Chapter 0

Introduction

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Chapter 1

Introduction

1.1. Formation of small Solar System bodies

Small bodies, including asteroid and comet populations, are leftover material from planet formation 4.6 Gya. At present we see several distinct populations of small Solar System bodies, and within each population, a wide diversity of small bodies in terms of size, shape, and material composition. Near-Earth objects (NEOs), asteroids and comets with closest approaches to the sun of <1.3 au, are a convenient source of extraterrestrial materials, including leftovers from Solar System formation.

Near-Earth asteroid orbits evolve from main-belt asteroids' orbits migrating via Yarkovsky drift into mean-motion resonances, which then deliver them onto obits passing through the inner Solar System (Morbidelli and Vokrouhlický, 2003). Meteorites, delivered from asteroids to Earth, provide an accessible source of extraterrestrial material for terrestrial lab-based study.

Jupiter-family comets (JFCs) have a two-part evolutionary pathway. Trans-Neptunian/Kuiper Belt objects from a region of small icy bodies beyond the orbit of Neptune evolve into Centaurs, transition objects with orbits between Jupiter and Neptune stable on ∼1–10 Myr timescales (Duncan and Levison, 1997; Duncan et al., 2004; Dones et al., 2015; Tiscareno and Malhotra, 2003; Di Sisto and Brunini, 2007). Through a "gateway" region (Sarid et al., 2019) Centaurs evolve into JFCs (Steckloff et al., 2020), which themselves are stable on so many year timescales. JFCs have orbital periods less than 20 years, low orbital inclinations, and have dynamical lifetimes of $\sim 10^3$ years (Di Sisto et al., 2009).

By studying the heating of near-Earth asteroid material in carbonaceous chondrite meteorites, and gas and dust interactions between the nucleus and inner coma of a Jupiter-family comet, we can learn about compositions of these bodies.

1.2. ??: Understanding near-Earth asteroid (101955) Bennu from meteorites

Useful tracers of past thermal metamorphism of an asteroid or in meteorite material are labile elements. Labile elements are elements that can mobilize and turn into a vapor when heated to hundreds of K. Mobilization of labile elements on an asteroid's surface will be a function of the object's thermal history, in particular its minimum achieved perihelion distance. Similarly, should asteroid material be sufficiently heated labile elements will begin to be thermally released from the meteorite, altering the primitive state of the asteroid material.

We present the results of thermal studies of labile element release from carbonaceous chondrite meteorites to quantify the amounts of labile elements lost from meteorite analog material similar to what will be sampled from the surface of near-Earth asteroid (101955) Bennu. A series of heating experiments were performed on a suite of CI, CM, CV, and CO carbonaceous chondrites. Carbonaceous chondrites are meteorites comprising some of the oldest and most volatile materials in the Solar System, with bulk elemental abundances for CI chondrites similar to that of the solar photosphere, with the exception of C, N, O, and noble gases (Anders and Grevesse, 1989). Other carbonaceous chondrites are depleted in volatile elements compared to CI chondrites. Certain types of volatile elements—labile elements—are mobilized during events such as aqueous alteration, metamorphic heating, and impact shock, and can provide information regarding the intensity and duration of these events. Studying the rate of labile element loss from meteorites with heating experiments can show whether Small aliquots of the meteorites were heated from room temperature to 1200 K under an inert atmosphere (Lauretta et al., 2001). The emission of seven labile elements–S, As, Se, Cd, Sb, Te, and Hg–was monitored throughout the experiment using high-resolution ICP-MS. These thermal experiments measure element loss from meteorite materials as a function of temperature, important for answering the following science questions.

The OSIRIS-REx mission to asteroid (101955) Bennu will return samples from this asteroid in 2023. Bennu shows a B-class spectra (Clark et al., 2010); it is thus likely the composition of Bennu will be primitive. Laboratory studies of the Bennu samples will allow for direct measurement of labile element depletion in material from what is likely considered a primitive body. Thermal modeling by Delbo and Michel (2011) provide maximum temperatures experienced by Bennu based on possible dynamical histories of the asteroid: labile element experiments are a way to connect laboratory results with theoretical models to constrain the past thermal history of a body. Quantifying the amount of labile elements lost on Bennu over its dynamical history can inform models of the thermal effects of the orbital history of Bennu regarding labile element loss. Additionally, preserving the primitive nature asteroid material collected from Bennu is important for future laboratory analysis of the sample. Having asteroid material in the sample return canister experience large temperature excursions could thermally metamorphose the material such that labile element mobilization occurs, rendering a previously primitive sample heated to a point where an appreciable percentage of elements are lost.

