Spectral Mapping and Long-Term Seasonal Evolution of Pluto

By

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Abstract
NASA’s New Horizons mission has provided a wealth of new data about the Pluto system, including detailed surface geology and volatile distribution maps revealing striking latitudinal and longitudinal variations. We begin by studying the methane distribution and surface colors using data from New Horizons’ Ralph/MVIC instrument. From this study we find that Pluto’s equatorial region shows a broader diversity of terrains and more stark longitudinal contrasts than the more homogeneous north polar region. Pluto’s south polar region is currently in constant shadow and thus was not observed by New Horizons. We consider how this diversity formed and survived in the context of Pluto’s extreme Milankovitch cycles and resultant “super seasons”. Over timescales of roughly 3 million years Pluto’s obliquity varies by 23 degrees (between 103 degrees and 126 degrees) while its longitude of perihelion regresses. This pair of cycles create “super season” epochs where one pole experiences a short intense summer and long winter in constant darkness, while the other experiences a short winter and much longer, but less intense summer. Through thermal modeling and volatile sublimation and deposition modeling we determined that Pluto’s high obliquity creates conditions at its equator that favor albedo contrast and can support them on million year timescales more effectively than Pluto’s polar regions can. Finally, we look ahead to a possible next step in small body spacecraft exploration, a study of Apophis during its 2029 close approach to Earth. Since the earlier portion of this thesis focussed on the encounter, data collection, and scientific analysis portion of a spacecraft mission (New Horizons), we go full circle by exploring the early stage of the mission life cycle and the process of going from science concept to mission design study.

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“No one achieves anything alone”

– Leslie Knope, Parks and Recreation

“The ideal thesis advisor would advise you from your first tentative steps on campus, help you find a thesis topic, help you choose your thesis committee, read your thesis drafts, and edit them as needed... Ideally, he or she should be a mentor, that rare being who is part confidant, part parent, spiritual and temporal guide. You will never find such a paragon, but the closer you get, the better.”¹ I found it. It’s Rick Binzel. Thank you Rick for everything.

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Introduction

1.1 A very Brief History of Pluto Observations

The history of Pluto is linked to the early history of Uranus and Neptune. Neptune was first observed by Galileo in December of 1612 and January of 1613, but it was not identified as a planet until September 1846 (Kowal and Drake, 1980). Its existence and position were predicated by Urbane LeVerrier and John Couch Adams, based on perturbations of the orbit of Uranus (Leverrier, 1872; Adams, 1846). This success inspired further study of the planets’ orbits and numerous predictions of a ninth planet beyond Neptune, most notably those by William Pickering and Percival Lowell (Pickering and Pickering, 1909; Lowell, 1915).

Lowell Observatory began its first serious search for the ninth planet in September 1906. Searches for the ninth planet were conducted throughout the early 1900’s. In 1929, Clyde Tombaugh was hired by Lowell Observatory to continue the search. The following year he discovered Pluto and on March 13th, 1930 Lowell Observatory announced the discovery of “Planet X”, releasing an initial orbit determination the following month (Slipher, 1930). The name “Pluto”, after the god of the underworld, was chosen for the object, after first being suggested by Venetia Burney, an 11-year-old girl from Oxford, England (Slipher, 1930). The astronomical symbol, P, was chosen to represent the first two letters of “Pluto” and as a
head-nod to the observatories founder, Percival Lowell. Over the next several months its orbit was refined and the object was confirmed to be a trans-Neptunian planet. Lowell’s predictions for Pluto’s orbit were even closer to its actual orbit than predictions for Neptune had been, but Pluto was two orders of magnitude fainter than Lowell predicted (Reaves, 1997).

Based on infrared photometry Cruikshank et al. (1976), suggested Pluto’s surface was covered in methane ice, which would imply both a higher albedo and lower density than a solid rock composition. The presence of methane was confirmed by direct observation a few years later by Cruikshank and Silvaggio (1980). It was later suggested that Pluto’s surface also contained nitrogen in either an ice or liquid state (Clark et al., 1986). Owen et al. (1993) was able to confirm the presence of nitrogen through spectral observations.

In 1978 James W. Christy discovered Pluto’s largest satellite, Charon, at the U.S. Naval Observatory. A regular series of astrometric observations of Pluto showed an elongation that rotated in position angle at regular intervals, matching Pluto’s known 6.4 day rotation period. The elongation was determined to be caused by a satellite, believed to have a diameter about 0.4 times that of Pluto, orbiting with a synchronous period of ~ 6.4 days at a distance estimated to be between 15,000 – 20,000 km (Christy and Harrington, 1978).

The discovery of Charon made it possible to more accurately constrain the size, mass, density, and albedo (Lupo and Lewis, 1980). These parameters confirmed Pluto was not massive enough to account for the residuals in Uranus’ orbit that Lowell and Pickering’s predictions had been based on and its discovery was a fortuitous coincidence (Reaves, 1997). It has since been suggested that the perturbations of Uranus were in fact a calculation error from using the incorrect masses of the Jovian planets (Standish, 1993).

Another “fortunate coincidence” in the history of Pluto observations is the timing of Charon’s discovery. Shortly after Charon’s discovery it was determined that the orientation of the Pluto-Charon system put Charon’s orbital plane in an edge-on alignment (as seen from Earth) once every 124 years, creating a series of transit, occultation, and eclipse events.
referred to as “Mutual Events”. Andersson (1978) predicted that Pluto and Charon were heading into their next mutual events season with the first even observable as early as 1979 (later shifted to the early 1980s). This set of events would allow planetary scientists to measure individual diameters and surface compositions for Pluto and Charon, the bulk density of the Pluto-Charon system, and albedo maps for both bodies.

The first definitive transit detection was made at McDonald Observatory on February 17, 1985 by Richard Binzel and then confirmed 3.2 days later with detection of the corresponding occultation from Mauna Kea by David Tholen (Binzel et al., 1985). This initial detection served to prove the existence of Charon and constrain its orbit enough to determine the geometry for the entire sequence of mutual events which would last until 1990.

The deepest of the occultation events provided the opportunity to independently determine the spectra of each object. It was found that Charon’s reflectance spectra was indicative of a water ice composition with no evidence of methane or ammonia frost, while Pluto’s was redder, higher albedo, and showed several methane absorption bands (Sawyer et al., 1987; Buie et al., 1987). Using the mutual events light curves and least square models Young and Binzel (1993) were able to generate the first detailed albedo maps of Pluto, mapping the entire sub-Charon hemisphere.

The Hubble Space Telescopes Advanced Camera for Surveys made it possible to produce two-color albedo maps for both Pluto and Charon (Buie et al., 2010). These maps were able to achieve more complete longitudinal coverage than those produced from the mutual events data, however due to Pluto’s changing viewing geometry they do not include the Southern most latitudes of Pluto (which will not be fully visible again until after the end of this century).
The Hubble Space Telescope also allowed for deeper searches for additional satellites. Weaver et al. (2006) announced the discovery of Nix and Hydra, making Pluto the first Kuiper Belt object known to have more than one satellite. Kerberos, with a diameter less than a 1/3 that of the other small satellites, was discovered in 2011, and Styx, Pluto’s smallest moon, was discovered the following year (Showalter et al., 2012).

It had long been speculated that Pluto had an atmosphere, supported by its surface volatiles (e.g. Kuiper, 1944), but it was not directly detected until an occultation of a bright star by Pluto was observed from the Kuiper Airborne Observatory on June 9, 1988 (Elliot et al., 1989). This event revealed unexpected structure in Pluto’s atmosphere and conclusively showed Pluto had an atmosphere of more than a few microbars (Elliot et al., 1989). Unfortunately, it was not until August 2002 that another occultation of a bright star by Pluto was observable from Earth, at which point it was determined the Pluto’s atmospheric pressure had increased during 14 years between observable events (Elliot et al., 2003).

By the late 1980s it had become apparent that Pluto and Charon were interesting scientific targets, deserving of further detailed study. It was also becoming apparent that we were reaching the limit of what could be done to study them with ground based techniques. The 1989 flyby of Neptune and Triton by Voyager II revealed Triton to be a surprisingly geologically active world. Since Triton is believed to be a captured KBO and at the time was thought to be a Pluto analog, the revelation about its surface complexity further supported the case for Pluto being a mission target of great scientific significance. The first study of a dedicated Pluto mission resulted in a concept for a 350 kg, RTG-powered (radioisotope thermo-electric generator) spacecraft with a four instrument scientific payload called “Pluto-350” (Farquhar and Stern, 1990). The 1990s saw several concepts for dedicated Pluto missions covering a broad range of budgets and complexities however, none them made it beyond “Phase A” design studies (Stern, 2008). After the failure of two Mars missions, the “faster, better, cheaper” era at NASA ended in 2000 and ushered in the era of PI-lead proposal competitions (Neufeld, 2016). In January of 2001 NASA released an Announcement
of Opportunity competition for a Pluto Kuiper Belt mission, to complete the flyby of Pluto before the end of 2020. In November of that year the New Horizons missions was selected for Phase B development (Stern, 2008). The mission continued to face challenges on its journey from proposal to launch pad, including tight time constraints and repeated threats to its budget, ultimately it was saved by the start of the New Frontiers program and pressure from the National Academies' decadal survey, which in mid-2002 ranked a Pluto-Kuiper belt mission as the number one medium-sized mission (Neufeld, 2016). What started as an effort to finish the initial recognizance of the solar system by studying the ninth planet had become a mission to understand the solar systems newly discovered third zone beyond Neptune.

1.2 The New Horizons Mission

1.2.1 Mission Objectives

The New Horizons mission was designed to meet a broad range of Science Objectives outlined by the Pluto Kuiper Belt Announcement of Opportunity. The three primary objectives, written as “required Group 1 goals” were for the mission to (1) characterize the global geology and morphology of Pluto and Charon, (2) map surface composition of Pluto and Charon, and (3) characterize the neutral atmosphere of Pluto and its escape rate. In addition, the Announcement of Opportunity also included nine Group 2 (strongly desired) objectives and four Group 3 (desired) objectives, including tasks such as characterizing the time variability of Pluto’s surface and atmosphere, mapping the surface composition of selected areas of Pluto and Charon in high resolution, searching for neutral species in Pluto’s upper atmosphere and characterizing the energetic particle environment of Pluto and Charon (the complete, detailed list can be found in Young et al., 2008). The mission, as proposed, was expected to meet all of the science objectives, with the exception of a Group 3 goal of searching for magnetic fields of Pluto and Charon, which New Horizons is only able to do indirectly (Young et al., 2008).
1.2.2 Mission Design and Science Payload

The New Horizons mission launched on January 19, 2006 and received a gravity assist from Jupiter in February 2007 (during which it observed Jupiter and several of its satellites). In January of 2015 New Horizons began its scientific observations of the Pluto system, making its closest approach to Pluto (at a distance of 12,500 km) on July 14, 2015. The New Horizons spacecraft is now continuing on into the Kuiper belt, where it will flyby the classical Kuiper Belt object designated (486958) 2014 MU₆₉, making its closest approach on January 1, 2019.

New Horizons is the first of NASA’s New Frontiers mid-sized planetary exploration missions. In order to reach Pluto in nine-and-a-half years, the spacecraft’s mass had to be kept below 480 kg, leaving less than 50 kg allotted for the science payload, and only 12 W of power were to be available to the scientific instruments at any time during the encounter (Weaver et al., 2008). Thus the seven scientific instruments on New Horizons were selected to fulfill the science objectives of the mission while being lightweight, low power, and capable of surviving the nine-and-a-half year, 3 billion mile, journey to the Pluto system. The New Horizons payload instruments are described in turn.

Ralph is a visible and near infrared imager which consists of a single telescope that feeds into two focal planes: the Multi-spectral Visible Imaging Camera (MVIC) and the Linear Etalon Imaging Spectral Array (LEISA) (Reuter et al., 2008). Its primary purpose is mapping surface geology and composition but it was also used for the study of Pluto’s atmosphere (some of the results from the Ralph/MVIC instrument are presented in Chapter 2).

The LOng-Range Reconnaissance Imager (LORRI) is a narrow-angle Richey-Chretien telescope used for high-resolution, panchromatic imaging. LORRI was designed to study the geology and surface morphology of Pluto and its satellites, the collisional history of the system, the atmosphere-surface interactions on Pluto, and to be able to image the Pluto
system at higher resolution than any Earth-based telescope for 90 days prior to encounter. This incoming detailed reconnaissance was necessary to provide an extended time base for observations as well as to search for rings and other potential hazards (Cheng et al., 2008).

The ultraviolet imaging spectrograph on New Horizons, Alice, was designed for both airglow and solar occultation measurements and is used for studying the composition of Pluto’s atmosphere (Stern et al., 2008).

The New Horizons Radio Science Experiment (REX) was designed to perform thermal scans of Pluto and Charon’s surfaces as well as radio occultations to study the atmosphere of Pluto and look for an atmosphere on Charon (Tyler et al., 2008). The instrument consists of a small amount of signal processing hardware that was added to the radio system New Horizons uses for communications and tracking.

The New Horizons payload also includes two in situ particle detection instruments, SWAP and PEPPSI. The Solar Wind at Pluto (SWAP) instrument measures the angles and energies of solar wind ions in the Pluto environment (and throughout New Horizons journey into the Kuiper Belt) (McComas et al., 2008). The Pluto Energetic Particle Spectrometer Science Investigation (PEPPSI) measures pick-up ions from Pluto’s outgassing atmosphere to characterize Pluto’s neutral atmosphere, any extended ionosphere and solar wind interactions, the energetic particle environment around the Pluto system, and provide a check on the atmospheric escape rate of Pluto (McNutt et al., 2008).

The Student Dust Counter (later renamed the Venitia Burnie Student Dust Counter-VBSDC) is the first science instrument on a planetary mission to be designed, built, tested and operated by students. It operates continually and measures the spatial and size distribution of dust along New Horizons’ path as it crosses the solar system and heads out into the Kuiper Belt (Horányi et al., 2008).
1.2.3 Preliminary Results from New Horizons

With almost 60 papers published in just the first 2 years after encounter NASA’s New Horizons mission has clearly generated a wealth of new knowledge about Pluto, its satellites, and the Kuiper Belt. Here we highlight just a few of the early results from New Horizons which are most relevant to this thesis.

The initial data returned from New Horizons revealed a diverse and geologically active world displaying a remarkably broad range of landforms, albedos, colors, and compositions (Stern et al., 2015). Pluto’s surface shows evidence of surface ice convection, volatile transport, glacial flow, and wind streaks (Stern et al., 2015). It also shows a wide range of surface ages, as evidenced by the varying crater abundances, with some regions showing many large, deteriorating craters and others being apparently crater free (Robbins et al., 2017).

Spectral imaging of Pluto revealed the complex spatial distribution of $N_2$, $CO$, $CH_4$, and $H_2O$ ices and tholin-like material across Pluto’s surface (Grundy et al., 2016). Spectral data combined with geologic evidence point to Pluto having widespread, water-ice “bed-rock” with a volatile veneer (Grundy et al., 2016; Stern et al., 2015; Moore et al., 2016). Pluto has the second widest range of albedos of any solar system object (with the widest being Iapetus), with its brightest and darkest terrains occurring side-by-side around its equatorial region (Stern et al., 2015). Pluto’s equatorial region, particularly between 25°S and 10°N shows large areas of dark terrain interspersed with bright regions (Stern et al., 2015). The most notable of these regions, formally named Tombaugh Regio, measures 1,800 km East to West and 1,500 km North to South and straddles the equator on the anti-Charon hemisphere (Stern et al., 2015).

The western side of Tombaugh Regio, named Sputnik Planitia, stands out for several reasons. It shows no discernible craters, indicating it’s still geologically active (Robbins et al., 2017). It is also the one region on Pluto that shows an abundance of $N_2$, $CO$, and $CH_4$ ice (Grundy et al., 2016). The polygonal pattern across Sputnik Planitia’s surface
is believed to be the result of convection, indicating the ice in Sputnik Planitia is several kilometers deep (McKinnon et al., 2016). Schenk et al. (2015) suggest Sputnik Planitia is the remnant of a large impact basin that has been infilled with volatile ices.

Figure 1.1: Progress of Pluto imaging. **Left:** Hubble image of Pluto from 2003 (one of the best available images of Pluto at the time I started graduate school in 2013). **Center:** Image of Pluto taken by New Horizons' LORRI instrument on June 11th, 2015 (the date of my general exam). **Right:** Best, full-disk, enhanced color image of Pluto from New Horizons.

Figure 1.1 illustrates how over the course of my time in graduate school, New Horizons has changed our view of Pluto from a distant astronomical object to a complex, geologically active world. New Horizons has provided us with a detailed snapshot of the current state of the Pluto system. Pluto’s surface shows stunning albedo variegations with normal reflectances from 0.08 – 1.0, a range broader than any other body in the solar system except Saturn’s moon Iapetus (Buratti et al., 2017). Of even further interest, is the complex distribution of Pluto’s volatiles and albedo units, which place Pluto’s brightest and most volatile-rich region (Tombaugh Regio) next to one of its darkest and most volatile depleted (Cthulhu Regio). This thesis seeks to understand the current state of Pluto’s surface by exploring the complex seasonal cycles it undergoes on million year timescales.

Chapter 2 presents the results of the study of Pluto’s methane distribution using data from New Horizons’ Ralph/MVIC instrument and provides an overview of Pluto’s complex volatile distribution. Pluto’s complex seasonal cycles (the result of obliquity and longitude of perihelion variations on million year timescales) and some of their consequences are in-
roduced in Chapter 3. Surface temperature modeling is conducted in Chapter 4 to explore how albedo differences on Pluto could affect surface temperatures and in turn sublimation and deposition rates. Chapter 5 employs a simple volatile transport model to further this study and explore the latitudinal limits of runaway albedo variations.

This thesis concludes by looking ahead to a possible next step in small body spacecraft exploration. We look at a mission concept to study the asteroid Apophis during its 2029 close approach to the Earth and perform a “pre-Phase A” study of a hardware design intended to aid the mission in its study of surface seismic activity during the encounter.
Methane Distribution on Pluto as Mapped by the New Horizons Ralph/MVIC Instrument

2.1 Introduction

Most of the work for this chapter was originally published in Earle et al. (submitted). This chapter uses data from the New Horizons spacecraft to explore Pluto's current volatile distribution and provide context for the modeling performed in the later chapters.

The New Horizons spacecraft is equipped with seven scientific instruments to study the origin of the Pluto system, the surface processes, volatile transport cycles, and the energetics and chemistry of the atmosphere (Young et al., 2008; Weaver et al., 2008). This work addresses results obtained with the Ralph instrument consisting of two components; the Multispectral Visible Imaging Camera (MVIC) and the Linear Etalon Imaging Spectral Array (LEISA). MVIC is composed of seven independent CCD arrays most of which operate in time-delay integration mode (TDI) to produce panchromatic and colored images (by pairing CCDs with appropriate filters). The calibration and reduction processes for MVIC images are described in detail in Howett et al. (2017) and Olkin et al. (2017). We use
data from the red channel (540-700 nm), near-infrared (NIR) channel (780-975 nm), and narrow band methane (CH4) channel (860-910 nm) to produce high-resolution methane "equivalent width" (MVIC E.W.) and spectral slope maps of Pluto's surface. From these maps we quantitatively study the relationships between methane distribution, redness, and other parameters like latitude and elevation. Quantifying these relationships provides useful constraints for volatile transport modeling and for understanding the geomorphology of Pluto.

