ON THE FORMATION LOCATION OF URANUS AND NEPTUNE AS CONSTRAINED BY DYNAMICAL AND CHEMICAL MODELS OF COMETS

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ABSTRACT

The D/H enrichment observed in Saturn’s satellite Enceladus is remarkably similar to the values observed in the nearly-isotropic comets. Given the predicted strong variation of D/H with heliocentric distance in the solar nebula, this observation links the primordial source region of the nearly-isotropic comets with the formation location of Enceladus. That is, comets from the nearly-isotropic class were most likely fed into their current reservoir, the Oort cloud, from a source region near the formation location of Enceladus. Dynamical simulations of the formation of the Oort cloud indicate that Uranus and Neptune are, primarily, responsible for the delivery of material into the Oort cloud. In addition, Enceladus formed from material that condensed from the solar nebula near the location at which Saturn captured its gas envelope, most likely at or near Saturn’s current location in the solar system. The coupling of these lines of evidence appears to require that Uranus and Neptune were, during the epoch of the formation of the Oort cloud, much closer to the current location of Saturn than they are currently. Such a configuration is consistent with the Nice model of the evolution of the outer solar system. Further measurements of the D/H enrichment in comets, particularly in ecliptic comets, will provide an excellent discriminator among various models of the formation of the outer solar system.

Key words: comets: general – Kuiper Belt: general – planets and satellites: composition – planets and satellites: dynamical evolution and stability – protoplanetary disks

1. INTRODUCTION

Levison (1996), following on previous work by Carusi et al. (1987) and others, proposes two broad classes of comets, the ecliptic and the nearly-isotropic. Objects are selected into these dynamical classes by their Tisserand parameter with respect to Jupiter. Levison finds that the value $T_J \sim 2$ results in a secure boundary between comets from different reservoirs. Different reservoirs likely indicate different source regions within the primordial solar nebula. Determining the source regions from which the comet reservoirs were first populated, and modeling the chemical evolution of those source regions as constrained by observations of comets, will provide important clues on the physical and chemical structure of the primordial solar system.

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 (Drouart et al. 1999; Mousis et al. 2000; Horner et al. 2007). 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 (Waite et al. 2009) 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. We pay particular attention, in this analysis, to the source region of the reservoir of nearly-isotropic comets under the conditions described in the Nice model scenario (Levison et al. 2008) of the formation of the outer solar system. We demonstrate that the measured D/H abundance ratios for Oort cloud comets are consistent with their formation having been in the 10–15 AU zone of the solar system. Further, comets with (D/H)$_{ab,0} \lesssim 5 \times 10^{-4}$ are precluded from forming more than $\sim 15$ AU from the Sun.

2. RESERVOIRS OF COMETS AND THEIR SOURCE REGIONS

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 ecliptic comets has been demonstrated to be the Kuiper Belt and may be, more precisely, the “scattered disk” component of that population (Duncan & Levison 1997). The source region of the Kuiper Belt is a matter of current debate. In the Nice model, Uranus and Neptune originate in the 10–15 AU region of the primordial solar system and later are transported to their current locations via dynamical interactions. During this process, material in the 20–30 AU region is deposited into the Kuiper Belt and scattered disk. More classically, the source of the Kuiper Belt may be the remnant of an in situ population. Regardless, the ecliptic comets now being delivered from some part of the Kuiper Belt formed beyond the formation location of Neptune.

For the isotropic comets the reservoir region is, generically, the Oort cloud (see Dones et al. 2004 for a good review). Some fraction of the isotropic comets with $a < 20,000$ AU may arrive from the “innermost” component of this distribution (Kaib & Quin 2009), the remainder coming from the outer Oort cloud. Modeling of delivery into the Oort cloud reservoir (e.g., Dones...
Sedna (Brown et al. 2004), motivated Brasser et al. to consider pericenters, such as 2000 CR105 (Gladman et al. 2002) and other icy bodies (Brown et al. 2004) generally finds this process to be controlled by the interactions of the icy bodies with the gas. In the pre-solar nebula, fractionation resulted in heavier hydrogen being retained in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became the abundant hydrogen bearer in the solar nebula, water became 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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 ($D/H = (73 \pm 12) \times 10^{-5}$; Deloule et al. 1998) compared to the protosolar value ($(2.1 \pm 0.4) \times 10^{-5}$; Geiss & Gloeckler 1998). The highly enriched component in LL3 meteorites is presumed to originate from ISM grains that were not reprocessed when entering the nebula (Mousis et al. 2000) and is consistent with $D/H$ measurements from the Infrared Space Observatory in grain mantles in W33A (Teixeira et al. 1999).