Labile element mobilization in laboratory heating experiments on primitive meteorites is relevant to the thermal metamorphism history of rock comets. Rock comets, such as B-class asteroid (3200) Phaethon, have comae devoid of sublimation products of ice, unlike classical comets (Jewitt and Li, 2010). Licandro et al. (2007) determined that Phaethon is a B-class asteroid from near-infrared spectra and this object likely has a composition similar to aqueously altered primitive meteorites such as CI- or CM-type meteorites. Other workers have established a correlation between B-class asteroid spectra and experimentally thermally metamorphosed Murchison meteorite samples (Clark et al., 2010, and references therein). We have shown that a potential tracer of thermal metamorphic history in primitive meteorites is Hg; rock comets composed of material similar to primitive meteorites could be heated to hundreds of K (based on the perihelia of sungrazer comets given in Knight et al., 2010). Future space telescopes equipped with UV spectrometer capabilities could potentially detect strong ultraviolet mercury lines on rock comets such as (3200) Phaethon, or other "activated asteroids" (Hsieh and Jewitt, 2006).

1.3. Gas and dust behaviors of comet 45P/Honda-Mrkos-Pajdušáková

Studying materials released from short-period Jupiter-family comets (JFCs) as seen in their inner comae, the envelope of gas and dust forming as the comet approaches the Sun, provides an improved understanding of the evolution and origin of these objects. Ground-based radar observations of the dust environments of three JFCs taken in 2016–2018 produced an extensive dataset of the dust environments of these objects to determine the size-frequency distributions and mass-loss rates of large dust grains into the inner coma regions. The data collected are unique: these three objects had close approaches of <60 lunar distances to Earth within three years, and the next predicted close approach of a comet is not until 2038. This was the last opportunity to compare similar JFCs at close range, and and therefore at high spatial resolution, for decades.

Due to their accessibility from regular forays into the inner Solar System, and as spacecraft targets, several missions have visited JFCs. Past missions to comets have observed asymmetries in emissions of volatile species into the inner coma from the nucleus. The *Deep Impact* spacecraft visited comet 103P/Hartley 2 in 2011 as part of the EPOXI mission, observing different source locations for the origin of several volatile species on the nucleus (A'Hearn et al., 2011; Dello Russo et al., 2011), as well as a population of large ice grains surrounding the comet (Hermalyn et al., 2013). Observations showed a strong correlation between the spatial distribution of water ice, dust, and CO_2 (Protopapa et al., 2014).

The *Rosetta* mission to comet 67P/Churyumov-Gerasimenko observed heterogeneities in gas emission (Hässig et al., 2015; Bockelée-Morvan et al., 2015; Migliorini et al., 2016) and that volatile source regions are not uniformly distributed over the nucleus surface (Fougere, N. et al., 2016). Further, Rosetta observations show jet formation corresponds to active pits (Vincent et al., 2015), and that dust and gas emission varies with temperature conditions/solar illumination (Alí-Lagoa et al., 2015; Lara et al., 2015). This suggests the source regions for ices and gases, regardless of solar illumination, are not uniform in distribution across the nucleus.

The inner coma—the temporary envelope of molecules and dust approximately 10,000 km across that forms around the nucleus of a comet when it approaches the Sun—of these JFCs reveals the most about cometary surface activity patterns and compositional uniformity. Studying the inner coma of comets as they approach Earth provides a rare opportunity to study inner-coma processes at close range, processes typically obscured by photodissociation product species of the outer coma. The inner coma is the region where we see the most interaction with the nucleus with the coma, whether release of dust or gaseous material by jets or other processes into the coma, or re-condensation of icy grains from the inner coma to the nucleus. High-resolution inner coma studies of comets require the comet to have a close orbital approach to Earth for ground-based telescopic observations, or, a dedicated spacecraft mission. Between 2016 and 2018, three $\sim$ 1-km JFCs, 45P/Honda-Mrkos-Pajdušáková (HMP), 41P/Tuttle-Giacobini-Kresák (TGK), and 46P/Wirtanen (Wirtanen), passed within 0.08 to 0.2 au of the Earth, allowing us to observe their inner coma regions.

After the close passage of Wirtanen in December 2018 *no similar close approaches of comets within 20 years are predicted.* The close approaches of these three comets allowed for detailed study of the objects at high spatial and temporal resolutions from ground-based optical and radar telescopes of their overall shapes, gas production sources, and dust environments as part of a coordinated multiwavelength observing campaign.

Visible wavelength observations yield size information of micron-scale particles in the coma; radar observations detect the ensemble properties of particles larger than 2 cm in diameter in the inner coma region, providing a range of dust particle sizes and properties. Understanding the asymmetries in grain ejection from the surfaces of these comets, and whether this corresponds to the presence of volatile species, gives a broader view of the interaction of species at the surface and in the near-surface environment of comets. Observations of past comets from ground-based telescopes as well as spacecraft show not only different spatial origins for volatile species in the inner coma from the nucleus, but also dust emission following the sources of volatiles (Feaga et al., 2007; A'Hearn et al., 2011; Hässig et al., 2015; Bockelée-Morvan et al., 2015; Fougere, N. et al., 2016; Migliorini et al., 2016). This dissertation aims to confirm if there comet 45P shows similar differences in emission directions for different volatile species, as well as dust and ice grains in the inner coma.