Methane was first detected on Pluto's surface from ground-based observations by Cruikshank et al. (1976). Ground-based spectral measurements could not spatially resolve Pluto's surface. However by taking advantage of Pluto's changing viewing geometry, particularly its 6.4 day rotation period, it was determined that the distribution of methane (and other ices) on Pluto's surface was heterogeneous (e.g. Grundy and Buie, 2001).

New Horizons has allowed us our first detailed look at the heterogeneous distribution of Pluto's surface ices (Stern et al., 2015). Several papers have already presented studies of Pluto’s surface using data from the LEISA instrument, which has moderate spectral resolution near-infrared mapping capabilities (Reuter et al., 2008; Grundy et al., 2016; Protopapa et al., 2017; Schmitt et al., 2017). However, while MVIC lacks the spectral resolution of LEISA (relying simply on filters), it achieves more than three times the spatial resolution of the LEISA instrument, providing more detailed and complete coverage of the methane distribution on Pluto's surface. MVIC also uses the shorter, 890 nm, absorption band to measure methane abundance, while LEISA uses the infrared bands between 1.25 and 2.5 \( \mu \text{m} \).
2.2 Methods

2.2.1 Data & Reduction

Seventeen image sets from the MVIC instrument were used to produce the global maps presented here. These images were taken over the last 5.5 days of New Horizons’ approach to Pluto. Since Pluto is currently experiencing northern summer (with a sub-solar latitude of 52°N at the time of encounter), this series of images provides full longitudinal coverage from the North pole down to 10°S latitude, with limited longitudinal coverage from 10°S extending slightly beyond 30°S. Table 2.1 outlines the observation details of the 17 image sets used here, including the mid-time of each observation, image scale, sub-spacecraft longitude and sub-spacecraft latitude. The RED, NIR, and CH4 MVIC filter images were registered to the geometry of the corresponding BLUE filter image, using the Integrated Software for Imagers and Spectrometers (ISIS3) from the United States Geological Survey.

Table 2.1: Ralph/MVIC Observations

<table>
<thead>
<tr>
<th>Observation Mid-Time (UTC)</th>
<th>Image Scale (km/pix)</th>
<th>Sub-s/c Long. (Deg E)</th>
<th>Sub-s/c Lat. (Deg N)</th>
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<td>18.8</td>
<td>43.0</td>
</tr>
<tr>
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<td>0.2</td>
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</tr>
<tr>
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<td>0.0</td>
<td>43.0</td>
</tr>
<tr>
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<td>335.1</td>
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<td>43.0</td>
</tr>
<tr>
<td>2015-07-11 16:49:46.439</td>
<td>66.49</td>
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<td>43.0</td>
</tr>
<tr>
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<td>0.66</td>
<td>168.0</td>
<td>26.0</td>
</tr>
</tbody>
</table>
These images are publicly available through the NASA Planetary Data System (PDS): Small Bodies Node. Mutually-registered versions of the images, as well as the MVIC E.W. and spectral slope maps are currently undergoing the PDS review process, after which they will also be made public through NASA PDS.

2.2.2 The Model

To create the methane absorption “equivalent width” and spectral slope maps, we start by producing grids of CH4/NIR and Red/NIR ratios over the parameter space of slope and “equivalent width” values. For spectral slope we use 151 steps ranging from values of -40 to 61.6 \% \text{reflectance/nm}. For MVIC E.W. we use 201 steps from values of -40 \text{nm} to 81 \text{nm}. These limits were chosen to cover the range of extreme cases, including no counts in the RED filter and no counts in the CH4 filter. To create these grids we make a model spectrum for each pair of MVIC E.W. and spectral slope values. We start with a line running from 540 nm to 975 nm (to cover the range of the Red and NIR filters) with the given spectral slope and normalized to one at 890 nm. Since we are working with three values (one for each filter) rather than a complete spectrum, we cannot measure equivalent width using traditional techniques and rather use a simplified parameter we call “MVIC E.W.”. For positive MVIC E.W. values we set the area around 890 nm with the given width equal to zero. For negative MVIC E.W. values we set the value equal to two for an area of the designated width around the 890 nm band (indicating those wavelengths are reflecting more light than the surrounding wavelengths).

The model is then multiplied by a solar spectrum and the filter passbands for the MVIC instrument to determine the predicted values for each filter for the given parameter pair (see Figure 2.1). Multiplying by the solar spectrum accounts for the fact we are looking at reflectance spectra (which are inherently dependent on the Sun’s spectra), and multiplying by the filter passbands allows us to account for the quantum efficiency of the chip and the throughput of the optics and filters in the MVIC instrument. We work in units of photons, since counts are the native units of the MVIC instrument.
Figure 2.1: Schematic showing the process for calculating CH4/NIR and Red/NIR ratios over the MVIC E.W. and spectral slope parameter space. This example is for the case of an MVIC E.W. of 10 nm and a spectral slope of -10. The ratios are calculated based on the shaded areas in the final (bottom) diagram, where red is the Red filter, grey the NIR filter, and blue the CH4 filter.

Calibrated, co-registered MVIC Red, NIR, and CH4 images are input into the code, which then finds the best match for each pixel on the CH4/NIR and Red/NIR grids. From here it uses an interpolation routine to find the best common MVIC E.W. and spectral slope value for that pixel. This process is used for all pixels of the target object and builds up spectral slope and MVIC E.W. maps for the input images.

Finally we estimate the error for the maps using the errors on the adjustment factors for each filter presented in Howett et al. (2017). To do this, we first created a grid of 2,500 points, equally spread across the Red/NIR and CH4/NIR parameter space. Then, using the
errors from Howett et al. (2017) we calculate the minimum and maximum possible deviation of each ratio. These values are all run through the interpolation code to determine the best common MVIC E.W. and spectral slope values for each pair of ratios. We then take the mean of the absolute value of the difference between the MVIC E.W. for the original ratio pair and the deviated ratios (and then repeat this calculation for spectral slope). From these calculations we determine that the MVIC E.W. values reported below have an error of ±1.18 nm and the spectral slope measurements an error of ±0.46. These error calculations are limited by the fact they are not dependent on the flux of a given pixel. They provide a reasonable estimate for most of Pluto's surface except regions with high incidence or emission angles, where the extreme viewing geometry and very low flux introduce additional sources of error. These regions were not included in the production of the global maps (Figure 2.4) used for most of the analysis presented in this paper (the mosaicking process is described in detail in the next section).

2.3 Results

2.3.1 The Maps

Figures 2.2 and 2.3 show the MVIC E.W. and spectral slope maps generated from the eight highest resolution images from the Ralph/MVIC instrument taken on New Horizons’ approach to Pluto. The images range in resolution from 42.59 km/pixel to 0.66 km/pixel and were taken between July 12th and July 14th, 2015 (details about these observations can be found in Table 2.1).

In Figure 2.2 dark blue areas indicate little to no methane absorption while redder areas have greater absorption around the 890 nm methane band. However, it is worth noting the equivalent width is not simply an indicator of methane abundance, as it can also be affected by dilution state, ice texture, or grain size (Schmitt et al., 2017; Protopapa et al., 2017). The 890 nm band is a weak band, probing large depths, making it more comparable to the 1950nm doublet (see Figure 13.3 in Schmitt et al. 2017, which maps the 1900 – 2000 nm
Figure 2.2: Maps of the MVIC E.W. of the 890 nm methane absorption band produced from the 8 highest resolution Ralph/MVIC approach images. These values have an error of ±1.18 nm. The number in the top, left corner of each panel indicates the sub-spacecraft longitude of each observation. Note that the images are arranged by observation time/increasing resolution, thus the sub-spacecraft longitudes are not in order.

integrated band depth) than to medium and strong (1.7 μm and 2.3 μm) methane bands, so these maps are more sensitive to coarser grained and also purer CH₄ than maps based on those wavelengths. When areas with large equivalent widths are near the limb they appear particularly red on these maps (indicating greater CH₄ absorption), as can be seen along the lower right edge of several of the maps. This is due to the low signal-to-noise in these areas.

Figure 2.3 shows the spectral slope maps simultaneously produced while modeling the equivalent width of the 890 nm methane absorption band. In these maps a larger spectral slope indicates redder material, while negative slopes indicate bluer material.

The maps shown in Figures 2.2 and 2.3 along with those produced from the nine lower resolution observations listed in Table 2.1 have been mosaicked together to produce global MVIC E.W. and spectral slope maps, which are shown in Figure 2.4, along with a topographic map of Pluto’s surface.
Figure 2.3: Maps of the spectral slope produced from the 8 highest resolution Ralph/MVIC approach images. These values have an error of ±0.46. The number in the top, left corner of each panel indicates the sub-spacecraft longitude of each observation. Note that the images are arranged by observation time/increasing resolution, thus the sub-spacecraft longitudes are not in order.

The mosaic was produced by using USGS’s ISIS3 (Integrated Software for Imagers and Spectrometers) routines. The dataset cubes were prepared for mosaicking by eliminating the pixels in the terminator region. First, we eliminated pixels having an incidence angle greater than 80°, and an emission angle greater than 75°. The values were empirically chosen by several trials, aimed to produced a coherent integrated map of planetary surfaces of airless objects, like Pluto. An upper limit of 80° was selected as the incidence angle cut-off. This was found to be the best compromise to crop off those ares where shadows are more extensive than illuminated terrains (and the illuminated pixels have steep slopes). For the emission angle, we chose a value of 75° as the best one to mask off those areas where severely oblique geometry smears out the pixels and blurs their values. The ISIS3 routine used for this task was MASK. Then, Pluto’s edge pixels were further cropped using a circular mask (ISIS3’s routine CIRCLE). The mosaic was produced overlapping the 17 selected cubes, in order of increasing spatial resolution, by using ISIS3’s NOSEAM function. In this way, the
Figure 2.4: Cylindrical projections of Pluto's surface. **Top:** global mosaic of maps of the MVIC E.W. of the 890 nm methane absorption band **Middle:** global mosaic of spectral slope maps **Bottom:** digital elevation model from (Schenk et al., 2016), projected to match the resolution of the equivalent width and slope maps. The boxes labeled A-F indicate areas shown in detail in Figures 2.5-2.10 and discussed in subsection 2.3.2. A: al-Idrisi Montes, B: Sputnik Planitia cellular terrain, C: Northeast Cthulhu (Virgil and Beatrice Fossae and Elliot Crater), D: Enrique Montes, E: Viking Terra (Inanna and Dumuzi Fossae), F: Pioneer Terra.
highest spatial resolution cubes are on top of the lowest resolution ones. These maps have a resolution of 0.65km/pixel to match the resolution of the best available images (however the resolution on the non-encounter hemisphere is 100's of kilometers per pixel).

2.3.2 Areas of Interest

Using the global mosaics we focus on six areas on Pluto’s surface that show particularly interesting results when comparing the MVIC E.W., spectral slope, and topographic maps. These areas were selected to highlight interesting features on Pluto (where volatile processes involving methane are occurring) and demonstrate the level of detail in the high resolution images and how they could be used for further detailed study of Pluto’s surface and the relationships between geology, color, and composition (note that some of the feature names on Pluto are formal and others are informal).

Figure 2.5 shows the Al-Idrisi Montes and part of the shore line of Sputnik Planitia. The Al-Idrisi Montes are located along the northwest shoreline of Sputnik Planitia, which is believed to be a volatile-filled basin (Stern et al., 2015). The mountains consist of randomly oriented, closely packed, water ice blocks rising several kilometers above Sputnik Planitia (Moore et al., 2016; Grundy et al., 2016). The mountain blocks are neutral in color while the material between them and to the west of them is redder. The upper surfaces and southern slopes of the blocks show MVIC E.W.s of 4 nm or more, indicating the presence of methane ice. Sputnik Planitia also shows signs of methane, but with slightly weaker absorptions between 2 – 4 nm. Comparing the MVIC E.W. and spectral slope maps we see an anti-correlation between red terrain and broad MVIC E.W.s, a trend we will discuss more in section 2.4.

Sputnik Planitia is believed to be a nitrogen-dominated, volatile filled basin that undergoes solid-state convection, creating cells or polygons about 10 – 40 km across on the surface (McKinnon et al., 2016; Protopapa et al., 2017). Part of this cellular/polygonal terrain is shown in Figure 2.6. From the DEM we see that this is a low lying region of generally uniform elevation, with some of the cell walls showing up as being slightly lower than the
Figure 2.5: **Left:** Box “A” in Figure 2.4. Cylindrical projections of Pluto’s surface showing the Al-Idrisi Montes and part of the shoreline of Sputnik Planitia. **Top:** MVIC E.W. of the 890 nm methane absorption band. **Middle:** spectral slope. **Bottom:** digital elevation model from (Schenk et al., 2016), projected to match the resolution of the equivalent width and slope maps. **Right:** The same set of Figures zoomed closer to show even greater detail.

cells themselves. Comparing the MVIC E.W. map and spectral slope maps we again see an anti-correlation between the two, with the strongest methane signal showing up along the
northern part of Sputnik Planitia and the west edge. Looking at a more detailed level we notice the centers of the cells appear more methane rich and bluer in color, while the borders of the cells show less methane absorption and redder spectral slopes.

Figure 2.6: Box “B” in Figure 2.4. Cylindrical projections of Pluto’s surface showing the cellular terrain in Sputnik Planitia. **Far-Left:** MVIC E.W. of the 890 nm methane absorption band. **Mid-Left:** spectral slope. **Mid-Right:** digital elevation model from (Schenk et al., 2016), projected to match the resolution of the equivalent width and slope maps. **Far-Right:** The same region shown from LORRI imaging (cylindrical projection) to show the cellular patterns.

Part of Cthulhu is shown in Figure 2.7, including Elliot Crater, the large, complex crater (officially named for the late MIT professor, James Elliot), and Virgil and Beatrice Fossae. Cthulhu is a large region characterized by dark mantling (possibly the result of atmospheric tholin deposition) thin enough to not obscure the underlying topography (Moore et al., 2016; Grundy et al., 2016). Again, we see an anti-correlation between red material and areas with broad methane equivalent widths, with Cthulhu itself being very red and showing little to no methane absorption while the area just north of Cthulhu (seen at the top of the image) is less red and shows MVIC E.W.s of 2 nm and greater. This trend continues onto the small
scale features in these images. The fossae show up bluer and with broader MVIC E.W.s than the surrounding area. Elliot and the other craters also show this anti-correlation with their north-facing slopes showing up with broader MVIC E.W.s and bluer spectral slopes, while their bottoms are red and methane-depleted.

Figure 2.8 shows another interesting part of Cthulhu, a chain of methane topped mountains informally known as Enrique Montes. Again we see a very obvious anti-correlation between MVIC E.W. and spectral slope. Comparing with the DEM we see the methane rich (bluer spectral slope) regions are exclusively at higher elevations while the redder, methane depleted material is mostly at lower altitudes.

Viking Terra, part of which is shown in Figure 2.9, is west of Sputnik Planitia and north of Cthulhu. Unlike the red, volatile-depleted Cthulhu, Viking is bluer and shows broad MVIC E.W. methane absorption, particularly between 15° and 30° north latitude where it borders the northern edge of Cthulhu. This region is heavily cratered and features several fossae, including Inanna and Dumuzi, which both run the width of the image in the top half of each image in Figure 2.9. Again we see an anti-correlation between 890 nm MVIC E.W. and spectral slope. In the fossae and many of the craters we see red bottoms and bluer rims and walls with broader methane absorption.

Pioneer Terra lies directly north of Tombaugh Regio, and is the most northern latitude region we consider here, with the images in Figure 2.10 showing a patch of Pioneer Terra between 55° and 75° north latitude. Unlike the region shown in Figures 2.5, 2.7, and 2.9, the methane absorption and redness somewhat correlate (although in general this region is also more neutral to blue than the other regions). The redness and methane absorption also show noticeable correlation with the higher terrains on the digital elevation model. The craters in this region do not show up as distinctly in the spectral slope and equivalent maps and are generally bluer with less methane absorption than the surrounding area.
2.4 Discussion

2.4.1 Analysis

Figure 2.11 shows the spectral slope vs. MVIC E.W. for the images shown in Figures 2.2 and 2.3. The first image (with a sub-s/c longitude of 247.7°) is dominated by neutral colored terrain with 890 nm equivalent widths between 0 and 10 nm. All of the images contain some amount of neutral material, but as Cthulhu rotates into the spacecraft’s view more red material is also present on the plots. The red material shows a strong anti-correlation with MVIC E.W., with most of the reddest material (with a spectral slope of 10 or more) showing little to no methane absorption (with MVIC E.W. values of 5 nm or less). The areas with the broadest equivalent widths are also generally neutral in color (with spectral slopes between 0 and -5). This color range also shows the broadest range of MVIC E.W.s with materials ranging between some of the broadest MVIC E.W.s (of 15nm or more) to areas that show little to no methane absorption.

Influence of Latitude

The trends between MVIC E.W. and spectral slope change from one latitudinal region to another (Figure 2.12). Near the north pole the global maps show little to no absorption around the 890 nm methane band (with MVIC E.W.s of 5 nm or less) and relatively neutral colors (with spectral slopes between 5 and -5). At latitudes from 60°N to 90°N there is a correlation between spectral slope and MVIC E.W. (which match linear fits with slopes between 0.74 and 0.63), but moving down towards the equator this trend flips with the reddest spectral slopes showing little to no methane absorption and the areas with the most methane absorption appearing neutral in color (similar to the trend we saw in Figure 2.11). This can be seen on a more localized scale by comparing Figure 2.10, which shows the high latitude Pioneer Terra, with Figures 2.5, 2.7, and 2.9, which show lower latitude regions. While the MVIC E.W. and spectral slope maps of the lower latitude regions are almost inverses of each other, the maps of Pioneer Terra correlate.
Moving from the pole towards the equator we also see progressively more red material. The equatorial region shows the broadest range of spectral slopes and MVIC E.W.s; from Figure 2.4 we see that the reddest material is concentrated around the equator.

Figure 2.11: Scatter plots of spectral slope vs MVIC E.W. for each of the images shown in Figures 2.2 and 2.3. The number in the upper, right corner of each plot is the sub-spacecraft longitude at the time of the observation. For the three largest images (with sub-spacecraft latitudes of 169.5, 161.4, and 168.0) the images have been subsampled for computational reasons.

To study these latitudinal trends further we take the mean and standard deviation of the MVIC E.W. (and spectral slope) as a function of latitude (Figure 2.13). This highlights a couple of trends between MVIC E.W., spectral slope, and latitude. The equatorial latitudes show much larger standard deviations for both parameters, implying these regions have more diverse color and volatile distributions than the northern terrain. The albedo maps presented in Buratti et al. (2017) and the composition maps in Schmitt et al. (2017) also show more diversity near the equator than at the pole. This is consistent with the results
of Earle et al. (2017b, 2018) (see Chapters 4 and 5) which suggest the equatorial latitudes are more susceptible than the poles to runaway albedo variations, and thus more likely to form and support stark contrasts in albedo and volatile abundance. Figure 2.13 also shows that the reddest material is concentrated just below the equator (where Cthulhu is located). Just north of the equator there is a broad mix of colors that shift towards the blue north of Cthulhu and into Tombaugh Regio. The northernmost latitudes show a narrow range of neutral colors. This is in agreement with the report by Olkin et al. (2017) of relatively blue terrain in Tombaugh Regio, red terrain in Cthulhu and yellow terrain at the north pole.

