SESSION 5

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Kuiper Belt object 2014MU$_{69}$, Pluto and Phoebe as windows on the composition of the early solar nebula

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Abstract. The initial chemical composition of a proto-planetary nebula depends upon the degree to which 1) organic and ice components form on dust grains, 2) organic and molecular species form in the gas phase, 3) organics and ices are exchanged between the gas and solid state, and 4) the precursor and newly formed (more complex) materials survive and are modified in the developing planetary system. Infrared and radio observations of star-forming regions reveal that complex chemistry occurs on icy grains, often before stars even form. Additional processing, through the proto-planetary disk (PPD) further modifies most, but not all, of the initial materials. In fact, the modern Solar System still carries a fraction of its interstellar inheritance (Alexander *et al.* 2017). Here we focus on three examples of small bodies in our Solar System, each containing chemical and dynamical clues to its origin and evolution: the small-cold classical Kuiper Belt object (KBO) 2014MU_{69}, Pluto, and Saturn's moon, Phoebe. The New Horizons flyby of 2014MU_{69} has given the first view of an unaltered body composed of material originally in the solar nebula at $\sim$45 AU. The spectrum of MU_{69} reveals methanol ice (not commonly found), a possible detection of water ice, and the noteworthy absence of methane ice (Stern *et al.* 2019). Pluto's internal and surface inventory of volatiles and complex organics, together with active geological processes including cryo-volcanism, indicate a surprising level of activity on a body in the outermost region of the Solar System, and the fluid that emerges from subsurface reservoirs may contain material inherited from the solar nebula (Cruikshank *et al.* 2019a,b). Meanwhile, Saturn's captured moon, Phoebe, carries high D/H in H_2O (Clark *et al.* 2019) and complex organics (Cruikshank *et al.* 2008), both consistent with its formation in, and inheritance from, the outer region of the solar nebula. Together, these objects provide windows on the origin and evolution of our Solar System and constraints to be considered in future chemical and physical models of PPDs.

Keywords. Kuiper Belt objects, Proto-planetary disk Models, Methanol Ice, Solar Nebula

1. Introduction

The New Horizons flyby of the small, cold-classical object 2014 MU_{69} (MU_{69}) in 2019 provides a new window into the environment and composition of the Solar System at $\sim$45 AU, a region stable against dynamical forces that contains the most primitive object we have ever visited with a spacecraft. In contrast to Pluto, tiny MU_{69} (~ 33 km) formed where it is today and the paucity of impact craters on its surface suggests that details of accretion are well preserved. The stability of ices in the cold classical region of the Solar System is currently under investigation (Lisse *et al.* 2020).

Pluto, having formed from material significantly closer to the Sun, was later perturbed outward to its current location by the migration of Neptune (Nesvorny 2015). Its composition and dynamical history provide an important contrast to MU_{69}. Another small body of compositional and dynamical relevance is Saturn's satellite, Phoebe, which formed out of material beyond Neptune's orbit as did Pluto, and through some dynamical process was subsequently captured into the Saturnian system as a distant, retrograde satellite. Phoebe is probably too small to have melted substantially and differentiated, so may represent a sample of material closely similar to Pluto's initial composition, but without the heating and differentiation experienced by the much larger Pluto. Although they are likely to preserve the basic compositions of the outer regions of the protosolar nebula where they aggregated, with their widely different histories and dimensions Phoebe (~ 218 km), Pluto (~ 2376 km) and MU_{69} (~ 33 km) provide data points to be explained by future chemical and physical models of the origin and evolution of the Solar System and other planetary systems.

2. Forming planetary systems

Theoretical models of the proto-planetary disk (PPD) phase in stellar evolution use observational input of various stages of star formation to develop the steps that lead to planetary systems. The dynamical movement of the gas and dust, the physical conditions of the solar nebula, and the composition of the PPD drive the chemical evolution at every stage. Chemical reactions occur in the solar nebula as ice-mantled grains cycle vertically and radially through the PPD (e.g., Ciesla & Sandford 2012), and observations that can spatially resolve details in some of the nearby forming systems are critical to provide insight at the many stages along the way (Brogan *et al.* 2015). How do the new observations of MU_{69} and comparisons with other primitive bodies of the Solar System fit in with the theoretical models of PPD formation?