1.3.1. ??: Cyanide gas ejection events from 45P/Honda-Mrkos-Pajdušáková

We present observations targeting volatile species and dust of comet 45P, including CN, C_2, OH, and dust, taken at Kitt Peak National Observatory in February 2017.

Comet 45P has been well-characterized from observations from its 2017 apparition, and also previously. Comet 45P is approximately 0.6–0.65 km in diameter, with a 7.6 $\pm$ 0.5 h rotation period (Lejoly et al., 2017). It has low H_2O production rates compared to similar JFCs and is depleted with respect to H_2O in some volatile species, including CN and H_2O (Fink, 2009).

Other observations taken during the 2017 apparition of 45P on January 6–8, shortly after perihelion on 2017 December 31 show volatile species preferentially released from one section of the nucleus and processing of nucleus ices before being incorporated into the broader coma (DiSanti et al., 2017). Moulane et al. (2018), observing from 2017 February 10–March 30, confirmed low gas and dust activity and did not detect any outbursts; and that 45P, like 41P, has a carbon-bearing species composition typical of comets. Observations by Dello Russo et al. (2020), taken 2017 February 13 and 19, indicated "a relatively symmetric and uniform coma [...] with small spatial differences noted between some volatile species." Observations from previous as well as the 2017 apparitions measuring C_2 and CN production rates, as well as C_2H_2 and HCN abundances, appear consistent with HCN being the primary parent of CN. Dello Russo et al. (2020) noted the dust-to-gas ratio increased from February 13 to 19.

We conducted narrowband imaging of comet 45P in filters designed to target common comet volatile species (CN, C_2, C_3, and NH, Farnham et al., 2000). These filters isolate species corresponding to strong emissions bands emitted from comets, particularly CN. With careful calibration we can make photometric measurements to calculate production rates and other quantities of the species emitting in these bands. The advantage of making narrowband photometric measurements over spectrophotometry is that photometry can be used to measure larger areas of the coma than spectroscopy, and detect coma structures. We were able to prioritize photometric imaging with the medium-sized (61" and 90") telescopes we have access to through the University of Arizona, and save spectroscopy for larger telescopes (e.g., spectroscopic observations of comet 46P were conducted MMIRS instrument on the MMT Observatory telescope Kareta et al., 2022).

1.3.2. ??: Large grain characterization in the inner coma of 45P/Honda-Mrkos-Pajdušáková

In **??** I discuss studying large (radius >2 cm) dust grains as they are ejected from the comet surface into the inner coma, how this allows for understanding the characteristics of particles this size, and also how they compare to particles in smaller size regimes ($\lessapprox \mu$m for visible-wavelength observations. Planetary radar systems, such as Arecibo Observatory, are tools well-suited for detecting grains in the inner coma of a variety of comets (Campbell et al., 1989; Harmon et al., 1989, 1997, 1999, 2011; Nolan et al., 2006). Characterizing the behavior of these large-grain particles is important for understanding the formation processes of smooth terrains on comets, where centimeter- to decimeter-sized particles, after being ejected from the surface, fall back onto the nucleus (Sunshine et al., 2016; Keller et al., 2017, and references therein). What is less-well understood are the surface-modifying processes on comets, particularly ones responsible for building vertical relief in terrain, not just smoothing out or eroding of existing topography (Sunshine et al., 2016; Birch et al., 2019). Mechanisms responsible for lofting large grains (up to 2 m for 103P, depending on optical scattering properties, Kelley et al., 2013) from the surface of comets include gas drag from sublimation of ices (Whipple, 1951) and other, more exotic, mechanisms (Christou et al., 2020). Harmon et al. (2011) asserted that surface gas mass fluxes of 0.01 kg m^{-2} s^{-1} can loft cm-sized grains to their escape velocities, and also lift >meter-sized boulders from the surface of the nucleus, where they may stick together, refreeze, and fall back to the nucleus, undergoing processing themselves as they change the comet's surface.

Connecting dust grain observations from continuous wave radar with visible imaging of volatile species and smaller dust particles, as well as radar-derived shape models of nuclei, allows for a more holistic understanding of processes contributing to mass ejection from the surface of these comets and the origin of these grains. Studying the near-surface inner coma environment of comets is important for risk management of future sample return missions, understanding the composition of comet nuclei in the context of their location of origin in the protoplanetary disk, and future potential impact hazard mitigation of these comets as near-Earth objects. Specifically, Wirtanen has regular returns to near-Earth space and was the original target of ESA's *Rosetta* comet mission (Rickman and Jorda, 1998). Whether for future *in situ* study or sample return, learning more about these objects and their behavior as they approach Earth will reduce risk and increase science for future comet missions.

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