![Scatter plots of spectral slope vs MVIC E.W. based on the global maps shown in Figure 2.4. Each subplot is a 10° latitude band from the global maps (the latitude range of each subplot is given in the upper, right corner).](image-url)
Influence of Topography

In addition to looking at latitudinal trends we also look at the relationships between methane absorption (and spectral slope) and elevation using the digital elevation model (DEM) from Schenk et al. (2016) and preforming a similar analysis to Figure 2.13. Based on Figure 2.14 the average MVIC E.W. is highest for elevation above 2 km, for most of these elevations the average MVIC E.W. is around 6 nm. Below 2 km the average MVIC E.W. steeply drops to 2 nm then gradually declines to zero. Low elevations, below −3 km, also show signs of methane absorption, with average MVIC E.W.’s around 2 nm.

Moore et al. (2018) found that while both methane and nitrogen precipitate at low elevations, at higher elevations the atmospheric temperature and pressure do not allow nitrogen to condense so only methane will accumulate. The broad MVIC E.W.’s observed above 2 km may be an indication that this region not only contains an abundance of methane but that it is also purer (less $N_2$ contaminated) than the methane found at lower elevations.

Spectral slope does not appear to be as dependent on elevation, with broad error-bars throughout Figure 2.14 and averages around 0 for most elevations. The red and yellow material is most likely the result of atmospheric haze that has settled on the surface and is found in topographic highs and lows (Grundy et al., submitted). Pluto’s coloration is most likely being driven by other factors besides elevation. The one trend that can be identified is that low elevations, those below −2 km, tend to have bluer spectral slopes; this includes regions like Sputnik Planitia and the impression near the north pole. Sputnik Planitia is a volatile-filled basin measuring approximately 750 x 1,400 km (Moore et al., 2016). Haze landing on Sputnik Planitia may be quickly buried by volatile sublimation and deposition and the area may be undergoing solid state convection (McKinnon et al., 2016; Grundy et al., submitted). Most of Pluto’s terrain below −2 km lies within Sputnik Planitia, where haze is buried, which explains why these elevations show a bluer average than the rest of Pluto’s surface.
Figure 2.13: **Left:** MVIC E.W. as a function of latitude based on the global maps presented in Figure 2.4. **Right:** Spectral slope as a function of latitude based on the global maps presented in Figure 2.4. The points represent the mean value for that range and the error bars are the standard deviation. A subsampling correction has been applied to account for the cylindrical projection.

The influence of topography can also be seen on a smaller scale in Figures 2.5, 2.7, 2.8, 2.9, and 2.10. Strong methane absorption is seen on the peaks and south facing slopes of the Al-Idrisi Montes, with slightly weaker absorption in the adjacent, low-lying Sputnik Planitia (Figure 2.5). In Figure 2.10 methane absorption only shows up on the highest regions of Pioneer Terra. Figure 2.8 shows a chain of methane topped mountains sticking out of the otherwise flat, red, and methane depleted Cthulhu. The craters and fossae in Figures 2.7 and 2.9 also show a strong relationship between topography, color and methane absorption. Many of these features have broad methane absorption on their rims or walls, as does the floor of Elliot Crater, and for many their coloration does not match that of the surrounding area. These trends do not hold for Pioneer Terra (Figure 2.10), however,
where the craters appear smoother, potentially from burial by atmospheric transport and deposition or potentially cryovolcanic or glacial flow (Singer et al., 2016). Earle et al. (2018) (see Chapter 5) found that while equatorial latitudes on Pluto are highly sensitive to runaway albedo and maintain albedo-driven volatile deposition contrasts over long timescales, polar latitudes will experience seasonal transport (with albedo having a minimal effect). This could explain why, for the example regions shown here, small-scale features like craters and fossae have a larger effect on color and methane absorption than they do at higher latitudes. A more complete and detailed study of this potential trend is warranted but outside the scope of this paper.

Figure 2.14: **Left:** MVIC E.W. as a function of elevation based on the global maps presented in Figure 2.4. **Right:** Spectral slope as a function of elevation based on the global maps presented in Figure 2.4. The points represent the mean value for that range and the error bars are the standard deviation.
2.4.2 Slope-MVIC E.W. Units and Comparison with LEISA results

In addition to the MVIC channel, the Ralph instrument also contains the Linear Etalon Imaging Spectral Array (LEISA) channel, a short-wavelength, 1.25 – 2.5μm IR, spectral imager (Reuter et al., 2008) that has also been used to map the surface composition of Pluto and its satellites (e.g. Grundy et al., 2016; Protopapa et al., 2017; Schmitt et al., 2017). Given the low spectral resolution of the MVIC data and lack of laboratory measurements, there is no way direct way to draw conclusions about grain size, abundance, dilution state, etc. from MVIC date alone. However we can gain some insight by looking for correlations between LEISA and MVIC results, leveraging the higher spectral resolution of LEISA and higher spatial resolution and surface coverage of MVIC.

To aid in our interpretation of the spectral slope and MVIC E.W. maps, we divide Pluto’s surface into six categories based on that pair of parameters and how they correspond with different regions on the LEISA maps presented in Protopapa et al. (2017) and Schmitt et al. (2017). Figure 2.15 shows where each of these terrains is found on Pluto’s surface, allowing us to see which areas show similar colors and compositions to each other. The general characteristics of each region have been determined through comparison with Ralph/LEISA results in order to leverage LEISA’s higher spectral resolution to decipher how different methane properties manifest themselves in the MVIC maps (since the MVIC maps alone do not have sufficient spectral resolution to distinguish between different grain sizes, dilution states, etc.). To better understand the latitudinal constraints on each region, Figure 2.16 shows histograms of each region as a function of latitude.

In Figure 2.15 the areas with the strongest absorption in the 890 nm band are shown in purple; most of these areas have neutral to blue spectral slopes. The equivalent width is sensitive to not only the abundance but also other factors like grain size and mixing state. MVIC alone does not provide enough spectral information to detangle these factors, but by comparing our maps with those presented in Protopapa et al. (2017) and Schmitt et al.
(2017) we see that the areas in purple correlated with areas in the LEISA maps that are not only methane rich, but also contain the purest methane. These areas are most abundant at the equator and are found exclusively between 40°N and 40°S (Figure 2.16). On the approach hemisphere (where digital elevation map coverage is available for comparison) they correlate with higher elevation areas. This type of terrain is scattered throughout the eastern side of Tombaugh Regio, where Schmitt et al. (2017) found strong spatial variability between nitrogen and methane. Moore et al. (2018) identified this area as bladed terrain, a distinctive landscape on Pluto formed from large methane deposits at low latitudes (30°N and 30°S) and high elevations (above 2 km), where nitrogen does not condense. Figure 2.15 shows additional purple regions around Pluto's equator on the non-encounter hemisphere, indicating the possibility of additional bladed terrain. Since these particularly pure methane deposits only seem to form at high elevations, this would indicate that these regions (which are not covered by the digital elevation model) are likely to have elevations above 2 km.

Areas with bluer spectral slopes (value less than 0) and little (between 0 and 5 nm) or no (less than 0 nm) methane absorption around the 890 nm band are shown in blue and green, respectively, in Figure 2.15. Sputnik Planitia contains a mix of methane, nitrogen, and carbon monoxide (Grundy et al., 2016; Protopapa et al., 2017; Schmitt et al., 2017). Schmitt et al. (2017) reported that outside of Tombaugh Regio nitrogen was found concentrated between 30°N and 60°N latitude with less uniform deposits between 60°N and 70°N, and Protopapa et al. (2017) found a similar latitudinal trend. In Figure 2.15, most of the areas found to have nitrogen with some methane mixed in appear in green, while the areas with more methane than nitrogen appear in blue (or yellow, to be discussed below). Figure 2.16 shows that about 80% of the green terrain is concentrated between 30°N and 70°N latitude. These terrains appear to be N₂ ice-rich with the equivalent width of the 890 nm methane band being driven by the concentration of methane. On the non-encounter hemisphere the mid-northern latitudes (30°N and 60°N) are predominantly blue, however the lack of green terrain at these longitudes may be driven more by artifacts of the calibration (as can be
seen by comparing the maps in Figures 2.2 and 2.3) than an actual absence of nitrogen. Many of the blue areas in this region lay close to the cut-off between blue and green terrains (such that shifting the cut-off between the two categories will change their classification), as opposed to the purple and yellow regions on the non-encounter hemisphere which are not as effected by minor changes to the Slope-MVIC E.W. unit boundaries.

Areas with intermediate methane absorption (MVIC E.W.s between 0 and 5nm) and intermediate spectral slopes (between 0 and 10) are shown in yellow in Figure 2.15. On the encounter hemisphere, yellow terrain is particularly common in two regions: a band just north of Cthulhu and Lowell Regio (near Pluto's north pole). Protopapa et al. (2017) found the area north of Cthulhu to be composed of both methane and tholins. Lowell Regio is both methane-rich and contains a “gold material” which follows a unique mixing line from the one between bulk Pluto colors and Cthulhu (Grundy et al., submitted; Olkin et al., 2017). The terrain shown in yellow is scattered in additional areas across Pluto’s non-encounter hemisphere and does not seem to be as constrained by latitude or elevation as other terrains. These regions most likely contain a mix of methane ice and tholins.

The least abundant terrain type in Figure 2.15 is shown in orange and has no methane absorption (MVIC E.W.s less than 0nm) and intermediate spectral slopes (between 0 and 10). Comparing the location of this terrain with the results of Protopapa et al. (2017) we see these areas contain minimal methane ice and substantial tholin deposits (though not as substantial as Cthulhu). The orange terrain is found in areas that Schmitt et al. (2017) found to contain the strongest indication of $H_2O$ ice defined to optimize the separation from the red material signature and methane containing ices.
Figure 2.15: **Left:** Map of Pluto's surface with mapped elements divided into six categories based on MVIC E.W. and spectral slope. **Right:** Spectral slope vs MVIC E.W. with points color coded based on MVIC E.W. and spectral slope cutoffs to group similar terrain types.

Figure 2.16: Histograms of the relative frequency of the six different terrain types introduced in Figure 2.15 as a function of latitude. Correction factors have been applied to account for pixel widths changing as a function of latitude and the frequencies have been normalized to the total mapped area.
The areas shown in red in Figure 2.15 have steep spectral slopes (of 10 or more) and show little to no methane absorption. Like the purple terrain it is found exclusively between 40°N and 40°S, with more than 98% of it concentrated between 30°N and 30°S (Figure 2.16). On the close approach hemisphere most of the red material is concentrated in Cthulhu. Cthulhu is most likely composed of tholins, deposited from atmospheric haze and/or formed from the irradiation of methane ice (Cruikshank et al., 2016). The presence of additional red patches along Pluto’s equator may indicate tholin-covered regions like Cthulhu (but smaller) on Pluto’s non-encounter hemisphere.

Comparing the results presented here with those from the Ralph/LEISA instrument gives us further insight into Pluto’s surface composition. The region between 30°N and 30°S latitude shows the broadest diversity of colors and compositions. Earle et al. (2018) (see Chapter 5 and discussed further in Chapter 6) show that these latitudes are more sensitive to runaway albedo variations and can form and support stark albedo and volatile distribution contrasts over million-year timescales better than the polar latitudes. This could explain why these latitudes harbor both the reddest and most pure methane deposits on Pluto’s surface, while higher latitudes show fewer extremes and less diversity. The terrains near the equator, like the in-filled Sputnik Planitia, heavily tholin covered Cthulhu, and unique bladed terrain, are developed over million-year timescales. The polar terrains experience more seasonal extremes and are expected to undergo significant changes from volatile transport over seasonal timescales, and thus cannot support the extreme red deposits and broad methane absorptions (most likely from purer deposits and larger grain sizes) seen near the equator. There is evidence for more bladed terrain as well as more dark tholin deposits like Cthulhu on Pluto’s non-encounter hemisphere. Pluto’s more northern latitudes are more homogeneous and do not encompass the same extremes as the equatorial latitudes. The intermediate latitudes, between 30°N and 60°S, seem to be ice-rich, containing a mixture of both methane
and nitrogen, which makes the 890 nm band appear less broad. The north polar latitudes, above 60°N, show mostly moderate methane absorption with some tholin mixed in places, particularly within Lowell Regio.

2.5 Conclusions

We present here maps of the equivalent width of the 890 nm methane absorption band and spectral slope across Pluto’s surface as mapped by the Ralph/MVIC instrument. We find Pluto’s surface to show a diverse and complicated distribution of methane abundance and colors. MVIC E.W. and spectral slope both show some latitudinal dependence. The equatorial latitudes, between 30°N and 30°S, show a much broader diversity of colors and equivalent widths.

MVIC E.W. also shows dependence on elevation, with most of the broadest MVIC E.W. occurring above 2 km. This could be explained by the results of Moore et al. (2018), who found that between 30°N and 30°S and above 2 km methane will condense but it is too warm for nitrogen to condense, making these deposits more pure than lower elevation deposits where methane is often mixed with nitrogen. This dependence can also be seen looking at smaller features on Pluto, like mountain tops and crater rims, many of which show methane deposits. Spectral slope does not show as strong a dependence on elevation.

The reddening on Pluto’s surface is most likely related to the settling of atmospheric haze (which is a global process) or the formation of tholins in ice by irradiation from UV and/or charged particles (Grundy et al., submitted; Cruikshank et al., 2016) and thus less sensitive to elevation.

The maps presented here provide new insight into understanding Pluto’s global methane and color distribution, they also open the door for potential further detailed study of the complicated relationship between Pluto’s composition and geology. Additionally, Pluto’s current volatile distribution provides context and constraints for studying Pluto’s long-term seasonal evolution, as we will do in the next several chapters.
Figure 2.7: Box “C” in Figure 2.4. Cylindrical projections of Pluto’s surface showing part of Cthulhu containing Elliot crater (the large, complex crater in the upper right corner), Virgil Fossa (the fossa that runs from Elliot crater to the lower left corner of the image), and Beatrice Fossa (shorter and south of Virgil). Top: MVIC E.W. of the 890 nm methane absorption band. Middle: spectral slope. Bottom: digital elevation model from (Schenk et al., 2016), projected to match the resolution of the equivalent width and slope maps.
Figure 2.8: Box “D” in Figure 2.4. Cylindrical projections of Pluto’s surface showing part of Cthullu containing a chain of methane frost covered mountains, informally known as Enrique Montes. Left: MVIC E.W. of the 890 nm methane absorption band. Middle: spectral slope. Right: digital elevation model from (Schenk et al., 2016), projected to match the resolution of the equivalent width and slope maps. Note, this region is near the edge of the DEM where the map transitions from using stereo imaging to using limb shadowing to determine elevation, the seam running across the image from $-3^\circ$ to $-17^\circ$ latitude is an artifact of this transition.
Figure 2.9: Box “E” in Figure 2.4. Cylindrical projections of Pluto’s surface showing part of Viking Terra, the region west of Sputnik Planitia and north of Cthulhu. **Top**: MVIC E.W. of the 890 nm methane absorption band **Middle**: spectral slope **Bottom**: digital elevation model from (Schenk et al., 2016), projected to match the resolution of the equivalent width and slope maps.
Figure 2.10: Box “F” in Figure 2.4. Cylindrical projections of Pluto’s surface showing part of Pioneer Terra, the region north of Tombaugh Regio. Top: MVIC E.W. of the 890 nm methane absorption band Middle: spectral slope Bottom: digital elevation model from (Schenk et al., 2016), projected to match the resolution of the equivalent width and slope maps.
Pluto’s Insolation History and “Super Seasons”

3.1 Introduction

This chapter is primarily based on work published in Earle and Binzel (2015), along with work contributed to Binzel et al. (2017) and Stern et al. (2017).

Pluto’s high obliquity (currently around 119°) varies by about 23° over a period of less than 3 million years while Pluto’s longitude of perihelion regresses 360° over 3.7 million years (Dobrovolskis et al., 1997; Spencer et al., 1997). As a result of this pair of orbital variations Pluto’s sub-solar latitude at perihelion has ranged between 53°S and 76°N over the past 3 million years (Figure 3.1). Pluto has a high orbital eccentricity ($e \approx 0.25$) which causes its heliocentric distance to vary from less than 30AU out to almost 50AU, which leads to the solar constant changing by a factor of ~ 3 over the course of its orbit (Spencer et al., 1997).

Insolation intensity and distribution is dependent on instantaneous heliocentric distance and obliquity (Levine et al., 1977). Pluto’s high eccentricity coupled with its changing obliquity and sub-solar latitude at perihelion create substantial differences in insolation patterns on Pluto when averaged over different time intervals (Binzel, 1990, 1992). Understanding
these patterns can provide important insight in interpreting surface features revealed by New Horizons and understanding volatile transport on Pluto. Pluto’s atmosphere is probably in vapor pressure equilibrium with isothermal surface ice, so the surface atmospheric pressure is controlled by the surface volatile temperature (Spencer et al., 1997; Hinson et al., 2018). Insolation is one of the key inputs for volatile transport and atmospheric pressure models, however most of the modeling done to date only focusses on short timescales during the current epoch (Hansen and Paige, 1996; Young, 2013; Hansen et al., 2014). Given the magnitude of Pluto’s orbital variations (and consequently its insolation distribution) over million year timescales, it could be expected that Pluto’s volatile distribution, atmospherics pressure and surface geology are impacted by these variations. Over the next several chapters we explore Pluto’s insolation history and its implications for Pluto’s atmospheric pressure, surface temperatures, and volatile distribution.

Before we discuss the implications of Pluto’s insolation history in detail it is worth acknowledging the instability of Pluto’s orbit. Pluto’s motion is found to be chaotic on timescales of 10 to 20 million years (Sussman and Wisdom, 1988, 1992). We chose to focus our work on timescales of less than three million years, as this is sufficiently long enough to encompass the last two extrema for Pluto’s sub-solar latitude at perihelion but short enough to be well within the limit of Pluto’s orbit being predictable.

3.2 Insolation Model

The work presented here is based on the model originally published in Earle and Binzel (2015), but with a minor update to better correct for the Keplerian slowing of the orbital velocity near aphelion (Nadeau and McGehee, 2017). The model determines the insolation at the top of Pluto’s atmosphere as a function of latitude and time. First, the timescales of interest must be set and then the integration step size determined. For our purposes the size of the time step varied based on the duration of interest and the time frame over which the insolation was going to be averaged. Before the insolation can be calculated Pluto’s position
Figure 3.1: Top: Pluto’s changing obliquity as a function of time over the past 3 million years. Middle: Regression of Pluto’s longitude of perihelion over the same interval. Bottom: Pluto’s resulting sub-solar latitude at perihelion as a function of time. As noted in the text, possible long-term chaotic orbital variations occur over substantially longer timescales than considered here. Calculations are based on the analysis of Dobrovolskis et al. (1997).

must be established for each time step. This is done by determining sub-solar latitude and angle from perihelion as a function of time. Both of these values were calculated using the orbital model of Pluto initially presented in Dobrovolskis and Harris (1983) and refined in Dobrovolskis et al. (1997), which uses the time and corresponding eccentric anomaly to calculate the angle from perihelion, phase angle, and angle between Pluto’s longitude of
perihelion to its vernal equinox, which in turn can then be used to calculate the sub-solar latitude at any time (Dobrovolskis and Harris, 1983; Dobrovolskis et al., 1997). This process is described in detail in Appendix A. This model well represents Pluto's orbit for time scales of 10 million years, which is several times the length of our longest trial making this model sufficiently accurate for our purposes (Dobrovolskis et al., 1997).