Recent observations have revealed a depletion of gas phase CO in the warm (T>22K) upper regions of young PPDs up to 2 orders of magnitude below the canonical value of 10^{-4} (Bruderer *et al.* 2012; Favre *et al.* 2013; Du *et al.* 2015; Kama *et al.* 2016; Ansdell *et al.* 2016; McClure *et al.* 2016; Schwarz *et al.* 2016; Zhang *et al.* 2017). PPD models have explored CO removal by either a purely physical means (sequestration on icy grains growing in the midplane) (e.g., Krijt *et al.* 2018) or by local chemical processing (using the CO to form other chemicals) (Bergin *et al.* 2014; Bosman *et al.* 2018; Eistrup *et al.* 2018; Schwarz *et al.* 2018). The methanol in the spectrum of MU_{69} raises the question of whether or not the missing CO forms CH_3OH instead of returning to the gas phase in these PPDs. Indeed, the PPD models that use the CO to form other molecules can produce methanol on the relevant timescales (~ Myr), but neither the strictly physical nor strictly chemical evolutionary approach can reproduce the magnitude of CO depletion observed in nearby disks (Zhang *et al.* 2019). New efforts that combine both the physical and chemical processes are underway (Krijt, private communication).

3. The Solar System

Our Solar System represents a mature planetary system, encompassing many regularities (coplanar orbits, uniform direction of motion around the Sun, etc.), but also a number of anomalous bodies in terms of dimensions, compositions, and dynamical histories. Both categories reflect, to varying degrees, the original composition of the solar

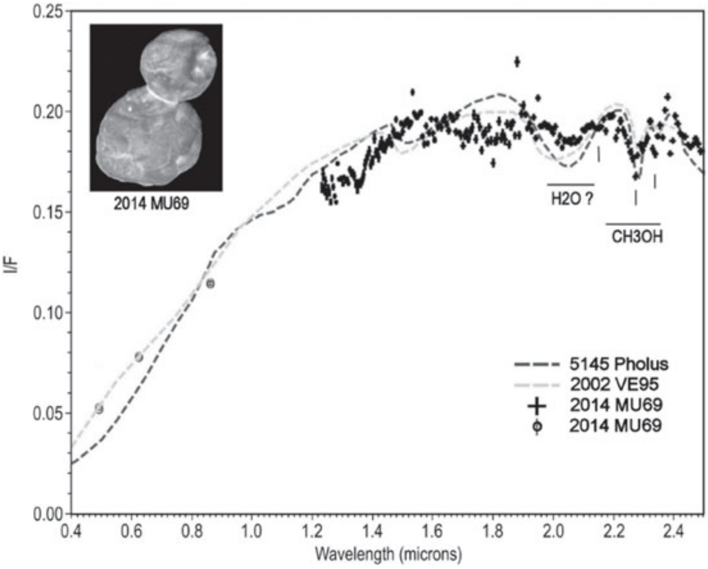

Figure 1. The spectrum of MU_{69} obtained by the New Horizons spacecraft compared to other primitive bodies, Pholus and VE_{95}. After Stern *et al.* (2019)

nebula, but a few bodies may be especially helpful in deciphering the earliest stages of formation. Here we consider the specific characteristics of MU_{69}, Pluto and Phoebe.

3.1. *2014*MU$_{69}$

Orbiting the Sun in a near-circular (e = 0.042), low-inclination (2.45 degree) orbit that is dynamically stable over the age of the Solar System, MU_{69} appears in images obtained by the New Horizons spacecraft to be a contact binary body composed of two components that fused in a low-energy collision (Stern *et al.*2019). Its stable orbit suggests that MU_{69} aggregated in the solar nebula at or near its present heliocentric distance. Because it is small and has never approached the Sun or differentiated chemically or physically, MU_{69} is thought to retain the composition of material in the solar nebula at $\sim$45 AU.

The near-infrared spectrum of MU_{69} obtained by the New Horizons spacecraft reveals absorption bands of methanol ice at 2.1, 2.27, and 2.33 μm and a possible water ice band at 2.0 μm (Fig. 1). In the visible spectral region, the very red spectral slope of both lobes closely matches that of Pholus, the small body where methanol ice was first discovered (Cruikshank *et al.* 1998), and on KBO 2002VE_{95} (Barucci *et al.* 2012). The high abundances of CH_3OH relative to H_2O, especially in MU_{69}, could provide important constraints for the PPD models.

