Tracing Formation and Evolution of Outer Solar System Bodies through Stable Isotopes and Noble Gas Abundances

*Kathleen Mandt[1]

1. Johns Hopkins University Applied Physics Laboratory

Comparative planetology using isotope geochemistry has played a critical role in understanding processes at work in and the history of outer Solar System bodies [see 1, and references therein]. The $^{12}C/^{13}C$ measured in methane on Titan has enabled us to determine the maximum length of time that methane has been present in the atmosphere [2,3], showing that methane has not been present in Titan's atmosphere throughout the history of the solar system and is limited to no more than 1 billion years (Gyr) [3]. We have also determined how much methane has been converted to organics over that were then deposited on the surface [3] and find agreement with estimates of surface inventories [4]. Observations of $^{14}N/^{15}N$ in HCN and N_2 in the atmosphere of Titan provides direct evidence of how photochemistry influences stable isotopes [5,6]. We have used these observations to determine that Titan's nitrogen originated as NH_3 in the protosolar nebula [7]. All of this work relies on spacecraft-based observations made at Titan. Ground-based observations combined with spacecraft observations are also of high value. The lower limit observed for $^{14}N/^{15}N$ in HCN in Pluto's atmosphere by ALMA [8] combined with New Horizons observations of the atmospheric composition [9] provides a valuable tool for determining the origin of nitrogen for Pluto if the influences of condensation and aerosol trapping on isotopes can be constrained [10] for which work is ongoing. All of this work is relevant to a future Ice Giants mission to Neptune, where the same methods could be applied to Triton and combined with ALMA observations. Furthermore, a mission to Io that makes in situ observations of the isotopic composition of the atmosphere could provide important information about volatile loss and interior processes at Io, assuming production and loss processes can be well constrained. Finally, noble gas abundances have been an important tool for understanding the origin and evolution of volatiles in the terrestrial planet atmospheres [see review in 1]. The recent measurement of cometary noble gas abundances [11] provides important information on the composition of the icy bodies that contributed to the formation of the gas giants, providing constraints for future in situ measurements that should be made with an atmospheric probe [12].

[1] Mandt K. E. et al. (2015a) *SSRv, 197,* 297–342. [2] Mandt K. E. et al., (2009) *PSS, 57,* 1917–1930. [3] Mandt K. E. et al., (2012) *ApJ, 749,* 160. [4] Lorenz, R. D. et al. (2008). *GRL*, *35*(2), L02206. [5] Liang et al. (2007) *ApJL, 664*, L115-L118. [6] Mandt et al. (2012b) *JGR, 117*, E10006. [7] Mandt K. E. et al., (2014) *ApJL, 788,* L24. [8] Lellouch et al. (2017) *Icarus, 286*, 289-307. [9] Young et al. (2017). [10] Mandt et al. (2017) *MNRAS*, *472*, 118-128. [11] Rubin et al. (2017) *Sci Adv*, *4*(7), eaar6297. [12] Mandt et al., in preparation.

Keywords: Titan, Pluto, Triton, Ice Giants, Stable Isotopes, Noble Gases