Once Pluto's geometric parameters have been calculated as a function of time, the heliocentric distance and local hour angle at sunset must also be determined in order to calculate the insolation for each time step and latitude. Since we know the shape of Pluto's orbit (from its semi-major axis and eccentricity) we can determine instantaneous heliocentric distance \( r \) using the angle from perihelion (which tells us where in its orbit Pluto falls at a given time). The instantaneous heliocentric distance \( r \) is given by

\[
r = \frac{a(1 - e^2)}{1 + e \cos \theta}
\]

where \( a \) is the semi-major axis, \( e \) the eccentricity, and \( \theta \) the angle from perihelion (Levine et al., 1977).

For mapping insolation dependence onto the sphere of Pluto, we chose to use a 2° latitude step, which converts to \( \sim 40 \text{ km} \) between each planetary latitude location for each insolation calculation. In order to determine the local hour angle at sunset \( h \) for each latitude we must first consider two special cases where the sun will neither rise nor set at certain latitudes on a given Pluto day. The first special case is for those latitudes that are in constant sunlight during the Pluto day in question (in which case \( h = \pi \)). The second case is the opposite scenario where the latitude is in shadow and receives no sunlight for the full Pluto day (in which case \( h = 0 \)). For all other scenarios the sun will set at some point during the Pluto day and the local hour angle of sunset \( h \) is given by:

\[
\cos h = \frac{-\sin \phi \sin \delta}{\cos \phi \cos \delta}
\]
where \( \phi \) is the planetary latitude and \( \delta \) the latitude of the sub-solar point (Levine et al., 1977). With a diurnal period of 6.38726 ± 0.00007 days (Tholen and Buie, 1997) (which is much shorter than its 248 year orbital period), Pluto can be considered a rapidly rotating planet for the purpose of the insolation calculations presented here. This assumption and its implications were studied in detail in Young (2012) which found that atmospheric buffering dominates over diurnal timescales and restricts Nitrogen temperatures and surface pressure variations to less than 0.2% over a single Pluto day. The insolation \( I \) for a given latitude \( \phi \) on a rapidly rotating planet (where rotational period \( \ll \) orbital period) is given by

\[
I(\phi) = \frac{P S_0}{\pi} \left( \frac{a_e}{r} \right)^2 \left[ \cos \delta \cos \phi \sin h + h \sin \phi \sin \delta \sin \phi \right]
\]

(3.3)

where \( P \) is Pluto’s rotational period in minutes, \( S_0 \) the solar constant at 1 AU, and \( a_e \) is the semi-major axis of the Earth’s orbit (1 AU) (Levine et al., 1977). After the insolation has been calculated at each latitude for all of the time steps, the average for each latitude can be taken over the desired time interval.

### 3.3 Results

#### 3.3.1 Diurnal Insolation

We initially set out to study how the insolation received above Pluto’s atmosphere varies when integrated over different epochs. For all comparisons we divide the total integration’s timescale by the interval. This provides “average insolation” values in units of \text{ergs cm}^{-2} \text{s}^{-1} received over each timescale so that time dependent latitudinal variations can be revealed (next, in subsection 3.3.2 we will consider maximum diurnal insolation as a function of latitude over various timescales). There are clear trends in how integrated insolation varies with the time period over which it is averaged (Figure 3.2). We are particularly interested in how insolation varies over different timescales leading up to the close approach of the Pluto
system by New Horizons, so for each of the timescales presented the average was taken from the designated start date to mid-July 2015. These timescales are intended to inform interpretation of surface composition and geology as revealed by New Horizons.

Over short timescales, ranging from a few days to a few decades, Pluto's average insolation varies dramatically with latitude. For each of these short timescales, the maxima occurs at one pole and minima at the other. The most extreme case occurs at the current orientation where for a single Pluto day the average insolation values vary by more than $950 \text{ ergs cm}^{-2} \text{ s}^{-1}$ across Pluto's latitudes. At this time, Pluto experiences arctic summer, so the North Pole and the entire region above $38^\circ N$ latitude (including the $51^\circ N$ sub-solar latitude) are experiencing constant sunlight ("midnight sun") while the region below $38^\circ S$ latitude resides in constant shadow and receives zero insolation during this period.

Another epoch of interest when considering how Pluto's surface may respond to changes in insolation is the time since Pluto's surface was mapped based off data from observations of a series of transit, occultation, and eclipse events between Pluto and Charon that occurred from 1985 to 1990; referred to as the Mutual Events (Binzel et al., 1985). The late 1980s also marked the passing of Pluto's most recent perihelion and equinox. As Pluto has moved away from perihelion and into arctic summer since 1990 the average insolation has been significantly higher in the northern region, peaking at the North Pole, which since 1990, has received an average of over $650 \text{ ergs cm}^{-2} \text{ s}^{-1}$. In contrast, at the southernmost latitudes, Pluto has been receiving little or no insolation over the last two and a half decades.

Over slightly longer timescales of possible interest, such as the total time since Pluto was discovered in 1930 (i.e. decadal scales), we still see this trend of the maximum insolation occurring at one pole and the minimum at the other. However over this multi-decade timescale the difference between the minimum and maximum is less dramatic and the trend is in the opposite direction. From the time Pluto was discovered, the South Pole has averaged about $475 \text{ ergs cm}^{-2} \text{ s}^{-1}$ while the North Pole's average insolation has been less than half that.
Figure 3.2: Average insolation at each latitude over varying timescales. The “One Pluto Day” average is taken over a single Pluto day in mid-July 2015, when NASA’s New Horizons spacecraft flew through the Pluto system. All other averages are taken from the start time indicated to mid-July 2015. “M.E.” refers to the mutual events, a series of occultation and eclipse events occurring between Pluto and Charon.

Over longer timescales, ranging from one Pluto orbit (248 Earth years) to millions of years, Pluto’s average insolation is symmetric across the equator, with the maxima occurring at both poles in minima at or near the equator. Nadeau and McGehee (2017) and Hamilton et al. (2016) have explained this symmetry by showing that the slowly changing aspect angle at aphelion compensates for the greater heliocentric distance and balances out the pole-to-pole accumulated insolation over a single orbit. This balancing results in far less dramatic latitudinal variations over the longer timescales than those seen over the shorter timescales described above.
Over the single Pluto orbit (248 Earth years) leading up to the New Horizons fly-through of the Pluto system, Pluto’s poles have averaged 250 $\text{ergs cm}^{-2} \text{s}^{-1}$, the maximum average over that time period. The minimum average insolation, of less than 216 $\text{ergs cm}^{-2} \text{s}^{-1}$, occurs around 25°S and 25°N latitude. All of the latitudes between 35°S and 35°N receive less than 220 $\text{ergs cm}^{-2} \text{s}^{-1}$.

We next consider two longer timescales over which Pluto’s obliquity and longitude of perihelion cycles become relevant. Over the past 0.9 million years Pluto’s obliquity has gone from its most horizontal, 103°, to its current value of ~120°. As Pluto has undergone this portion of its obliquity cycle it has averaged a minimum insolation of about 200 $\text{ergs cm}^{-2} \text{s}^{-1}$ at its equator and maxima at each pole of 270 $\text{ergs cm}^{-2} \text{s}^{-1}$. Averaging over an even longer timescale of 2.35 million years, during which time Pluto’s obliquity reaches both its extrema, 103° and 126°, Pluto’s insolation begins to average out somewhere between that of the current orbit and that of the 0.9 million years timescale. Over this longer timescale the minimum average insolation still occurs at the equator, but is around 210 $\text{ergs cm}^{-2} \text{s}^{-1}$. Again, the maxima are found at the poles, but with a value of 259 $\text{ergs cm}^{-2} \text{s}^{-1}$, placing it almost exactly between values for the current orbit and 0.9 million years timescales. So while the difference between the average insolation at Pluto’s poles varies widely over short, sub-Pluto year timescales, over longer timescales the poles average the same amount of insolation, generally slightly greater than that of the equator.

### 3.3.2 Pluto’s “Super Seasons”

Over the course of a Pluto orbit the average diurnal insolation is symmetric across the equator. The location of the extrema and difference between them is largely dependent on Pluto’s obliquity cycles, described in section 3.1. Figure 3.3 (left) shows how the average annual insolation over a single Pluto year varies with different epochs. As was discussed in the previous section, over one Pluto year in the current epoch, the pole receive an average of 250 $\text{ergs cm}^{-2} \text{s}^{-1}$, while all of the latitudes between 35°S and 35°N receive less than 220 $\text{ergs cm}^{-2} \text{s}^{-1}$ and the minimum average insolation occurs around 25°S and 25°N latitude.
When Pluto's obliquity is closer to horizontal, the poles receive an average of close to 280 ergs cm$^{-2}$ s$^{-1}$ while the equator averages less than 200 ergs cm$^{-2}$ s$^{-1}$. At the other extrema, when Pluto's obliquity is more vertical (up to 126$^\circ$), the equator and poles average almost the same amount of insolation over a Pluto year while the minima occur around 30$^\circ$ S and 30$^\circ$ N.

![Graph showing annual average and maximum diurnal insolation](image)

**Figure 3.3**: **Left**: Annual average insolation vs. latitude for a single Pluto year during three different epochs. **Right**: Maximum diurnal insolation vs. latitude over a single Pluto year during three different epochs.

Studying Pluto's insolation averaged over an orbital period does not give the full picture of Pluto's insolation history because of Pluto's highly eccentric orbit and regressing longitude of perihelion. Currently Pluto experiences equinox and perihelion around the same time, resulting in both hemispheres experiencing fairly similar seasonal cycles. However, as Pluto's orbit evolves and goes through phases where equinox and perihelion are further apart, each hemisphere experiences very unique seasons. While both poles accumulate the same amount of insolation over the course of one full Pluto orbit, whichever pole is tipped towards the Sun at perihelion will experience a shorter, more intense summer. So the maximum diurnal insolation at that pole will be significantly higher than the opposite pole, which will experience a longer, but less intense summer at aphelion. Figure 3.3 (right) shows the maximum
diurnal insolation reached at each latitude over a single Pluto year during the three epochs being considered. 0.9 million years ago and 2.35 million years ago were selected for more detailed study since there are the two most recent epochs when Pluto’s sub-solar latitude at perihelion was at extrema (Figure 3.1). Over the 0.9 million years ago epoch the sub-solar latitude was high in the northern hemisphere at perihelion, resulting in a maximum diurnal insolation of $1,600 \, \text{ergs cm}^{-2} \, \text{s}^{-1}$. During that same epoch the southern hemisphere never received more than $500 \, \text{ergs cm}^{-2} \, \text{s}^{-1}$. 2.35 million years ago the southern hemisphere experienced a less extreme version of this with the south pole ($\sim 1,200 \, \text{ergs cm}^{-2} \, \text{s}^{-1}$) more than double the maximum diurnal insolation of the north pole ($\sim 470 \, \text{ergs cm}^{-2} \, \text{s}^{-1}$).

Figure 3.4: Diurnally averaged insolation over 1 Pluto orbit for select latitudes. **Top:** current orbit. **Middle:** 0.9 million years ago. **Bottom:** 2.35 million years ago.
To look at this effect in greater detail we plot the insolation for select latitudes over the three different epochs in Figure 3.4. The equator always receives diurnal insolation even as Pluto’s orbit evolves over million year timescales. Every single Pluto rotation the equator received some insolation and never average more than 490 ergs cm\(^{-2}\) s\(^{-1}\). The poles receives a far less even distribution of sunlight. During Pluto’s current epoch, each pole spends roughly half of Pluto’s 248 year orbit in sunlight (and the other half in shadow, receiving no insolation). During the peak of their summer season each pole averages around 1,000 \(\text{ergs cm}^{-2}\ \text{s}^{-1}\) of insolation. Over the two historical epochs considered, Pluto experiences what we refer to as “Super Seasons”, where one hemisphere experiences a short, intense summer and long winter, while the other experiences a short winter and long, less intense summer. This can be seen most dramatically for the 0.9 million years ago epoch (Figure 3.4; middle). Over this epoch the north pole experienced a maximum diurnal insolation of 1,600 \(\text{ergs cm}^{-2}\ \text{s}^{-1}\) during its summer season and then spent more than 160 years at a time in darkness, receiving no insolation. In contrast, during this same epoch the South Pole received a maximum diurnal insolation of less than 500 \(\text{ergs cm}^{-2}\ \text{s}^{-1}\), but spent more than 100 years at a time averaging over 350 \(\text{ergs cm}^{-2}\ \text{s}^{-1}\), and spent less than 90 years at a time in darkness. The dramatically different insolation patterns experienced over these “Super Season” Epochs have the potential to not only effect volatile transport during the epochs themselves but also have a lingering effect on the surface geology and composition of Pluto.
3.4 Discussion

3.4.1 Climate Zones

An additional consequence of Pluto’s orbital variations are its unusual “climate zones”, which are defined and discussed in detail in Binzel et al. (2017). Here we will give a brief overview of the “climate zones” and how they relate to Pluto’s insolation history and “Super Seasons”. The zones we describe here are defined astronomically based on sub-solar latitudes and do not incorporate atmospheric circulation.

Table 3.1: Pluto’s climate zones defined by astronomical cycles. The number in brackets denotes the percentage of total surface area covered by the specified range. Adapted from Binzel et al. (2017).

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Defining Characteristics</th>
<th>Current Range</th>
<th>Maximum Range</th>
<th>Permanent Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropics</td>
<td>Sun reaches overhead point during orbital year</td>
<td>60N to 60S [87%]</td>
<td>77N to 77S [97%]</td>
<td>53N to 53S [80%]</td>
</tr>
<tr>
<td>Arctic</td>
<td>Experiences periods of midnight Sun in summer and darkness in winter lasting one full rotation or more</td>
<td>30N to 90N 30S to 90S [50%]</td>
<td>13N to 90N 13S to 90S [78%]</td>
<td>37N to 90N 37S to 90S [40%]</td>
</tr>
<tr>
<td>Tropical Arctic</td>
<td>Experiences both overhead sun and arctic seasons, during orbital year</td>
<td>30N to 60N 30S to 60S [37%]</td>
<td>13N to 77N 13S to 77S [75%]</td>
<td>37N to 53N 37S to 53S [20%]</td>
</tr>
<tr>
<td>Diurnal</td>
<td>Day/night cycle occurs, each and every rotation, throughout orbital year</td>
<td>30N to 30S [50%]</td>
<td>37N to 37S [60%]</td>
<td>13N to 13S [22%]</td>
</tr>
<tr>
<td>Polar</td>
<td>Sun never reaches the overhead point at any time during the orbital year</td>
<td>60N to 90N 60S to 90S [13%]</td>
<td>53N to 90N 53S to 90S [20%]</td>
<td>77N to 90N 77S to 90S [3%]</td>
</tr>
</tbody>
</table>

Pluto’s high obliquity means it lacks the temperate zones that cover much of Earth’s surface. Instead it features a zone unique to high obliquity planets that we refer to as the “tropical arctic”, which encompass mid-latitudes that experience overhead sun (like the tropics) as well as periods of sunlight in summer or darkness in winter that last one full rotation or more (like the arctic). Currently this region spans between roughly 30°N to 60°N and 30°S to 60°S, but in the past had a maximum range of 13°N to 77°N and 13°S to 77°S, encompassing 3/4 of Pluto’s surface area (Table 3.1). Pluto’s large arctic
circles currently cover half the planet, reaching from each pole down to 30°, and in the past have extended as far down as 13° in each hemisphere. Currently 87% of Pluto is tropical, meaning it experiences direct overhead sunlight at some point during Pluto’s orbital year as the subsolar point ranges from roughly 60°N to 60°S. The complement to Pluto’s arctic zone is its diurnal zone, the region near the equator which is not arctic and thus experiences a day/night cycle for every single Pluto rotation. Currently this region covers half of Pluto’s surface and lies between 30°N to 30°S, but in the past it has covered as much as 60% of the surface and as little as 22% (extending from only 13°N to 13°S). Almost all of Pluto (97%) has experienced direct sunlight at some point in the last few million years as the maximum extent of the tropic region is 77°N to 77°S. The compliment of the tropics is the polar zone, where the sun never reaches the overhead point during Pluto’s orbital year.

Since climate zones and insolation are both dependent on obliquity, the ranges of Pluto’s climate zones fluctuate with its changing insolation patterns. When Pluto’s tropic, arctic, and tropical arctic zones are at their maximum range, Pluto’s poles receive the maximum annual average insolation and the equator the minimum with about 30% less average annual insolation. At the other extrema, when the diurnal and polar zones are at their maximum range, Pluto’s equator receives the maximum annual insolation with the poles receiving slightly less and the minima occurring near near 30°N and 30°S. During these epochs Pluto’s insolation is more evenly distributed and the minimum and maximum annual insolation vary by less than 10%.

In the always-diurnal zone (13°N to 13°S) the maximum diurnal insolation varies by less than 40% as Pluto undergoes its obliquity variations, where as always polar zone (77°N to 90°N and 77°S to 90°S) sees variations of 55% to more than 70%. The average annual insolation in the alway diurnal zone varies by 12-15% and in the alway polar region it changes by about 18%. The intermediate, alway tropical arctic zone (37°N to 53°N and 37°S to 53°S) shows smaller variations of as little as 5% to less than 14%.
Binzel et al. (2017) includes a discussion of surface features, both geologic and compositional, that correlate with climate zones. These correlations suggest climate zones may be relevant to Pluto's surface morphology, but more detailed thermo-physical modeling of the long-term evolution of the system is needed to confirm this. In the following chapters we will perform thermal and volatile sublimation/deposition modeling to further explore these corrections.

3.4.2 Past Epochs of Higher Atmospheric Pressure

Stern et al. (2017) suggests Pluto's "Super Seasons" may have produced higher atmospheric pressures capable of supporting liquids on Pluto's surface and presents multiple lines of geomorphological evidence consistent with higher pressure epochs in Pluto's past. For Stern et al. (2017), we performed modeling of $CH_4$ and $N_2$ surface vapor pressure variations over one Pluto orbit for Pluto's current epoch, as well as well as its last two "Super Season" epochs, 0.9 and 2.35 Myrs ago. That model is presented here.

