formed. Particularly, such an investigation could help distinguish regions where bodies of long-period and short-period comets were formed. The comparative study of short- and long-period comets would also help to check current ideas about the origin of the comets.

It is widely accepted now that short-period comets, whose aphelia are situated at the interval of distances from just beyond Neptune's orbit to a few of its radii, were agglomerated *in situ*, i.e., beyond 30 AU [5]. The region of formation of long-period comets is more controversial. The most popular hypothesis implies that these comets were formed as planetesimals in the region of giant planets, and then ejected onto highly eccentric orbits due to gravitational perturbations of planets. This hypothesis was suggested first by Oort in 1950, and continues to be dominant today.

This paper suggests that precise measurement of the D/H ratio in comets can put some restrictions on the distances where the comets were formed, and therefore provide an important clue to the understanding of solar system formation. If Oort's hypothesis is correct, then long-period comets were formed closer to the Sun and, hence, exposed to higher temperatures than short-period ones. Therefore, they should be more thermally reprocessed and have lower D/H ratios. The enrichment of the outer solar system with heavy isotopes is associated with the preservation of interstellar dust, which includes deuterium-enriched ices. It is known from observations that solar type stars are formed in dense cores of molecular clouds. It is assumed that the solar system has been formed under similar conditions. The temperature in the clouds is typically as low as 10 to 30 K. Under these conditions, the processes involved in molecular production and destruction could result in a large D/H fractionation. For example, observations show that the D/H ratio in water molecules ranges between 10^{-4} and 10^{-2}; and the typical value for the interstellar medium is 2×10^{-5}; a similar abundance of deuterium is in the Sun and, hence, in a presolar cloud. In a cold cloud most molecules (except molecular hydrogen) ultimately become frozen-in dust particles and aggregates. The gaseous fraction of the cloud becomes underabundant in heavy isotopes.

In this paper we study the processes that affect the D/H ratio in water ice during the infall stage of the formation of the solar nebula. The restrictions imposed by radial mixing in the solar nebula, and the thermal processing of planetesimals during planetesimal formation will be studied soon. During collapse of the presolar cloud, dust particles composed of water ice and more volatile components would be partially or completely evaporated in a wide region of the infalling envelope, accretional shock, or within the solar nebula. Infalling gas generates shock when it hits the solar nebula. The intensity of the shock depends on the distance from the Sun and the angle between the lines of flow of infalling gas and the surface of the solar nebula. Here we consider a case of normal infall, with the velocity of free infall, for which $\upsilon_\perp$, the Mach number, is $\upsilon_\perp/c_s \geq 10$, where c_s is the sound speed in the solar nebula gas. The gas is heated in the shock to

$$T_2 = \frac{7}{36}\frac{\mu m_H}{k_T}\upsilon_\perp^2 \sim 5\times10^3\,\frac{1\,\mathrm{AU}}{R}\ \mathrm{K}.$$

Under these conditions, exchange reactions are very fast, and therefore one can expect that isotopic exchange in the gas will establish a new high-temperature equilibrium.

Maximum temperature of dust aggregates. Three main processes—absorption of ultraviolet radiation and the thermal IR radiation emitted by other particles, thermal collisions with gas atoms and molecules, and drag associated with the inertial motion of the particles through the decelerated gas—contribute to the heating of solid particles in the vicinity of the shock front.

The most important heating of large grains in the postshock region is due to gas drag as the grains move by inertia through the decelerated gas. The grains are cooled mainly by their thermal emission. The emissivity of large grains is supposed to be similar to that of the black body. For smaller dust grains the absorption and emission efficiency are given by the Mie theory.

The temperature to which dust aggregates are heated in the shock front depends on the size of grains. For submillimeter and larger grains, the peak temperature can reach

$$T_{gr} = 2.8 \cdot 10^3 \xi \left(\frac{\dot{M}}{10^{-5}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}} \right)^{1/4} \left(\frac{\mathrm{M}_\odot}{M} \right)^{-1/4} \left(\frac{R}{1\,\mathrm{AU}} \right)^{-1} \mathrm{K},$$

and hence the temperature of the evaporation of water ice $T_{ev} \simeq 175$ K is reached at heliocentric distances

$$R \leq 16 \left(\frac{\dot{M}}{10^{-5}\mathrm{yr}^{-1}} \right)^{1/4} \left(\frac{\mathrm{M}_\odot}{M} \right)^{-1/4} \left(\frac{T_{gr}}{175\mathrm{K}} \right)^{-1} \mathrm{AU}.$$

It follows from this equation that the region of evaporation of ice grains extends to 28.5 AU if the density of infalling gas is 10 times larger than the average density of infalling gas for the rate of accretion 10^{-5} $M_\odot$ yr^{-1} and $M \simeq M_\odot$. Submicron ice particles are evaporated in $\sqrt{\upsilon_\perp / c_s} \sim 3$ times smaller region. (The distances of evaporation of more volatiles ice H_2S, NH_3, and CH_4 are larger—1.7, 2.0, and 3.9 times respectively—than the region of evaporation of water grains of the same size.)

Within this region, evaporation of interstellar ices results in the loss of excess deuterium in the hydrogen-bearing molecules. Planetesimals formed in this region would have a lower abundance of deuterium than those formed at larger distances. It is worth noting that the D/H ratio in the atmospheres of planets increases about 5 times between Jupiter and Uranus, and then changes much less remarkably. An accurate determination of the deuterium abundance in volatile ices of comets makes it possible to put restrictions on the region of intervals where the comets were formed and, particularly, to check the hypothesis about comet formation in the region of the giant planets.

Summary. Thus, if evaporation of interstellar ices during formation of the solar nebula results in a loss of excess deuterium in the hydrogen-bearing molecules, then planetesimals formed in this region would have a lower abundance of deuterium than those formed at larger distances. Therefore studying the deuterium abundance in volatile ices of comets makes possible to put restrictions on the region of intervals where the comets were formed and particularly, check the hypothesis about comet formation in the region of giant planets.

References: [1] Jewitt d. C. and Luu J. X. (1995) *ApJ., 109,* 1867. [2] Safronov V. S. (1969) in *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets* (Moscow: Nauka Press); also NASA-TT-F-677 (1972). [3] Fernandez J. A. and Ip W.-H. (1983) *Icarus, 45,* 377. [4] Weissman P. R. and Levinson H. F. (1996) the *Population of Trans-Neptunian Region.* Preprint JPL D-13386. [5] Weidenschilling S. J. (1996) *Icarus,* in press.