Noteworthy is the uniformity of color, spectral signature, and physical texture of the two lobes of MU_{69}. All three characteristics support the contention that it is composed of a homogeneous mixture of indigenous material with a surface that has been uniformly processed by the space environment, and has not endured many collisions with small impactors. The native material is expected to be a composite of ice (primarily H_2O, but also CH_4, N_2, CO and others), rocky material of basic chondritic composition, and complex organics inherited from the nascent interstellar cloud and from processes in the early solar nebula. The lack of a clear H_2O detection in the spectrum of MU_{69} does not preclude its presence under a space-weathered surface (Grundy *et al.* 2019).

3.2. *Pluto*

As a consequence of its larger size and its previous and current geological activity, Pluto's composition and organic molecular inventory, is more complex than that seen on MU_{69}. Various lines of geophysical evidence point to the existence of an internal global ocean in Pluto's history; remnants of the ocean may persist to the present time, either globally or in fluid pockets in the subsurface (Cruikshank *et al.* 2019a,b). Pluto's surface has strongly colored exposures of H_2O ice bearing the spectral signature of NH_3 (Dalle Ore *et al.* 2019) appearing in regions where geological forces have cracked the bedrock, thus enabling the effusion of a fluid from subsurface reservoirs by way of cryovolcanic processes (Cruikshank *et al.* 2019b). The ammoniated liquid H_2O that emerges from subsurface environs is laden with organics that likely contain a mixture of original and processed constituents.

Pluto's surface shows solid N_2, CH_4, CO, H_2O, NH_3 ices, plus colored refractory organics from photolysis/radiolysis of surface ices (Materese *et al.* 2014, 2015; Baratta *et al.* 2015; Grundy *et al.* 2018). The surface deposits of non-ice components that are varied in color, but primarily red-brown, are interpreted as a refractory polymer-like organic complex (termed tholin) made by the energetic processing of hydrocarbons and other molecules in the surface ices and the atmosphere.

3.3. *Phoebe*

Phoebe is in a high inclination, eccentric, retrograde orbit around Saturn, indicating that it originated outside the Saturn system and was later captured by the planet. Clark *et al.* (2019) report the detection of HDO in spectra obtained by the Cassini spacecraft, measuring a high D/H in H_2O (8.3 x Vienna Standard Mean Ocean Water) and an anomalously high $^{13}C/^{12}C$ in CO_2 (4.7 x the terrestrial value). Also, Phoebe exhibits absorption bands around 3.4 μm attributed to both aliphatic and aromatic moieties that bear some similarities to the spectra of primitive carbonaceous meteorites and to organics seen in interstellar dust (Clark *et al.* 2005; Cruikshank *et al.* 2008; Coradini *et al.* 2008).

From dynamical and compositional considerations, Johnson & Lunine (2005) suggested that Phoebe formed in the Kuiper Belt, but recent studies argue that it formed closer in, from a reservoir that may have originally existed close to the orbit of Neptune (Castillo-Rogez 2019). Phoebe's density, albedo and largely neutral spectral reflectance are consistent with C-type asteroids which formed from that reservoir, however, the H_2O and CO_2 ices found on Phoebe are not seen on C-type asteroids. Whether Phoebe formed in the solar nebula beyond Neptune or in the company of a population of C-type asteroids near Neptune's orbit, the feedstock upon which it drew was characteristic of material far from the young Sun. That material included ices, a significant rocky component, and organics.

4. Summary

The three examples of small bodies in our Solar System, 2014MU_{69}, Pluto, and Phoebe, each contain chemical and dynamical clues to their origin and evolution. Such clues provide information not only on the composition of the early solar system, but also the degree to which original material is retained in small bodies. Moreover, the New Horizons flyby of 2014MU_{69} has given us the first view of an unaltered body composed entirely of material originally in the solar nebula at $\sim$45 AU. Having formed at the location where we observe it today, in a region seemingly undisturbed by frequent impacts, the spectrum of MU_{69} offers chemical and dynamical constraints to be considered by future chemical and physical models of planetary system formation.

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