The model assumes either $CH_4$ or $N_2$ ice on Pluto's surface and uses a simple model to account for first order surface albedo variations. Within the equatorial zone Tombaugh Regio is included as a volatile rich region with an albedo of 0.6 extending from $45^\circ N$ to $30^\circ S$ with a width of $45^\circ$ in longitude. The remaining equatorial band is assumed to have no volatiles. Trials were run with the poles extending to $\pm60^\circ$ and $\pm45^\circ$ latitude, and with emissivities of 0.9 and 0.6 for each case to span the range of likely emissivities. The poles are modeled for three different scenarios to span the parameter space: a high albedo where the poles are fresh (0.6 albedo), an intermediate albedo where the poles are partially depleted of fresh volatiles (0.3 albedo), and a low albedo (0.1 albedo) case representing a darker volatile base. Within each trial the volatile spatial distribution, albedo, and emissivity are held static. The surface pressure is calculated using a modified version of the energy balance equation given in Trafton (1984) and described in detail in Earle et al. (2017b) and Chapter 4 of this thesis.
Here we focus on the $N_2$ model results since Nitrogen most likely exerts the controlling influence on atmospheric pressure (Summers et al., 1997; Hinson et al., 2018) and is more sensitive to pressure variations over “Super Seasons”. Model results are shown in Figures 3.5 and 3.6. The best match for the current atmospheric pressure on Pluto is the scenario with polar caps extending to $\pm 45^\circ$, a polar cap albedo of 0.3, and emissivity of 0.9. Comparing the atmospheric pressure over the current epoch (top rows of Figures 3.5 and 3.6) with the diurnal insolation over this epoch (top plot in Figure 3.4), we see that pressure trends with maximum diurnal insolation being received anywhere on Pluto rather than simply
Figure 3.6: Model of atmospheric molecular nitrogen pressure over a single Pluto orbit at three different epochs. (Top row) Current epoch where perihelion occurs at “equinox.” (Middle row) The “Extreme Northern Summer” epoch occurring 0.9 Myrs ago where the subsolar point is at high northern latitudes at perihelion. (Bottom row) The “Extreme Southern Summer” epoch occurring 2.35 Myrs ago, where the subsolar latitude is furthest south at perihelion. These model polar caps extend to ±75° latitude and have an emissivity of 0.6. Adapted from Stern et al. (2017)

heliocentric distance (in which case we would expect atmospheric pressure to have peaked at perihelion). The volatile distribution on Pluto may also play a role in the peak pressure being offset from perihelion (Young, 2013). The peak pressure for various trials with the model
show differences of nearly two orders of magnitude. The trials run during Pluto’s current
epoch (characterized by equinox and perihelion occurs close together) show the lowest peak
pressures. The highest peak pressures are seen in the trials during Pluto 0.9 million year ago
“Super Seasons” epoch, when the sub-solar latitude was high in the northern hemisphere
at perihelion. While more detailed modeling is needed to more precisely estimate the past
atmospheric pressures on Pluto, these models indicate that it is plausible that over Pluto’s
past “Super Seasons” epochs it could have reached surface atmospheric pressures much higher
than its current value. This modeling also shows that the current epoch is near the minimum
atmospheric pressure state of the parameter space we covered.

Stern et al. (2017) goes on to present geomorphological evidence for past epochs of higher
pressure including features such as dendritic channels, cryovolcanism, wind streaks, and
a ponded, lake-like feature informally referred to as Alcyonia Lacus (Figure 3.7). While
some of these features may be explained by mechanisms other than higher atmospheric
pressure, it is unlikely that none of them formed from epochs of higher atmospheric pressure.
This observational evidence paired with the simple atmospheric pressure modeling suggest
Pluto’s atmosphere and surface processes are substantially different during epochs of “Super
Seasons”.

3.5 Conclusions

Pluto undergoes obliquity variations and longitude of perihelion regression on cycles of 3
million and 3.7 million years, respectively (Dobrovolskis et al., 1997). These cycles, coupled
with Pluto’s high eccentricity \( e \approx 0.25 \), create substantial differences in the insolation
patterns experienced on Pluto. When studying average insolation and comparing timescales
of days, years, centuries, and millennia we observe stark latitudinal dichotomies on shorter
timescales, and symmetry across the equator coupled with slight variations in the extrema on
timescales lasting one full orbit or more. When looking at insolation averaged over a single
Pluto orbit during the current epoch and two historical epochs (selected for their extreme
Figure 3.7: Examples of geomorphological evidence for past epochs of higher atmospheric pressure on Pluto. (a) Dendritic network northeast of Sputnik Planitia. (b) Other network terrain to the northwest of Sputnik Planitia. (c) A 4km high, 150km wide feature informally named Wright Mons and likely cryovolcanic. (d) Isolated ponded, lake-like feature informally named Alycynonia Lacus. All scale bars are 30km and images are oriented with north up unless otherwise noted. Images a-c are ~320m/pix from the P_MVIC.LORRL.CA (MVIC) observation and image d if ~130m/pix from P_MPAN.1 (LORRI). Adapted from Stern et al. (2017)

sub-solar latitudes at perihelion), we see dramatic variations caused predominantly by Pluto varying obliquity. We break things down a step further to look at the maximum diurnal insolation reached at each latitude over these three epochs, as well as the diurnal insolation
for various latitudes over a single Pluto year during each epoch. From this analysis we see Pluto undergoes epochs of “Super Seasons”, where one pole receives a short, intense summer followed by a prolong period of darkness, while the other pole received a short period of winter darkness and longer but less intense summer.

Pluto’s obliquity variations are also responsible for the oscillating limits of its “climate zones” defined in Binzel et al. (2017). We see that over Pluto’s obliquity cycles the maximum diurnal insolation in the always diurnal zone varies by less than 40% while the always polar zone undergoes variations of 55-70%. The always diurnal and always polar zones in general show larger variations in average annual insolation than the intermediate, alway tropical arctic zones.

Stern et al. (2017) shows the Pluto’s “Super Seasons” may be responsible for past epochs of significantly higher pressure on Pluto. The modeling shows variations of peak atmospheric pressure ranging almost two orders of magnitude, with the lowest peak atmospheric pressures occurring during the current epoch. This provides preliminary evidence for Pluto’s “Super Seasons” effecting volatile transport, atmospheric pressure, and surface morphology. In the following two Chapters we perform more detailed studies of Pluto’s surface temperature (Chapter 4) and volatile sublimation and deposition (Chapter 5) over the current epoch as well as the two most recent “Super Season” epochs to explore how high obliquity and orbital variations impact its surface evolution.
Long-term Surface Temperature Modeling of Pluto

4.1 Introduction

This chapter is based on work originally published in Earle et al. (2017b) as part of the *Icarus*’ Special Issue about The Pluto System inspired by NASA’s New Horizons mission flying through the Pluto system in July 2015.

NASA’s New Horizons mission has provided a wealth of new data about the Pluto system, including detailed surface geology and volatile distribution maps (Stern et al., 2015; Grundy et al., 2016). The images of Pluto sent back by New Horizons also reveal striking latitudinal and longitudinal albedo variations on Pluto’s surface (Stern et al., 2015; Grundy et al., 2016) bringing to high resolution the intriguing variegation originally revealed from Earth through decades of mapping efforts (e.g. Buie and Tholen, 1989; Buie et al., 2010; Young and Binzel, 1993; Grundy et al., 2013). These features provide new motivation for studying surface temperature variations on Pluto both in the current epoch as well as over the past
few million years as Pluto’s orbit has undergone variations creating dramatic differences in Pluto’s seasons over million year timescales, such as the “Super Seasons” described in Chapter 3.

Here we set out to determine what effect Pluto’s “Super Seasons” as well as Pluto’s albedo variations have on Pluto’s surface temperatures. The impact on atmospheric pressure and possible implications for surface morphology are addressed by Stern et al. (2015) (and briefly discussed in Chapter 3, Section 3.4.2). In this work we focus on the asymmetric surface temperature effects of Pluto’s changing geometries as opposed to the effects of total accumulated insolation. Nadeau and McGehee (2017) and Hamilton et al. (2016) show that the Keplerian slowing of orbital velocity at aphelion compensates for the greater heliocentric distance and balances out the pole-to-pole accumulated insolation over a single orbit. While insolation is symmetric, here we find that maximum surface temperature, being a much more instantaneous effect, proves to be both asymmetric and a greater driver of volatile transport activity. Thus our focus on temperature modeling in the present work.

Previous work has already been done to model volatile transport on Pluto (and inherently surface temperature). With the exception of Young et al. (2015)\(^1\), most of this work predates the New Horizons’ flyby of the Pluto system so their only observational constraints are atmospheric measurements from occultation observations and lower resolution ground-based albedo maps (Young, 2013; Olkin et al., 2015; Hansen et al., 2014). These works also all focus on the current epoch. We try to build upon the previous work by making use of the results from NASA’s New Horizons mission as well as considering the long term variations in Pluto’s orbit and resultant “Super Seasons”.

As previously mentioned, Pluto’s orbit is believed to be chaotic on timescales of 10 to 20 million years (Sussman and Wisdom, 1988, 1992) so we choose to focus on timescales of 3 million years or less in order to stay well below the limit of Pluto’s orbit becoming chaotic.

\(^1\)Since the publication of Earle et al. (2017b), additional post-encounter models have been published. In Chapter 6 we discuss these models and compare them with the work presented here.
4.2 Methods

4.2.1 Local Temperature Model

A first step towards understanding seasonal surface temperatures is looking at the annual insolation averages and how they vary over million year timescales. To do this we start by calculating Pluto’s orbit over the timescales of interest using the orbital model of Pluto initially presented in Dobrovolskis and Harris (1983) and refined in Dobrovolskis et al. (1997) (and described in Chapter 3, Section 3.2). This model well represents Pluto’s orbit for time scales of 10 Myrs, which is several times the length of our longest trial making this model sufficiently accurate for our purposes (Dobrovolskis et al., 1997). This provides us with the inputs necessary to calculate Pluto insolation as a function of latitude using the equations found in Levine et al. (1977) and an updated orbitally symmetric model from Earle and Binzel (2015) as guided by the analytic solution by Nadeau and McGehee (2017) and discussed by Hamilton et al. (2016).

We choose to focus on three significant epochs in Pluto’s orbital history. The first is Pluto’s current orbit, characterized by equinox and perihelion occurring close together. Second is Pluto’s orbital geometry 0.9 million years ago, characterized by Pluto’s sub-solar point at perihelion being high in the northern hemisphere; we call this “extreme northern summer”. The third epoch of interest is Pluto’s orbital geometry 2.35 million years ago, characterized by Pluto’s sub-solar latitude at perihelion being low in the southern hemisphere; we call this “extreme southern summer”.

We begin comparing these epochs by examining the insolation averaged over one Pluto orbit (Figure 4.1, top left panel). At the current epoch (blue, solid line) one Pluto orbit yields insolation maxima at the poles and minima around ±30° (Earle and Binzel, 2015). During the epoch 0.9 million years ago (green, dashed line), the equator received a substantially lower minimum value for its insolation while the poles received almost 1.5 times as much insolation on average. For the epoch 2.35 million years ago, (purple, dotted line), a relatively
flat latitudinal insolation pattern emerges with the maximum occurring at the equator, with additional local maxima at each pole, and minima just beyond ±30°. During the current epoch, characterized by equinox occurring near perihelion and aphelion, both poles receive relatively similar insolation patterns. However during past epochs when Pluto underwent what we call “super seasons” one pole received more insolation over a shorter period of time while the other received less insolation but for a longer stretch of time, creating asymmetries in the maximum insolation as a function of latitude (Figure 4.1). These differences between maximum insolation and duration of time over which it is received become relevant when trying to model surface temperatures during different epochs.

While the average annual insolation and average surface temperature (Figure 4.1 top left and bottom left, respectively) show pole-to-pole symmetry, the maximum local insolation and surface temperatures reached show the asymmetries that we call “super seasons”, as discussed in Chapter 3. In order to calculate surface temperatures as a function of latitude and albedo we use the 1-dimensional thermophysical model presented in Spencer et al. (1989) (all temperatures calculated and presented herein are surface temperatures, unless otherwise indicated). The Spencer model was designed to calculate surface and subsurface temperatures on a rotating body as a function of local time and was originally written in IDL, but here has been rewritten in Python and adapted for seasonal changes corresponding to the varying sub-solar latitude and heliocentric distance.

The model determines heating in the surface layer by balancing thermal emission, insolation, and conduction with the layer below. The middle layers are balanced by conduction only from the layer above and below. The bottom layer is balanced by conduction with the layer above and the lower boundary heat flux (Spencer et al., 1989). For the lower boundary heat flux we use 2.5 ergs/cm²s. We assume an emissivity of 0.9 based on Spencer et al. (1989). For the other thermal parameters we used values for methane at 40 K given in Spencer and Moore (1992); a heat capacity of $1.8 \times 10^7$ ergs/gK, density 0.52 g/cm³, thermal inertia $6.3 \times 10^5$ ergs/cm²√sK.
Figure 4.1: To explore temperature effects, we begin with Figure 3.3; repeated here as the top two panels. **Bottom Left:** *Average* surface temperature over one Pluto orbit as a function of latitude. **Bottom Right:** *Maximum* surface temperature reached at each latitude over one Pluto orbit as a function of latitude. Blue, solid lines are over Pluto’s current orbit. Green, dashed lines over one Pluto orbit, 0.9 Myrs ago, and the purple, dotted line over one Pluto orbit 2.35 Myrs ago. Note the changing y-axis scales. For the temperature profiles a global albedo of 0.3 is assumed.

The original version of the model is designed to calculate local temperatures over timespans of a few rotations with a constant sub-solar latitude and heliocentric distance. We have adapted the model for seasonal use by having it read in instantaneous heliocentric distances...
and sub-solar latitude values calculated using the model from Dobrovolskis et al. (1997). These values are then used to take into account how Pluto's geometry relative to the sun changes throughout its orbit.

The model used here, of course, does have several limitations. The thermophysical parameters are not temperature dependent, thermal re-radiation is only from the surface layer, and most importantly, volatiles are assumed to escape without re-condensing so that the temperatures of volatile ices can vary over the surface (the global model is treated in section 4.2.3). Even with these limitations the model serves as a good starting point for understanding seasonal temperature variations on Pluto. For example with a homogeneous Pluto (which assumes a global uniform albedo of 0.3) a substantial range of temperatures with seasonally dependent asymmetrical latitude distributions become readily apparent (Figure 4.1, right column). Pluto is of course variegated; we address the non-uniform case below. It should be noted that this model and its associated figures (e.g. Figure 4.2) should not be interpreted as hard and fast results so much as a limiting case describing the absence of volatile transport for exploratory comparison to an opposing limiting case that includes volatile transport.

4.2.2 Pluto Albedo Model

In order to account for Pluto’s albedo variations we have created a simplified albedo map of Pluto (Figure 4.3) that takes into account several of the major albedo units on Pluto’s surface. We assume a static Pluto, in which the albedo units do not vary with time or with solar zenith angle. To represent the region known as Tombaugh Regio, we assign an albedo value of 0.6 to a patch 45° wide in longitude, and extending from −30° to 45° latitude. Elsewhere between ±25° latitude, we use a dark band with an albedo of 0.1 to represent the region informally known as Cthulhu Regio. At all other locations an albedo of 0.3 is assumed.
Figure 4.2: **Top:** average daily surface temperatures over the past Pluto orbit. **Middle:** average daily surface temperatures over one Pluto orbit, 0.9 million years ago. **Bottom:** average daily surface temperatures over one Pluto orbit, 2.35 million years ago. Southern hemisphere latitudes are indicated by dashed lines while, Northern hemisphere by solid lines and the shaded region the "diurnal zone".

### 4.2.3 Global Model

Most of the time Pluto’s atmosphere may be in surface temperature equilibrium with surface frosts (Owen et al., 1993; Trafton, 1984). Along with our local model we also consider a global temperature model for comparison. By looking at how the temperatures of the local
model compare with the instantaneous, global equilibrium temperatures we can get a better understanding of which regions will most likely be losing volatiles and which will be gaining volatile deposits.

Just as with the local model we start the global modeling using the heliocentric distance and sub-solar latitude calculated based on Dobrovolskis et al. (1997). Again we assume an emissivity of 0.9 based on Spencer et al. (1989). In order to avoid overlapping albedo regions in the model we simplify our albedo map to include poles, with an albedo of 0.3, which extend to ±45° and a bright patch with albedo 0.6 which extends from -30° to 45° and is 45° wide in longitude. All other areas on the surface are assumed to be depleted of volatiles. We can then calculate global temperatures based on the energy balance equations given in Trafton (1984). However, equation 10 in Trafton (1984) appears to contain an extra factor of $A$, which we removed. The original version also only accounts for polar caps as a volatile reservoir, we have modified it to include Tombaugh Regio as a volatile region. Our modified version of Trafton’s energy balance equation is:

$$(A_{NP} + A_{SP} + A_{TR}) \epsilon \sigma T^4 = \pi F_c [(1 - a_P)(A_{NP}^* + A_{SP}^*) + (1 - a_{TR}) A_{TR}^*]$$

(4.1)
where $\epsilon$ is the emissivity, $\pi F_0$ is the solar flux at Pluto, $a_i$ the albedo of the region, $A_i$ the area of the region, and $A^*_{NP}$ the effective insolation area of the region. The subscript $NP$ denotes the north polar region, $SP$ the south polar region, and $TR$ the bright equatorial region informally known as Tombaugh Regio (note: all features names are informal at this time).

Trafton (1984) also provides the equations necessary to calculate $A^*$ for the polar regions. If a pole is in shadow, $A^* = 0$. If the pole is sunward facing and the sub-solar latitude ($\phi$) is greater in magnitude than the colatitude of the polar cap boundary ($\theta_c$ or $\pi - \theta_c$) then $A^* = \pi \sin^2 \phi$. For the in-between cases, where a pole is partially lit, the equation becomes more complicated:

$$A^* = \frac{\pi}{2} - \cos \theta_c \sqrt{\cos^2 \phi - \cos^2 \theta_c} - \cos^2 \phi \sin^{-1} \left( \frac{\cos \theta_c}{\cos \phi} \right)$$

$$+ \sin \phi \sin^2 \theta_c \cos^{-1} \left( -\frac{\tan \phi}{\tan \theta_c} \right) + \sin^2 \phi \tan^{-1} \left( -\frac{\sec \phi}{\sqrt{\tan^2 \theta_c - \tan^2 \phi}} \right)$$  \hspace{1cm} (4.2)

Equation 2 is reproduced from Trafton’s equation 13 (a full derivation can be found in Trafton, 1984). The $\cos^{-1}$ term is in the second quadrant when $\phi > 0$ and in the first quadrant when $\phi < 0$. To calculate the contribution from the opposite hemisphere Trafton (1984) uses $-\phi$ instead of $\phi$.

We calculate $A^*$ for the northern and southern part of Tombaugh Regio separately (and then add them). For each side we use the process described in the previous paragraph to determine $A^*$ for the entire hemisphere as well as a cap reaching down to the extent of Tombaugh Regio in that hemisphere. By subtracting $A^*$ of this cap from $A^*$ of the entire hemisphere we are left with the latitudinal band on which Tombaugh Regio lies. We can then divide this band, based on the longitudinal width of Tombaugh Regio, to get $A^*$ for just Tombaugh Regio.
While this model provides us estimates of the global temperatures on Pluto that we can compare to our local temperatures model, this model does have limitations. Most notably, it does not take into account thermal inertia or internal heat flux. The temperatures provided by the model are instantaneous, and as a result drop below most of our local model temperatures when Pluto is at perihelion.

