Formation Location of Enceladus and Comets from D/H Measurements. J.-M. Petit[1], O. Mousis[1] and J.J. Kavelaars[2], [1]Institut UTINAM, CNRS / Université de Franche Comté, Besançon, France (Jean-Marc.Petit@normalesup.org), [2]Herzberg Institute of Astrophysics, National Research Council of Canada, Victoria, Canada.

Introduction: A comet's origins in the primitive nebula can be probed by examining the degree to which fossil deuterium is enriched compared to the protosolar abundance. Calculations of the temporal and radial evolution of the deuterium enrichment in the solar nebula can reproduce existing D/H measures for comets [1], [2], [3]. These calculations show that the deuterium enrichment in water ice strongly depends on the distance from the Sun at which the ice was formed. Comparing the D/H value measured in comets with those predicted by such models allows retrieval of their formation location. The measurement of the D/H ratio at Enceladus by the Ion and Neutral Mass Spectrometer aboard the Cassini spacecraft [4] provides a new, and tighter, constraint on the deuterium enrichment profile in the outer solar nebula prompting us to reconsider models presented in previous works [5].

Reservoirs and Source Regions of Comets: The ``cometary reservoir'' is the region of semi-stable phase space from which comets are currently being delivered, while the ``source regions'' are those parts of the primitive nebula in which the comets formed and were then delivered to the reservoirs. Ecliptic and isotropic comets are being delivered from at least two distinct reservoirs and, as such, are likely from different source regions.

The reservoir of the isotropic comets is, generically, the Oort cloud (see [6] for a good review). Some fraction of the isotropic comets with a<20,000 AU may arrive from the ``innermost'' component of this distribution [7], the remainder coming from the outer Oort cloud. Modeling of delivery into the Oort cloud reservoir generally finds this process to be controlled by Uranus-Neptune scattering.

If Uranus and Neptune originated at (roughly) 12 and 15 AU then material currently being delivered from the Oort cloud reservoir should have originated from a source much closer to the Sun than in cases where Uranus and Neptune formed at or near their current locations (~20 & 30 AU). A tracer of the chemical evolution of the primordial solar system that is sensitive to variations in the physical conditions between 10 and 30 AU, an example of which is described in the next section, provides a discriminator between these formation scenarios.

D/H in the Solar Nebula: Figure 1 describes the evolution of f, defined as the ratio of D/H in H_2O to that in molecular H_2, as a function of distance from the Sun in the case of a typical solar nebula. As in previous work, we assume that f is constant at $t = 0$ irrespective of the heliocentric distance and corresponds to the value measured in the highly enriched component found in LL3 meteorites (D/H = (73 ± 12) x 10^{-5} [8]) compared to the protosolar value ((2.1 ± 0.4) x 10^{-5} [9]). The highly enriched component in LL3 meteorites is presumed to originate from ISM grains that were not reprocessed when entering the nebula [2] and is consistent with D/H measurements from ISO in grain mantles in W33A [10].

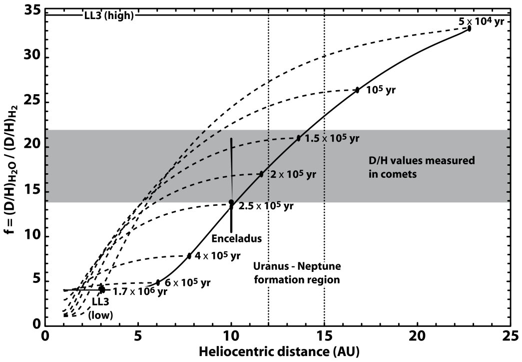

Figure 1: Enrichment factor f as a function of the heliocentric distance. The dashed curves correspond to the evolution of f in the gas phase prior to condensation terminated by dots at the heliocentric distance where H_2O condenses at the given epoch. The solid curve represents the value of f acquired by ice as a function of its formation distance in the nebula. D/H enrichments in LL3 (low and high) meteorites and Enceladus are shown for comparison. We take the LL3 (high) value as the initial, protosolar, value. The vertical dotted lines enclose the source region of Uranus and Neptune in the Nice model. The gray area corresponds to the dispersion of the central values of the f in the comets for which measurements are available.

For the adopted set of parameters, the deuterium enrichment profile simultaneously matches the nominal D/H value measured in H_2O in the moderately enriched component of LL3 meteorites at 3 AU and at the current heliocentric distance of Saturn matches the D/H enrichment of Enceladus. We were unable, in this investigation, to find models matching both the moderately enriched component of the LL3 meteorites at 3 AU and the value at Enceladus at 10 AU that did not also require the value of f to increase to much larger values in the region beyond 15 AU. Thus, the result that f in the 20-30 AU zone should have exceeded ~25 is a generic outcome of the temperature evolution of the disk, when constrained by the D/H measured at

Enceladus, and not particularly dependent on the model of that evolution.