For the adopted set of parameters, the deuterium enrichment profile simultaneously matches the nominal D/H value measured in H$_2$O 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 $\sim 25$ 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.

4. INTERPRETATION OF THE DEUTERIUM TO HYDROGEN RATIO MEASURED AT ENCELADUS BY THE CASSINI SPACECRAFT

One could argue that the building blocks of Enceladus were formed in Saturn’s subnebula, implying that the D/H ratio in H$_2$O measured at this satellite by the Cassini spacecraft might not be representative of the one acquired by planetesimals condensed in Saturn’s feeding zone in the solar nebula. In order to show that this hypothesis is unlikely, we have performed calculations of the evolution of the D/H ratio in H$_2$O in Saturn’s initially hot subnebula. The hypothesis of an initially hot subnebula is required if one wants to assume that the building blocks of the regular icy satellites, including Enceladus, were formed in situ. To do so, we have used the same turbulent disk model utilized to describe the evolution of the D/H ratio in water in the solar nebula, but in a version scaled to the plausible size and properties of the Saturn’s subnebula. This model has already been used to describe the thermodynamic evolution of cold subnebulae around Saturn and Jupiter (Mousis et al. 2002a, 2002b; Mousis & Gautier 2004). Here we consider the subdisk parameters of the initially hot Saturn’s subnebula depicted by Alibert & Mousis (2007) and whose evolution was constrained by Saturn’s formation models. The viscosity parameter, the initial mass, and outer edge of our Saturn’s subnebula have then been set to $2 \times 10^3$, $7 \times 10^3$ Saturn’s mass, and 200 Saturnian radii, respectively.

Figure 2 shows the temporal evolution of the temperature profile in the midplane of Saturn’s subnebula. Because the initial temperature of the subnebula is very high, any icy planetesimal entering the subdisk at early epochs of its evolution should be devolatilized and would then enrich the gas phase of the disk. In this model, ice forms again at the outer edge of the subnebula at $t \sim 3 \times 10^3$ yr (once the gas temperature has decreased down to $\sim 155$ K at the corresponding pressure conditions) and its condensation front reaches the orbit of Enceladus after only a few dozen thousands of years of its evolution.

Figure 3 represents the evolution of the D/H ratio in H$_2$O in the subnebula described with the same approach as in Section 3. We have assumed that the deuterium enrichment factor, $f$, is equal to 13.8 (i.e., the value measured at Enceladus by the Cassini spacecraft) in the whole subnebula at $t = 0$. Due to the high temperature and pressure conditions that favor the isotopic exchange between H$_2$O and H$_2$ within the subnebula, $f$ rapidly diminishes and converges toward 1 in about 1000 years, prior to the condensation of ice (see dashed curve in Figure 3). We find that planetesimals should present D/H ratios in H$_2$O very close to the protosolar value if they were condensed within Saturn’s subnebula. The isotopic exchange is so efficient at the temperature and pressure ranges likely to have been present the Saturn subnebula that $f$ would converge toward $\sim 1$ for...
system formation, where Uranus and Neptune form near their current locations of 20 and 30 AU, the ice-giants would have delivered cometesimals to the Oort cloud with values of \( f > 25 \), which is not seen. We find that, for our model of deuterium evolution, having a value of \( f \sim 15 \) (as required by the Enceladus measurement) at 10 AU and \( f \sim 15 \) at 25 AU is not possible.

The Nice model for the formation of the solar system, however, asserts that the formation location of Uranus/Neptune, and presumably then the region from which they delivered the majority of the material into the Oort cloud, was considerably nearer to present day Saturn, between 11 and 13 AU for Uranus and 13.5 and 17 AU for Neptune (Tsiganis et al. 2005). This is precisely that zone of the primordial solar system which our modeling indicates cometesimals would have formed with values of \( f \) similar to that observed in the nearly-isotropic comets. Thus, the current measured values of \( f \) in the isotropic comet population appears to support a more compact configuration for the early solar system. Our knowledge of the dynamics of the formation of the Oort cloud from a compact configuration remains uncertain, indeed the origin of the Oort cloud comets maybe varied (Clube & Napier 1984, for example). The homogeneity of \( D/H \) measures in Oort cloud comets and similarity of those values to that measured for Enceladus provides an interesting constraints for such scenarios.

5.2. Ecliptic Comets

At present, no comets in the ecliptic class have known \( D/H \) levels. The Rosetta mission, currently en route to the ecliptic comet 67P/Churyumov–Gerasimenko, may alter this situation. 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.

6. CONCLUSIONS

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 \( \sim 15 \) 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. 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.

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