4.3 Results

4.3.1 Annual Temperature Patterns - Uniform Albedo Model

We start our discussion by looking at local surface temperature variations at select latitudes over the course of one Pluto orbit for our three epochs of interest for the case of a globally uniform albedo of 0.3 across the entire surface. Figure 4.2 shows temperature variations at the poles, ±45°, and in the “diurnal zone”. We define the “diurnal zone” as the area between −13° south and +13° north. This is the region on Pluto’s surface that always receives diurnal insolation as the obliquity varies over million year timescales (for further discussion of the “diurnal zone”, see Chapter 3 or Binzel et al. (2017)). All other regions of Pluto have been in the arctic (or antarctic) circle at some point in the past few million years, experiencing extended periods of constant sunlight in “summer” and constant darkness in “winter”.

Looking at Figure 4.2 we see obvious latitudinal variations as well as two changing trends between the three epochs: (1) the differences between polar, mid-latitude and equatorial surface temperatures vary between epochs and (2) the surface temperature patterns of the two hemispheres, specifically the poles, contrast within each epoch as well as when comparing them between epochs.

The difference between polar, mid-latitude and equatorial local surface temperatures from one epoch to the next are largely driven by how Pluto’s obliquity (and as a result insolation patterns) are changing over million-year timescales. This can be seen by comparing the differences in Figure 4.2 with the insolation curves in Figure 4.1. Not surprisingly the areas
receiving the highest average insolation over the year also experience the warmest surface temperatures. The interesting exception to this can be seen in the 2.35-million-year-ago case. During this epoch the equator receives a higher average insolation, however since it is in the “diurnal zone” the insolation is fairly evenly distributed throughout the year, leading to steady surface temperatures that are generally lower than the peak polar surface temperatures. This is caused by the poles receiving constant insolation as “midnight sun” for part of the year. The diurnal zone surface temperatures are generally the most steady (varying by only $\sim 0.5K$ per year) while polar temperatures vary by 3 or more degrees throughout the year.

The other variations are the contrasts between the hemispheres during each Pluto year as well as the different epochs. These variations are driven primarily by variations in Pluto’s sub-solar latitude at perihelion coupled with its relatively high orbital eccentricity ($e \approx 0.25$). During the current epoch, equinox and perihelion occur close together. As a consequence, the north pole receives insolation from roughly the time Pluto passes perihelion until it reaches aphelion while the south pole receives insolation from aphelion to perihelion. This results in both poles having equal length dark seasons and summers of similar duration and intensity. In contrast, 0.9 million years ago when Pluto’s sub-solar latitude at perihelion was high in the northern hemisphere (at $\sim +76^\circ$), the northern hemisphere received direct sunlight at perihelion while the southern hemisphere received its most direct sunlight at aphelion where the insolation flux is diminished by a factor of three. This results in what we are referring to as “Super Seasons”, where one pole receives a short, “hot” summer and long winter, while the other receives a short winter and much longer, but less intense summer. A slightly less dramatic version of these “Super Seasons” can be seen in the epoch 2.35 million years ago when the sub-solar latitude at perihelion was $\sim -53^\circ$ leading to short-lived high local surface temperatures in the southern hemisphere and a much longer, but lower temperature summer in the northern hemisphere. We emphasize since the equatorial region always receives its
solar energy on a diurnal day/night cycle and never during an interval of continuous arctic summer, the equatorial region does not experience any "Super Seasons" the way the poles do.

4.3.2 Historical Temperature Extremes - Variegated Albedo Model

To get a more global view of trends on Pluto, and to incorporate Pluto’s striking albedo variations we ran the thermal model for various latitude and albedo combinations (based on the simple albedo map we presented in section 2.3 and shown in Figure 4.3). From these trials we were able to create minimum and maximum local surface temperature maps (Figure 4.4) to study how both albedo and latitude variations affect surface temperature extremes. The effects of the “Super Seasons” discussed in the previous subsection can be seen in these plots.

Figure 4.4 draws attention to the impact albedo variations have on surface temperature. The bright, 0.6 albedo region, representing Tombaugh Regio stays cold (never rising above \( \sim 37K \)) while the darker, 0.1 albedo, Cthulhu Regio stays warmer (never falling below \( \sim 42.5K \)), even though these two regions are at comparable equatorial latitudes.

To get a better idea of long term extrema we took the information from the subplots presented in Figure 4.4 and combined it to determine the absolute minimum and maximum temperature reached at each latitude and albedo combination over the three epochs of interest combined. These results can be seen in Figure 4.5. This emphasizes the contrast between the bright region which generally never exceeds 40K and the rest of Pluto where local surface temperatures never drop below 40K and reach almost 50K.

4.3.3 Comparison with Global Model

To better understand what regions we expect to be experiencing sublimation and deposition we compare some of our local model results with the global temperature model described in Section 2.3. Since the global model does not account for thermal inertia we can
Figure 4.4: This figure compares Pluto's current orbit with its past super seasons. **Left Column:** The simple albedo map of Pluto used to make local surface temperature maps. **Center Column:** The minimum temperature reached during the Pluto year for each latitude and albedo combination on Pluto's surface. **Right Column:** The maximum temperature reached during the Pluto year for each latitude and albedo combination. **Top Row:** The current Pluto orbit. **Middle Row:** One Pluto orbit, 0.9 million years in the past. **Bottom Row:** One Pluto orbit, 2.35 million years ago.

make more direct comparisons by comparing the global temperatures to the instantaneous equilibrium temperatures calculated by the local model. We chose to focus on three specific latitudes: the north pole (90°), the equator (0°), and the south pole (-90°).
Figure 4.5: **Left:** The simple albedo model of Pluto initially introduced in section 2.2, used for the local model. **Middle:** The minimum surface temperature reached at each latitude and albedo combination over the three epochs of interest. **Right:** The maximum surface temperature reached at each latitude and albedo combination over the three epochs of interest.

Table 4.1: Minimum and maximum global temperature (K) reached for each epoch

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Min T (K)</th>
<th>Max T (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>24.4</td>
<td>37.7</td>
</tr>
<tr>
<td>0.9 Myrs Ago</td>
<td>27.5</td>
<td>45.0</td>
</tr>
<tr>
<td>2.35 Myrs Ago</td>
<td>27.5</td>
<td>38.4</td>
</tr>
</tbody>
</table>

For each of the latitudes and epochs of interest we compare the instantaneous local temperature testing albedo values of 0.1, 0.3, and 0.6, with the global temperature over that same time period (Figure 4.6). The minimum and maximum global temperature for each epoch are also given in Table 1. Since there is no thermal inertia the equatorial temperatures will vary considerably throughout a Pluto rotation, so here we just look at the mean equatorial equilibrium temperature over each Pluto rotation. We see some obvious contrasts between the polar and equatorial cases. The equatorial temperatures never vary by more than a few degrees Kelvin while the polar temperatures show dramatic seasonal variations of 40K or more. The global temperatures range between roughly 25 - 45K, showing the greatest amplitude over the 0.9 myrs ago epoch when Pluto was near its minimum obliquity.
Figure 4.6: Comparison of instantaneous global temperatures to instantaneous local equilibrium temperatures for select latitudes and albedos. The columns are organized by latitude with left: latitude 90°, center: latitude 0°, right: latitude -90°. The rows are organized by epoch with top: the current Pluto orbit (where the time increment is Earth years), middle: one Pluto orbit, 0.9 Myrs ago, bottom: one Pluto orbit, 2.35 myrs ago. The global temperatures are indicated by the solid, black lines, the albedo = 0.1 local cases are purple, dashed lines, the albedo = 0.3 cases are blue, dot-dashed lines, and the albedo = 0.6 cases are marked with green, dotted lines.

4.4 Discussion

When considering long-term insolation patterns on Pluto, the relative minimum at the equator relative to the poles has been shown in several previous works (e.g. van Hemelrijck (1982), Dobrovolskis (1989), and Spencer et al. (1997)) and illustrated at multiple epochs by Earle and Binzel (2015). Thus if the minimum location served as the explanation for the location of Tombaugh Regio (Hamilton et al., 2016) our analysis indicates Pluto would show a bright equatorial band rather than a "spot". We argue that the equatorial region on Pluto is a "preservation zone" for whatever is seeded there, where the preservation capability is driven
by the coupling of the local albedo with an always diurnal cycle (and never a continuous arctic summer or winter), which we first showed qualitatively in Earle et al. (2015). Thus the equatorial zone is optimized to be the region of maximum contrasts that allows the darkest region (Cthulhu Regio) to abut directly the brightest region (Sputnik Planitia).

We find that once a region at the equator becomes bright it will become both the coldest and most consistently available cold trap, making it a likely area for volatile deposition, which in turn will refresh and brighten the surface. So for example, if Sputnik Planitia formed from an impact basin, as suggested by Moore et al. (2016), the topographic low would have initially attracted volatiles, creating a bright spot and triggering a strong feedback loop of volatile deposition in that area. Surface composition maps show that Tombaugh Regio is in fact volatile rich, showing high abundances of both $N_2$ and $CH_4$ (Grundy et al., 2016). In contrast, Cthulhu regio does not show any volatile abundances (Grundy et al., 2016). Given Cthulhu's low albedo and resulting higher local surface temperatures it could be expected that once a region at the equator began to darken it would become consistently one of the warmest regions of the planet and thus unlikely to gain any long term volatile accumulation, leading to further darkening.

Another way of looking at this effect is to compare the instantaneous equilibrium temperatures with the global temperatures, as we did in Figure 4.6. The polar temperatures show dramatic seasonal variations, spending portions of the year well above and well below the global temperatures. This suggest these regions will undergo cycles of deposition and sublimation and their volatiles (or at least a portion of their volatiles) will be seasonal. This effect persists for all of the albedo cases we tested, suggesting the polar regions are not likely to experience albedo variations caused by strong feedback. The equator on the other hand shows less seasonal variation, and remains close to the global temperature throughout the epochs studied. Over most of the time periods studied the bright (albedo = 0.6) equator temperatures are several degrees colder than the global temperature, it only briefly gets above the global temperature, and never by more than a few degrees, indicating net
deposition is most likely occurring in bright equatorial regions. Such ongoing long-term net deposition could be an important factor that keeps Tombaugh Regio’s morphology appearing ‘young’ and crater-free. On the other hand, the dark (albedo = 0.1) equator temperatures are generally higher than global temperatures, and only dip below the global temperatures for brief periods during each orbit. If all of the volatiles migrate away from a region, the bare surface will no longer be cooled by sublimation and a significant amount of seasonal cooling will need to take place before seasonally transient frosts can be deposited (Trafton, 1984). Taking this into consideration, it is very likely that dark, equatorial regions are generally bare of volatiles, any volatiles deposited are most likely minimal and seasonal. These comparisons show further evidence for “runaway” albedo variations at the equator and more stable, and spatially consistent albedos in the polar regions.

Thus the fact that the brightest and darkest regions on Pluto co-exist at the same latitude demonstrate that it is not the insolation minimum that drives the survival of Pluto’s “cold icy heart”. Rather it is the diurnal zone that allows self-preservation of an albedo extreme that gets seeded therein. To understand this phenomenon further we looked at the difference between the absolute maximum and absolute minimum local surface temperature reached at each latitude over the three epochs of interest, to see how much temperature variation each latitude experiences (Figure 4.7). We find that regardless of albedo, the variations in the equatorial and midlatitude region stay small, less than 3.5K. Moving away from the midlatitudes and towards the poles the variation in temperature increases. This effect is more dramatic in the northern hemisphere where the variation at the north pole is between 4.3 and 7.5K depending on the albedo. The stability of temperatures in the equatorial band independent of albedo makes it likely that once seeded, albedo variations in the equatorial region will be able to survive million-year or longer timescales while the polar region will be more susceptible to changing albedos.
Variations in Historical Temperature Extremes

Figure 4.7: Latitude on Pluto vs. the variation between the minimum and maximum temperature reached at that latitude considered over the three epochs of interest: the current orbit, 0.9 myrs ago, and 2.35 myrs ago. The red, dashed line uses an albedo of 0.6, the blue, solid line an albedo of 0.3, and the green, dotted line an albedo of 0.1

4.5 Conclusions

After performing thermal modeling to study surface temperature variations on Pluto as a function of latitude and albedo we see stark contrasts in the surface temperatures of high albedo regions (like Sputnik Planitia) and low albedo regions (like Cthulhu Regio) near the equator. Once seeded, a bright region at the equator will become the coldest cold trap on Pluto’s surface, making it a likely location for further bright, fresh volatile deposition. In contrast, once an equatorial region begins to darken, its lower albedo will help it stay warm,
making it an unlikely place for long term volatile deposits to form. We see that even with Pluto’s varying orbit, the bright, volatile rich Tombaugh Regio should be able to survive on million-year timescales. This also appears to be a unique characteristic of Pluto’s equatorial region, and we don’t expect such stark albedo variations would be able to survive in the polar regions. We will explore this effect and its latitudinal constraints in more detail in Chapter 5.

The New Horizons observations are allowing for the development of better albedo maps of Pluto. As these maps become available we will be able to take a more detailed look at the local surface temperature variations across Pluto’s surface. The first look presented here already points to some interesting results, including the survival of Tombaugh Regio over million-year timescales.
5

Albedo Matters: Understanding Runaway Albedo Variations on Pluto

5.1 Introduction

Most of the work in this chapter was originally published in Earle et al. (2018).

The images sent back from New Horizons show in high resolution the stark latitudinal and longitudinal albedo and surface volatile variations originally discovered from decades of Earth-based mapping efforts (e.g. Buie and Tholen, 1989; Buie et al., 2010; Young and Binzel, 1993; Grundy et al., 2013). While the latitudinal variations could be explained by prior volatile transport models (e.g. Hansen and Paige, 1996; Young, 2013; Spencer et al., 1997), these models do not address the dramatic longitudinal contrasts observed. It has been shown that on Saturn’s moon Iapetus, albedo differences are capable of triggering runaway global migration of water ice which would explain the moon’s extreme albedo dichotomy (Spencer and Denk, 2010). It has been suggested that Pluto’s surface may also be sensitive to “runaway” albedo variations which create and maintain its longitudinal contrasts (Earle et al., 2015, 2017b; Hamilton et al., 2016). We use the term “runaway” as a moniker for “strong feedback loop”, remaining consistent with how it is used in Spencer and Denk (2010);
Earle et al. (2017b); and Hamilton et al. (2016). Here we perform a detailed study of this effect over both the current epoch and past “Super Season” epochs to explore its effectiveness, latitudinal dependence, and sensitivity to Pluto’s orbital variations.

As discussed in chapters 3 and 4, Pluto’s varying high obliquity and regressing longitude of perihelion combine to create epochs of “Super Seasons” on Pluto, where one pole is oriented most directly at the Sun at perihelion and thereby experiences a short, intense summer and subsequent long duration, dark “arctic” winter. Figure 5.1 shows the diurnal insolation for select latitudes over the last Pluto orbital year (top) compared to the diurnal insolation for those latitudes during an orbital year occurring at the last two “Super Season” epochs (middle and bottom). These calculations are based on the equations for Pluto’s orbit presented in Dobrovolskis et al. (1997), which represent Pluto’s orbit well for timescales of 10 million years. Since we are focused on timescales of less than 10 million years and looking for general trends instead of strictly quantifying volatile distributions, this accuracy is sufficient for our work. Obliquity is an important driver in the orbitally averaged annual insolation for each latitude, as shown in Figure 5.2. Thus as Pluto’s obliquity varies we would expect Pluto’s volatile transport to also change. It has already been suggested that conditions on Pluto during these “Super Season” epochs could vary substantially from Pluto’s current environment (e.g. Stern et al., 2017; Earle et al., 2017b; Binzel et al., 2017, also see Chapters 3 and 4), however most of the previous volatile transport models only consider short timescales during the current epoch, keeping Pluto’s obliquity fixed to explore its effectiveness as a function of latitude.

Here we present a simple volatile sublimation and deposition model as a first step towards exploring the long-term relationship between albedo, latitude, and volatile sublimation and deposition when Milankovitch-like obliquity cycles are included. In considering all of these effects, we particularly focus on obtaining a quantitative understanding of possible runaway albedo and volatile distribution variations on Pluto’s surface. We look at these relationships not only during Pluto’s current epoch, but also over several of Pluto’s past “Super Season”
epochs. We purposefully chose a simple model to allow for quick computations and to minimize the number of assumptions that have to be made about parameters, such as thermal inertia; parameters that are still not well known for Pluto's surface. Given the simplicity of the model, our results are focussed on the qualitative relationships and do not make any effort to predict specific quantities of transport.

We use separate models to look at the behavior of Nitrogen and Methane, two of the most abundant volatiles on Pluto (Cruikshank et al., 1976; Cruikshank and Silvaggio, 1980; Clark et al., 1986; Owen et al., 1993; Grundy et al., 2016). Pluto’s surface ice probably con-
Figure 5.2: Annually averaged insolation (over one Pluto orbit) as a function of latitude for various obliquity values. For reference, we also show obliquity values for some additional cases (0°, 90°, 157°, and 135°), which are not reached during Pluto’s current obliquity cycle.

...sists mostly of methane and nitrogen in solid state solution, with vapor pressures different from those of the individual ices (Trafton, 2015). Again, to avoid assumptions and keep the computations efficient, we chose to use separate models for each species for this initial evaluation. We consider albedo variations as a possible mechanism for creating and maintaining the stark longitudinal albedo and volatile distribution contrasts seen around Pluto’s equator. For completeness, we explore quantitatively runaway albedo and volatile distributions at all latitudes. To assess the process of albedo feedback, this model assigns albedos to different regions on Pluto to see how volatile sublimation and deposition will respond to albedo variations, for example darkening from photochemistry (Cruikshank et al., 2016; Wong et al., 2017) or brightening from fresh deposits in an impact basin like Sputnik Planitia (Schenk...
et al., 2015; Moore et al., 2016). We explore how long such albedo features would be able to survive given Pluto’s orbital variations and “Super Seasons” and how sensitive different latitudes on Pluto are to runaway albedo and volatile distribution variations.