Discussion: *Isotropic Comets:* 1P/Halley, 8P/Tuttle, C/1995 O1 (Hale-Bopp), C/1996 B2 (Hyakutake), and C/2001 Q4 (NEAT) all have D/H values that are consistent with or slightly larger than that of Enceladus. These comets are all members of the nearly-isotropic class and are, thus, drawn from a reservoir in some part of the Oort cloud. Based on dynamical arguments, the Oort cloud itself was fed by material from the Uranus/Neptune region. Our modeling of the dependence of f (pinned by the measured deuterium enrichment of Enceladus) on formation location (see Figure 1) precludes these comets from having formed beyond ~15 AU from the Sun. This implies that Uranus and Neptune were originally closer to the current location of Saturn than observed today, a configuration quite similar to that preferred in the Nice model.

Ecliptic Comets: Dynamical processes that populate the ecliptic comet reservoir (either the Kuiper Belt, scattering disk, or some combination) all draw their source populations from beyond the orbit of Neptune (at least beyond 17 AU). Based on our model of the radial dependence of f (see Figure 1), we predict that the measured D/H ratio in the ecliptic comet population should exceed 24 times solar.

The D/H ratio of a Jupiter-family comet has been measured recently when the Herschel Space Observatory observed comet 103P/Hartley 2 [11]. The obtained value, $(16.1 \pm 2.4) \times 10^{-5}$ is very close to that of Earth's water ($(15.58 \pm 0.01) \times 10^{-5}$), corresponding to an enrichment factor $f \sim 8$, four times smaller than predicted by our model. This model depends on two major assumptions that may prove wrong and explain the discrepancy between the measured and predicted values.

A fraction of ecliptic comets could have formed at closer distances from the Sun than assumed here and has been ejected outward. In this case, ecliptic comets would display D/H ratios with strong discrepancies. However, most of them should present values close to the one predicted by [5] because the fraction of ecliptic comets formed closer to the Sun would remain marginal compared to those formed at higher heliocentric distances.

The high level of deuteration predicted in ecliptic comets from the description of the isotopic exchange between H_2 and H_2O in the gas phase of the disk is based on classical models of the solar nebula (the alpha-turbulent model) in which the disk's temperature, pressure and density decrease monotonically with increasing heliocentric distance. These models do not consider the possible presence of sporadic and local phenomena such as shock waves that have been invoked to speed up the formation of planetesimals and trigger the crystallization of initially amorphous silicates prior to their incorporation in comets. Shock waves in the outer nebula could have locally increased the disk's temperature and pressure conditions and might have significantly decreased the deuteration level of the H_2O ice formed at this place. A possibly extended, both in time and space, major shock wave could have been induced by the inflow of the presolar cloud or envelop onto the outer part of the accretion disk at the time of the disk's formation. The influence of this mechanism on the outer disk's thermodynamic conditions and chemistry remains to be investigated.

Future space probe missions and improved remote-sensing capabilities will likely provide a larger number and variety of cometary D/H measurements and will surely increase the constraints on the primordial configuration from which the planetary system evolved to its current state.

Acknowledgements: J. Kavelaars acknowledges support provided by Embassy France. O. Mousis acknowledges support provided by the Centre National d'Etudes Spatiales.

References: [1] Drouart, A. et al. (1999) *Icarus, 140,* 129-155. [2] Mousis O. et al. (2000) *Icarus, 148,* 513-525. [3] Horner J. et al. (2007) *Earth Moon & Planets 100,* 43-56. [4] Waite J. H. Jr. et al. (2009) *Nature, 460,* 487-490. [5] Kavelaars J. J. et al. (2011) *Astrophys. J. Letters, 734,* L30-L34. [6] Dones L. et al. (2004) *Comets II,* University of Arizona Press, Tucson. [7] Kaib N. A. & Quinn T. (2009) *Science, 325,* 1234-1236. [8] Deloule E. et al. (1998) *Geochim. Cosmochim. Acta, 62,* 3367-3378. [9] Geiss J. & Gloeckler G. (1998) *Space Science Reviews, 84,* 239-250. [10] Teixeira T. C. et al. (1999) *A & A, 347,* L19-L22. [11] Hartogh P. et al. (2011) *Nature, 478,* 218-220.