5.2 Methods

5.2.1 Basic Model

To start we created a simple sublimation and deposition model based on the work done for Triton in Spencer (1990). The model assumes all surface ice is in thermal equilibrium. Since we are focussed on patterns over long timescales, we use diurnally averaged insolation so the volatile equilibrium temperature varies with seasons, not over the diurnal cycle. Young (2012) explore the implications of this assumption in detail and found that atmospheric buffering dominates over diurnal timescales and restricts nitrogen temperature and surface pressure variations to less than 0.2% over a Pluto day. We purposefully chose a simple sublimation and deposition model, to allow us to focus on the role albedo plays in volatile transport over long timescales, while limiting the number of assumptions that must be made about parameters that are still not well known for Pluto, such as thermal inertia. The lack of thermal inertia and diurnally averaged insolation mean we are essentially assuming infinite thermal inertia or effective atmospheric buffering over diurnal timescales and zero thermal inertia over seasonal timescales. The implications of not including thermal inertia are discussed in subsection 5.4.3. The model is initiated with an even ice distribution, and is run for approximately 10,000 years (40 Pluto orbits) to give the volatiles a chance to reach a steady state for the epoch in question. For the simplest version of the model, the variables considered are the initial ice mass per area, the albedo of the ice, the albedo of the substrate, and the emissivity of the ice and substrate.
Global volatile temperatures are calculated by balancing insolation and thermal radiation averaged over the exposed volatiles. By rearranging equation 1 of Spencer (1990) to solve for the volatile temperature \((T_v)\) we get:

\[
T_v = \left( \frac{\int (1 - A) S(\theta) F(\theta) \, da}{\int \varepsilon \sigma F(\theta) \, da} \right)^{1/4} \tag{5.1}
\]

where \(\varepsilon\) is the emissivity, \(\sigma\) the Stefan-Boltzmann constant, \(F\) describes the ice coverage as a function of latitude \(\theta\), \(S\) is diurnally averaged insolation, \(A\) bolometric albedo and \(\int da\) is integration with respect to the surface area of the object. From here we can calculate the net mass sublimation rate as a function of latitude \((\dot{m}(\theta))\) using:

\[
\dot{m}(\theta) = \left( \frac{(1 - A) S(\theta) - \varepsilon \sigma T_v^4}{L} \right) \tag{5.2}
\]

where \(L\) is the latent heat of sublimation from Brown and Ziegler (1980). If the ice mass load at a given latitude drops to zero, that region is considered to be “ice free” (with \(F(\theta) = 0\)) and the local temperature is calculated by balancing the local diurnally-averaged insolation and radiation:

\[
T_{loc} = \frac{(1 - A_{sub}) S(\theta)^{1/4}}{\varepsilon \sigma} \tag{5.3}
\]

where \(A_{sub}\) is the albedo of the substrate. If the local temperature drops below the global ice temperature in a given area, then ice will start condensing on that area again. All the trials shown here use a substrate emissivity of 1.0 and an ice emissivity of 0.9 unless otherwise stated (Stansberry et al., 1996; Stansberry and Yelle, 1999).

### 5.2.2 Nitrogen Model

The focus of this paper is to study how albedo will affect volatile transport over time. In order to do this we set up a simple test case where Pluto's surface is divided longitudinally into three sections (each 120 degrees wide in longitude and stretching from pole to pole). Each section is assigned a different ice albedo value (0.1, 0.3, or 0.6), and the substrate is
assumed to be dark (albedo = 0.1). The trials start with nitrogen distributed evenly across Pluto’s surface. As the model runs the nitrogen is able to redistribute between sections. Within each of the sections the nitrogen ice keeps the same albedo throughout the run. We assume the nitrogen ice is essentially clear (Duxbury et al., 1997) and that its albedo is being driven by external circumstances, while for the variable ice albedo model described in the next section we allow the albedo of each section to change over time. We acknowledge that there are circumstances that could potentially lead to the clear nitrogen ice driving the surface albedo, for example solar gardening or scattering at $\alpha - \beta N_2$ transition fronts could lead to a bright albedo while precipitating dust and haze or cosmic rays altering impurities in the ice could darken the Nitrogen (Duxbury et al., 1997; Grundy and Stansberry, 2000). However, we chose not try to address these complex processes with this simple model.

5.2.3 Variable Ice Albedo Model

The variable ice albedo model builds on the nitrogen model described above with a few modifications. For example, we use the latent heat of sublimation of methane (instead of nitrogen) (based on Brown and Ziegler, 1980). The model is initiated, as described above, with three different albedo sections and an even ice distribution. However, unlike the nitrogen model, the methane albedo is allowed to vary as ice sublimates and deposits.

Based on the rate of hydrocarbon deposition from Wong et al. (2017) and assuming it takes roughly 0.005 $g/cm^2$ of irradiated hydrocarbons to darken the surface (Stern et al., 1988), we assume that Pluto’s surface darkens by about $3.2 \times 10^{-5}$ per year. Once the albedo in the model falls to 0.5, we assume no further darkening. If fresh ice is deposited on a dark layer, the model tracks the mass load of the fresh layer and should that fresh layer be depleted by sublimation, the albedo in that area will drop back down to that of the exposed, underlying dark layer.
As fresh ice is deposited the albedo increases by 0.5 for the first 0.5 $g/cm^2$ of methane deposited, and then by 0.1 per each additional $g/cm^2$ after that, until a maximum albedo of 0.85 is reached. These are rough estimates of how albedo varies with ice age and mass load, further laboratory measurements of the reflectance of methane ice and production of tholins could improve this model.

5.3 Results

5.3.1 Nitrogen Model Results

The nitrogen model was run with Pluto divided longitudinally into thirds with a different albedo assigned to each third (as described in subsection 5.2.2). Various emissivities (between 0.6 and 0.9) and initial ice mass loads (between 10 $g/cm^2$ and 1,000 $g/cm^2$) were tested and the results of a typical trial are shown in Figures 5.3 and 5.4, where the initial ice mass load was 10 $g/cm^2$ and the ice overlaid a dark, 0.1 albedo, substrate. Figure 5.3 shows how the ice mass load changed over the final Pluto year for each albedo section over each of the three epochs of interest, while Figure 5.4 shows snapshots of Pluto's Nitrogen distribution at four different times over the last orbit leading up to the New Horizons close approach in July 2015. For cases like this one, where the nitrogen layer is thin enough for the substrate to be exposed in areas experiencing significant sublimation, we find a number of trends dependent on albedo and epoch. The poles experience orbit seasonal polar caps extending as far as $\pm 30^\circ$ in each hemisphere more or less regardless of ice albedo and epoch. The results at the mid and equatorial latitudes are far more dependent on the ice albedo and epoch. If the equatorial latitudes are dark (0.1 albedo) or moderate (0.3 albedo) they quickly lose their volatiles during all three epochs. However, if these same areas are bright (0.6 albedo) they become a cold trap, and gain nitrogen.

The extent and depth of nitrogen accumulation is variable based on the epoch (obliquity and longitude of perihelion). During the current epoch (top row in Figure 5.3), over the 10,000 year trial a nitrogen layer reaching mass loads over 40 $g/cm^2$ in some places, builds
Figure 5.3: Nitrogen mass load as a function of latitude over the last Pluto year of a 40 Pluto year (~ 10,000 Earth year) trial for three different epochs in Pluto's orbital evolution, each started with an even, 10g/cm² distribution of nitrogen. Each row is a different epoch, and the three columns represent each of the thirds the surface has been divided into longitudinally, with a different ice albedo assigned to each. The polar latitudes generally show seasonal ice deposits, regardless of albedo. While the mid and equatorial latitudes are strongly albedo dependent, with the bright (0.6 albedo) region building up a large equatorial deposit while the dark (0.1 albedo) and intermediate (0.3 albedo) regions lose all of their equatorial nitrogen.

up between 45°N and 45°S. For the 0.9 Myrs ago epoch (middle row in Figure 5.3), where Pluto's obliquity is around 103° and the North Pole experiences short, intense summers and long, dark winters, the band of equatorial deposition is much narrower and thicker. At the equator more than 70 g/cm² of nitrogen accumulate, but the deposition site is much narrower, only extending between roughly 30°N and 30°S. 2.35 Myrs ago, Pluto's obliquity was around 126° and its South pole pointed towards the Sun at aphelion. Over this epoch
Figure 5.4: Nitrogen mass load for the three different albedo regions, shown at 4 different times in the past Pluto year, including 2015 (right) when NASA’s New Horizons spacecraft flew through the Pluto system.

(bottom row in Figure 5.3), nitrogen is broadly distributed over the entire high albedo region, with the thickest (45 g/cm²) deposits falling around 45° N and 45° S. The polar regions maintain ice year-round but the mass load varies seasonally. The equator maintains a thin layer of ice with very little seasonal variation.

Figure 5.4 shows an alternative visualization of the results presented in Figure 5.3. Here, the nitrogen mass load for each albedo is shown at four different quarters of a Pluto year up to and including 2015, when the New Horizons spacecraft made its close approach through the Pluto system. The polar cap is fairly uniform across all three albedo regions and shifts seasonally from the South to the North pole. At the time of the New Horizons encounter, the Northern hemisphere was entering into summer. According to the model, the north polar cap was in the process of migrating south, with darker, northern areas potentially already being depleted of volatiles, while brighter areas may still maintain some deposits. The model also predicts darker, equatorial regions will be completely nitrogen depleted, while a bright, equatorial region would have the potential to trap a majority of the surface nitrogen. This representation also makes it easier to see the migration within the bright, equatorial trap, where some nitrogen is exchanged seasonally between 30° N and 30° S.
Emissivity = 0.9 and Initial Mass/Area = 10.0g/cm$^2$

$\text{Alb} = 0.1$

$\text{Alb} = 0.3$

$\text{Alb} = 0.6$

Figure 5.5: Methane mass load as a function of latitude over the last Pluto year of a 40 Pluto year (~10,000 Earth year) trial for three different epochs in Pluto's orbital evolution, each started with an even, 10 g/cm$^2$ distribution of Methane. Each row is a different epoch, and the three columns represent each of the thirds the surface has been divided into longitudinally, with a different ice albedo assigned to each. Again, the polar latitudes show less albedo sensitivity than the mid and equatorial latitudes. The asymmetric bands are dependent on the starting conditions of the model, occurring in whichever hemisphere experiences winter first when the model begins running (further demonstrating the persistence of bright deposits near the equator).

5.3.2 Methane (variable albedo) Model Results

The results of the variable ice albedo model (Figure 5.5) are very sensitive to the rate at which the albedo varies (which is not well known), and the point in the seasonal cycle at which the model run begins. In particular the asymmetric banding is a function of which hemisphere experiences winter first (i.e. starting the model half a Pluto year earlier or later
will switch the banding to the other hemisphere). The width and mass load of the banding is also strongly driven by the rate at which the albedo varies. These latitudes are so albedo sensitive that a single season of sublimation and darkening or bright, fresh ice deposition can trigger the albedo to runaway.

There are still a number of interesting trends displayed by this model. As with the nitrogen model, the poles experience seasonal deposits, but here they show the possibility of more permanent deposits building up in past epochs (see bottom row of Figure 5.5). The bright region (0.6 starting albedo) shows very similar results to the nitrogen model but with slightly broader latitudinal coverage (compare the last columns of Figures 5.3 and 5.5).

Unique to the variable ice albedo model, are the mid-latitude deposits in the dark (0.1 starting albedo) and intermediate (0.3 starting albedo) regions. While these bands are very sensitive to the conditions of the model, their existence does show us that at mid-latitudes, a bright ice deposit could trap enough methane to survive seasons of sublimation.

5.3.3 Low-obliquity Model Results

For comparison we ran several nitrogen models for some general cases not specific to Pluto (with a starting ice mass load of 10 g/cm²) for the current Pluto epoch, but with Pluto’s obliquity changed (Figure 5.6). With an obliquity of 157°, comparable to Earth’s 23.5° but retrograde, all of the nitrogen is quickly sublimated away from the equatorial latitudes to form polar caps. Most of the nitrogen goes to the bright (0.6 albedo) polar region, forming caps extending down to around 45°N and 45°S. The intermediate (0.3 albedo) region developed smaller, thinner, permanent polar caps and a small amount of nitrogen is exchanged seasonally between the poles of the dark (0.1 albedo) region.

An obliquity of 135° was considered as an intermediate case (Figure 5.6, middle row). Again, all of the nitrogen at the equator was quickly sublimated away. The dark (0.1 albedo) and intermediate (0.3 albedo) regions both develop seasonal polar caps. The bright region develops large polar caps extending to 20°N and 20°S, with seasonal variations in mass load.
Figure 5.6: Nitrogen mass load as a function of latitude over the last Pluto year of a 40 Pluto year (~10,000 Earth year) trial each started with an even, 10g/cm² distribution of nitrogen. Each row is a different obliquity (Pluto's current longitude of perihelion is used for all three trials), and the three columns represent each of the thirds the surface has been divided into longitudinally, with a different ice albedo assigned to each.

The final case, with an obliquity of 126°, is the limit of Pluto obliquity. The dark and intermediate albedo regions develop seasonal polar caps very similar to the 135° case. The bright region develops deposits around 35°N and 35°S that vary in width over the seasonal cycle, all the other latitudes in this region maintain a thinner, but consistent nitrogen layer.
5.4 Discussion

The results of both the nitrogen model (section 5.3.1) and variable ice albedo model (section 5.3.2) quantitatively show that Pluto's equatorial and mid-latitudes are more sensitive to runaway volatile distribution and albedo variations than the polar latitudes.

For most parameters the poles experience seasonally exchanged volatile deposits. Since most of the deposition occurs when the pole is in shadow, the albedo has very little effect on the rate or quantity of deposition. It will however have a small effect on the speed at which the deposit sublimates away, with brighter regions staying volatile covered slightly longer once exposed to sunlight.

The mid and equatorial latitudes were far more sensitive to albedo variations and runaway volatile distribution and albedo effects. Since Pluto has a high obliquity, its mid and equatorial latitudes receive less annually averaged insolation than its poles (Figure 5.2), these regions also don't receive prolonged (multi-year) periods of shadow and sunlight like the poles do (Figure 5.1). This combination creates conditions where the albedo of the surface drives whether volatiles are being deposited or sublimated from a given area, giving rise to the strong feedback effects. Once an area near the equator becomes dark, it will become too warm to maintain volatile deposits. Conversely, if an area becomes bright, it will become a cold trap and rapidly attract further deposition.

Given the mid and equatorial latitudes sensitivity to albedo variations, once seeded, we would expect longitudinal albedo contrasts to be able to survive at these latitudes over multimillion year timescales. Broad features like the dark, volatile depleted Cthulhu Reggio (informal name), and bright, volatile rich Tombaugh Reggio should be able to persist in their current general state even over Pluto's super season cycles. Although there may be some variation within these broad features over the obliquity cycle, for example, we would expect to see some changes within Sputnik Planitia (the left side of Tombaugh Reggio, believed to be a volatile filled impact basin) (Schenk et al., 2015; Moore et al., 2016). As Pluto's obliquity varies, the bright, equatorial latitude receiving the most volatile deposition
shifts. Over the current epoch we would expect deposition over the entire latitudinal range of Sputnik Planitia. When Pluto’s obliquity reaches 103°, its closest to 90° (last experienced 0.9 Myrs ago), we would expect deposition to be most concentrated around the equatorial part of Sputnik Planitia, and possibly some sublimation at its northern most extent. At Pluto’s other obliquity extreme (126°, last experienced 2.35 Myrs ago) we would expect deposition at the higher latitudes of Sputnik Planitia (centered around 40°N) and little to no sublimation and deposition near the equator.

5.4.1 Low Obliquity Trials

The latitudinal extent of the “runaway zone” is coupled strongly with obliquity. To further explore this relationship we performed several trials with different obliquities (presented in section 5.3.3). For Earth-like (157°) and even moderate (135°) obliquities, where the poles receive less annually averaged insolation than the equator (Figure 5.2), the equatorial latitudes will lose all of their volatiles, while the polar latitudes will be somewhat susceptible to albedo variations, with the permanence and extent of the polar caps being albedo dependent. For Pluto’s most vertical obliquity, 126°, the insolation minima are actually around 35°N and 35°S (Figure 5.2), and trials show this as a transitional case, where the poles and equator are minimally effected by albedo while bands centered around 35°N and 35°S experience mild runaway albedo and volatile distribution variations.

The most dramatic variations are seen in the $T-0.9 \text{ Myrs}$ trials (e.g. Figure 5.3; middle row). During this epoch, Pluto’s obliquity was close to horizontal (103°) and it was experiencing “Super Seasons”. This means Pluto’s equatorial region was not only receiving the minimum annually averaged insolation (Figure 5.2), but it was also receiving a very consistent amount of diurnal insolation while the polar latitudes experienced dramatic diurnal insolation variations (Figure 5.1).

We propose this combination of minimum annually averaged insolation and minimal difference in diurnal insolation over an orbit creates conditions for runaway albedo and volatile distribution variations. Earle et al. (2017b) shows that instantaneous temperatures
at the equator are generally close (within $15K$) to the global ice temperature, with the albedo driving the local, instantaneous temperature above or below the global ice temperature, which in turn supports runaway albedo variations. The poles' decades-long periods of shadow and sunlight keep their instantaneous temperatures further from the global ice temperature (with variations of more than $30K$), with the albedo having very little effect of whether the local temperature is above or below the global temperature (thus limiting the feedback effects). Minimum annually averaged insolation keeps the area cold enough for volatiles to be deposited, while steady, diurnal insolation keeps the instantaneous local temperature close enough to the global average ice temperature that albedo plays an important role in whether volatiles are being deposited or sublimated.

To better quantify this behavior, we calculate the relative difference between the maximum nitrogen mass load reached over the last Pluto year in the bright (0.6) and dark (0.1) albedo regions (Figure 5.7). Values close to zero indicate little to no albedo sensitivity, while value close to one indicate runaway albedo variations. From this analysis we see that for low obliquity planets, the extent of the polar caps is albedo dependent, but the equatorial region is not sensitive to albedo differences (since it experiences the highest average annual insolation and does not have prolonged periods of sunlight and shadow, the volatiles will migrate away from the equator regardless of albedo). However for higher obliquity planets, like Pluto, the equator is the most albedo sensitive region and the poles show less albedo sensitivity.

Pluto's range of obliquities makes its equatorial latitudes sensitive to runaway albedo and volatile distribution variations and able to (once seeded) maintain longitudinal albedo contrasts over long (multi-millions year) timescales. Because of their prolonged (decade, and even century timescale) exposure to darkness and sunlight, Pluto's poles are far less sensitive to feedback effects, experience mostly seasonal volatile deposits, and are unlikely to be able to harbor longitudinal albedo variations over long (multi-orbit) timescales. The mid-latitudes are generally sensitive to runaway variations, although their sensitivity varies
Figure 5.7: Albedo sensitivity based on the relative difference between the maximum nitrogen mass load reached over the last Pluto year in the bright (0.6) and dark (0.1) albedo regions for various obliquities. Pluto's actual obliquity varies between 103° and 126° (and is currently around 120°), and additional obliquity values are shown for comparison.

strongly with the obliquity (particularly for the variable ice albedo model, where ice albedo varied with freshness and mass load, these latitudes were very sensitive to not only the obliquity but also the starting season of the model). Thus it is difficult to determine the expected end result for these latitudes from this simple model.

5.4.2 Comparison with Observations

Based on the model we would expect to see some lingering volatiles near the North pole at the time of the New Horizons' close-approach to Pluto. At equatorial latitudes, we would expect the volatile distribution to be strongly correlated with the albedo. As
previously mentioned (section 5.4.1), the limitations of the model make it difficult to predict the outcome for the mid latitudes, but most likely, they would be volatile covered, with some correlation between albedo and volatile deposition (but not as strongly correlated at the equator). Furthermore, the results of the model suggest that longitudinal albedo and volatile deposit variations can survive over long (multi-million year) timescales at the equator, but the poles should not be able to support such extreme, longitudinal variations and should be more uniform.

Comparison of composition maps from Protopapa et al. (2017); Schmitt et al. (2017); Earle et al. (submitted) and Chapter 2 with the preliminary Bond albedo map presented in Buratti et al. (2017) (see their Figure 5) show Pluto’s equator is mostly dark and devoid of volatiles with the major exception being Tombaugh Regio, the bright region near the anti-Charon that is volatile rich, showing signs of containing nitrogen, methane, and carbon monoxide. The region from 30°S to 30°N shows the greatest diversity of both albedos and volatile abundances and Earle et al. (submitted) shows there is a strong correlation between methane abundance and albedo throughout this region, as we would expect from our model. From 30°N towards the pole the albedo and volatile distribution become more homogeneous, with some latitudinal variations but very little longitudinal contrast, which again is consistent with what we would expect from the model. Schmitt et al. (2017) found nitrogen rich ice occurs mostly in 30°–60°N (and less uniformly in the 60°–70°N range) but above these latitudes only methane rich ice exists. Based on our model, during the current epoch we would expect most nitrogen to be drawn to high albedo areas between 60°S and 60°N latitude, while methane would be more evenly distributed between equatorial latitudes and the seasonally exchanged polar caps.

It is worth noting that this model focuses specifically on albedo and volatile distribution and does not account for topography and geology which can also be contributing factors. Geology can effect the change in albedo of a particular region, for example, possible solid state convection in Sputnik Planitia could be burying haze particles, preventing them from
accumulating and darkening the surface of Sputnik Planitia the way they do in other areas (McKinnon et al., 2016; Grundy et al., submitted). Topography will also play a roll in volatile transport, and it has been suggested that over time areas with low elevations should slowly fill with volatiles (Trafton and Stansberry, 2015; Bertrand and Forget, 2016). Counter examples can also be found across Pluto’s surface indicating other effects, such as insolation discrepancies, albedo variations, and local slopes, may take precedence on some timescales (Lewis et al., 2017). A more comprehensive study of the relationship between surface topography and volatile distribution could serve to better calibrate the effectiveness of runaway albedo variations versus topographic effects for more detailed future modeling.

5.4.3 **Consideration of Thermal Inertia**

As previously mentioned, this model does not account for thermal inertia, and thus does not try to make quantitative assertions about Pluto’s volatile transport, but rather explore how Pluto’s unique orbit and orbital evolution may create regions sensitive to runaway albedo variations, and thus the stark, longitudinal albedo contrast observed on Pluto.

The volatile transport parameter searches conducted by Hansen and Paige (1996), Young (2013), and Hansen et al. (2014) found that increased thermal inertia will generally keep the temperatures closer to the annual average, increase heating and cooling times (and thus lead to slower deposition and sublimation of polar caps) and could lead to zonal banding (which was also sensitive to other model parameters). The thermal inertia of Pluto’s surface is currently not well constrained, particularly over seasonal timescales, and while it is important for detailed volatile transport study, based on past results its absence in this model should not effect the general and strictly qualitative conclusions we are drawing from the model. The values of thermal inertia that have been calculated from observations are between 20 – 30 Jm$^{-2}$s$^{1/2}$K$^{-1}$, which is lower than would be expected for compact ice, and are discussed in detail in Lellouch et al. (2000, 2011, 2016).
5.5 Conclusions

Pluto’s high obliquity creates a unique set of conditions that make its equator and mid-latitudes highly sensitive to runaway albedo and volatile distribution variations. Quantitatively we find the combination of minimal annually averaged diurnal insolation and minimal difference in diurnal insolation over an orbit makes these latitudes capable of maintaining stark, longitudinal albedo and volatile abundance variations (like those observed by New Horizons) over long timescales. Large-scale longitudinal contrasts like the dark, volatile-depleted, Cthulhu Regio (informal name), and bright, volatile-rich Tombaugh Regio, should be able to co-exist at the same latitudes even over Pluto’s “Super Season” cycles (which occur roughly every $1.5 \text{Myrs}$). However, we do not expect Pluto’s polar latitudes to be able to support these kinds of longitudinal albedo and volatile abundance variations because of their prolonged (decades) periods of continuous sunlight and darkness.

These results help us to better understand the longitudinal contrasts observed by New Horizons and Hubble (Stern et al., 2015; Buie and Tholen, 1989; Buie et al., 2010; Grundy and Buie, 2001; Grundy et al., 2013) as well as draw attention to the need for more careful consideration of how ice albedo and its variation is considered in future volatile transport models. Further radiative transfer simulations and lab studies of the reflectance of nitrogen and methane ice, and how it varies with mass load and freshness will also aid in this effort.
6

Pluto: Context and Conclusions

6.1 Context for Pluto Results

The work presented in this thesis is just a subset of the roughly 60 papers published about Pluto and its satellites in the first 2 years since the New Horizons spacecraft flew through the Pluto system. The wealth of new data provided by NASA’s New Horizons mission has lead to rapid advancement in the study of the Pluto system. In this section we provide some context for the thesis work presented here relative to the full range of work being done on the Pluto system in recent years.

Earle and Binzel (2015) was written and published before New Horizons reached the Pluto system. The primary purpose of this paper was to serve as a resource during encounter. This paper calculated Pluto’s insolation history over varying timescales leading up to the encounter and was used to interpret data as it was returned from the spacecraft and helped guide preliminary science results. The work done for this paper also became the inspiration and foundation for many of the post-encounter models including Earle et al. (2017b), Earle et al. (2018), Binzel et al. (2017), Stern et al. (2017), and Bertrand et al. (2018).
The temperature modeling presented in Earle et al. (2017b) (Chapter 4) was the first post-encounter paper to address volatile transport. It was published as part of the Icarus Special Issue about the Pluto System, as were Binzel et al. (2017) (Climate Zones) and Stern et al. (2017) (past epochs of higher atmospheric pressure). Since then additional time and more detailed analysis and processing of the New Horizons data has allowed for more detailed modeling of Pluto’s volatile transport, like the model used to study albedo feedback in Earle et al. (2018) (Chapter 5) and the global circulation modeling presented in Bertrand and Forget (2016), Forget et al. (2017), and Bertrand et al. (2018).

Of the global circulation modeling papers, Bertrand et al. (2018) is the only one to consider timescales over which Pluto’s obliquity variations become relevant, thus making it the most relevant to the work presented here. Bertrand’s paper presents numerical simulations of volatile transport on Pluto with a model designed to simulate the nitrogen cycle over million year timescales, assuming all nitrogen ice has an albedo of 0.7 (and not including methane or carbon monoxide in the model) and taking into account the changes in obliquity, sub-solar longitude at perihelion, and eccentricity. During high-obliquity periods which induce intense polar summers they find intense sublimation rates in the northern part of the ice sheet in Sputnik Planitia, where as low-obliquity periods favor sublimation in the center of Sputnik Planitia and condensation at the north and south extremities. In some of their trials perennial nitrogen deposits formed at the mid-latitudes (but not the equator, which remained volatile free).

The results of Bertrand et al. (2018) are in general agreement with what we would expect based on the modeling presented in Earle et al. (2018) (Chapter 5). Based on Figure 5.3 we would expect Sputnik Planitia (since it is a high albedo area) to experience deposition near the equator and sublimation from its northern and southern extrema 0.9 million years ago, the last time Pluto’s obliquity was nearly perpendicular. Where as 2.35 million years ago, when the obliquity was low, we would expect more deposition at the northern and southern limits of Sputnik Planitia, similar to the findings of Bertrand et al. (2018). Based
on our variable albedo model shown in Figure 5.5 (which uses methane instead of nitrogen), we expect perennial volatile bands at midlatitudes will form if the presence of volatiles in those areas increases the albedo (where as polar deposits will remain seasonal regardless of albedo). Bertrand et al. (2018) found similar bands in some of their trials, and also suggested that (while not considered in their model) albedo and presence of methane may drive the existence and survival of mid-latitude nitrogen deposits outside Sputnik Planitia. Both Earle et al. (2017b) and Bertrand et al. (2018) agree that further detailed modeling is needed to fully understand how surface ices evolve on Pluto.

While it is the first result presented in this thesis and was started during the 2015 encounter, Earle et al. (submitted) (Chapter 2) is actually the most recent of the papers to be published due to the time it took for all of the New Horizons' MVIC images of Pluto to be sent back from the spacecraft and properly calibrated. Preliminary results of the MVIC E.W. maps were presented in Grundy et al. (2016) and Moore et al. (2018). Interpretation of the maps presented in Earle et al. (submitted) has been aided by results from the New Horizons LEISA instrument presented in Grundy et al. (2016); Schmitt et al. (2017) and Protopapa et al. (2017). The low spectral resolution of MVIC and lack of available laboratory data in the low temperature regime at Pluto makes it difficult to make direct conclusions about abundance, purity, or grain size based on the MVIC data alone. However, comparison with LEISA data (which has lower spatial resolution but higher spectral resolution and covers a different wavelength range) makes it possible to infer these properties and then leverage MVIC's higher spatial resolution and more complete spatial coverage. Moore et al. (2018) has already used the MVIC E.W. global map to suggest the possibility of additional bladed terrain on the non-encounter hemisphere, showing that further detailed analysis of these maps could aid in understanding the relationship between geology and composition and interpreting the lower-resolution data from the non-encounter hemisphere of Pluto.
6.2 Summary of Pluto Conclusions

Pluto's equatorial latitudes show a broader diversity of colors and methane distribution than its polar latitudes

The maps presented in Chapter 2 (originally published in Earle et al. (submitted)) show in a new light a broad diversity of terrains across Pluto's surface using MVIC E.W. and spectral slope. We confirm other studies of Pluto’s surface from New Horizons (e.g. Grundy et al., 2016; Protopapa et al., 2017; Schmitt et al., 2017) as well as pre-encounter studies performed by Hubble (e.g. Grundy and Buie, 2001; Buie et al., 2010; Grundy et al., 2013) and maps created from Mutual Events data (Young and Binzel, 1993). The MVIC data used to produce the maps in Chapter 2 provides the highest spatial resolution for compositional maps yet achieved and better coverage than the LEISA instrument used for the other New Horizons surface composition studies. From this more complete coverage we are able to determine that the most extreme terrains on Pluto (reddest spectral slope, broadest MVIC E.W., etc.), all occur exclusively along the equator in the latitude band between 30°S and 30°N. This region contains the most volatile depleted (and tholin rich) terrains, as well some of the purest methane deposits and areas with a mix of methane, nitrogen, and carbon-monoxide ices. Buratti et al. (2017) also shows this latitude range containing both the upper and lower limit of albedo values found on Pluto’s surface, further attesting to the uniqueness of this region. These physical data help guide and constrain the modeling efforts.

Pluto’s orbital variations create substantial changes in Pluto’s seasonal cycles, including creating epochs of “Super Seasons”

Pluto undergoes obliquity variations and longitude of perihelion regression on cycles of 3 million and 3.7 million years, respectively (Dobrovolskis et al., 1997). These cycles, coupled with Pluto’s high eccentricity \(e \approx 0.25\), create substantial differences in the insolation patterns experienced on Pluto, as seen in Chapter 3. One consequence of these cycles are
epochs of “Super Seasons” on Pluto, where one pole receives a short, intense summer followed by a prolong period of continuous darkness, while the other pole received a short period of winter darkness and longer but less intense summer.

Pluto’s “Super Seasons” epochs have the potential to strongly impact its volatile distribution and surface evolution. Analysis performed for this thesis (Chapter 3) and presented within Stern et al. (2017) suggests these epochs may even be able to trigger periods of substantially higher atmospheric pressure on Pluto and possibly even support liquid nitrogen on Pluto’s surface, which would explain a handful of unusual surface features (examples of which can be seen in Figure 3.7). Bertrand et al. (2018) performs more detailed atmospheric pressure modeling which finds surface pressures above 100 Pa are unlikely to occur and suggests that the surface features are instead the result of past liquid flow at the base of massive nitrogen glaciers. Despite arguing against the higher pressures suggested by Stern et al. (2017), Bertrand et al. (2018) still supports the significance of Pluto’s orbital variations as a driver of Pluto’s surface evolution and volatile transport. Further consequences of these orbital variations are explored in detail in Chapters 4 and 5, with their conclusions summarized below.

**Pluto’s high obliquity supports strong feedback loops creating stark albedo contrasts**

The surface temperature modeling performed in Chapter 4 (originally published in Earle et al. (2017b)) provided an early indication that Pluto’s equatorial and mid-latitudes were more sensitive to albedo variations than polar latitudes. At equatorial latitudes the surface temperature is strongly driven by the albedo of the surface, regardless of the global average temperature. In comparison, polar latitudes will dip well below the global average in winter and reach well above it in summer regardless of their albedo (particularly during “Super Season” epochs).
A simple volatile sublimation and deposition model is used in Chapter 5 (originally published in Earle et al. (2018)) to study how Pluto’s surface volatiles respond to albedo differences, exploring these processes in greater detail over the current epoch as well as past “Super Season” epochs. We find Pluto’s high obliquity creates unique conditions that make its equator and mid-latitudes highly sensitive to albedo feedback effects, resulting in them being able to maintain stark, longitudinal albedo and volatile abundance variations over long timescales. We do not expect Pluto’s polar latitudes to be able to support these kinds of longitudinal albedo and volatile abundance variations because of their prolonged (decades) periods of continuous sunlight and darkness. We conclude that Pluto’s poles experience seasonal volatile deposits, the extent of which is driven more by seasonal epoch than albedo.

**Albedo is an important driver in Pluto’s volatile distribution and surface evolution**

The modeling performed in Chapters 4 and 5 shows that Pluto’s high obliquity makes its equatorial latitudes susceptible to feedback loops which create stark albedo and volatile contrasts (as detailed above). Therefore we would expect Pluto’s surface to show a great deal of diversity near the equator and be more homogeneous towards the poles. Chapter 2 analyzes data from New Horizons, and concludes the region between 30°S and 30°N shows the broadest diversity of colors and surface compositions, while Pluto’s more northern latitudes are more homogeneous and do not encompass the same extremes. The agreement between the modeling and observations suggests that albedo is in fact an important driver of Pluto’s surface volatile distribution. Particularly since pre-encounter volatile transport models, which used a more simplified treatment of albedo, could not explain these longitudinal contrasts (e.g. Hansen and Paige, 1996; Young, 2013; Spencer et al., 1997). This suggests that future volatile transport modeling should use a more careful treatment of albedo and would benefit from further radiative transfer and lab studies of the reflectance of nitrogen and methane (and how it varies with mass load and freshness) to more accurately model how the albedo of volatile ice will vary.
6.3 Pluto Future Work

The next steps for building upon the results presented here for Pluto would be a detailed, quantitative study of the methane maps presented in Earle et al. (submitted) (Chapter 2), followed by a detailed volatile transport study. These are outlined, in turn below.

A visual study of the methane abundance and spectral slope maps presented in Earle et al. (submitted) (Chapter 2) reveals a complex relationship between geologic features, such as craters, fossae, and mountain tops, that appear to be latitudinally dependent. However, further work is needed to quantify these relationships. The maps could be used to quantify the methane abundance and spectral slope of each crater’s floor, walls, and rim which could then be catalogued and studied as a function of latitude as well as geologic region. The deposits and colors around fossae and mountain tops could also be explored as a function of elevation, latitude, and insolation angle during the time of the New Horizons encounter. Quantifying these relationships would improve our understanding of the surface evolution of Pluto (and other volatile-rich objects), and also provide useful input for volatile transport models and constraining the timescales over which surface processes occur on Pluto.

A volatile transport study could build upon the work presented in Earle et al. (2018) (Chapter 5), using the constraints determined from the quantitative study of the MVIC maps. Since Earle et al. (2018) was a preliminary study of Pluto’s sensitivity to albedo variations over the current epoch as well as past “Super Season” epochs, the model used is a simple sublimation/deposition model that does not account for factors that are still not well constrained for Pluto, such as thermal inertia. Volatile transport models done before New Horizons’ encounter of the Pluto system account for thermal inertia but don’t take into consideration Pluto’s topography and often used a very simple treatment of albedo variations (e.g. Hansen and Paige, 1996; Young, 2013; Spencer et al., 1997). Thus previous models are limited in explaining Pluto’s striking longitudinal contrasts. They also focus on shorter timescales with Pluto’s current obliquity and longitude of perihelion. Given that many geologic features are expected to form and evolve over timescales of millions of years
or more, it can be expected that Pluto’s “Super Season” epochs play a role in its surface evolution and are important to consider while studying the relationships between geology and composition. By combining the numerical methods laid out in Young (2017) with the albedo variations developed for Earle et al. (2018) a more rigorous, post-encounter study of volatile transport on Pluto could be completed. This would break down into two parts: first a parameter search to best match the constraints of the current epoch, then a study of how volatile transport varies as Pluto undergoes its extreme Milanković cycles.
Apophis and the “Smart Marbles” Package

Preface

This chapter aims to provide a more complete understanding of the NASA Project Lifecycle. I started graduate school two years before the New Horizons mission flew through the Pluto system, thus my involvement with the mission has been limited to the the data collection and analysis phase. For this final chapter we look ahead to a possible next step in small body spacecraft exploration, a mission concept to study the asteroid Apophis during its 2029 close approach to Earth. This provides an opportunity to start back at the beginning of the NASA Project Lifecycle with a Pre-phase A concept study, to see how missions go from being a rough idea to a spacecraft design and concept of operations.

The NASA Project Lifecycle begins with the space mission engineering process. For a need-based mission, like the one proposed for Apophis, Wertz (2015) divides space mission engineering into 14 steps, fitting into 4 broad processes: (1) defining objectives and constraints, (2) defining alternative mission concepts or designs, (3) evaluating the alternative
mission concepts, and (4) defining and allocating system requirements. Space mission engineering is an interactive process, during which each of these broad processes gets repeated as requirements and methods of achieving them get refined with each iteration.

This chapter explores a novel hardware concept for studying seismic activity on small planetary bodies, the “Smart Marbles” package, to enhance the scientific potential of a mission to Apophis. This hardware package is designed to be part of an Apophis mission for which the space mission engineering process was begun as part of MIT’s 12.43/16.83 Space Systems Engineering course during the Spring semester of 2017. MIT 12.43/16.83 Space Systems Engineering (2017) is the result of the first iteration of the space mission engineering process and provides a rough concept for the mission. Given the time constraints of the course, we had to abandon one of the science goals of the mission related to performing seismology on small solar system bodies. Here we perform the next iteration of the mission design process and revisit this science goal. We take a closer look at the scientific motivation for achieving it, the measurement requirements, and evaluate hardware options, including proposing a new hardware concept (Earle et al., 2017a), all in the context of the proposed missions system requirements.

This chapter begins with an introduction to Apophis and the scientific motivation for studying it (Section 7.1). Section 7.2 introduces the SET mission as it was designed by 12.43/16.83 Space Systems Engineering and highlights the additional scientific goals related to seismology we aim to accomplish through further development of the design, defining the objectives and constraints for this next iteration of the space mission engineering process. Next, Section 7.3 defines alternative mission concepts (which are evaluated in appendix B). From this process we rule out pre-existing hardware options and determine the need for development of a new hardware concept. In Section 7.4 we consider the scientific motivation in greater detail in order to further refine the science objectives and propose a preliminary design for a novel hardware concept. We then consider how it would fit into the system
requirements for the proposed mission and how, if successful, it would enhance the mission objectives of the originally proposed mission. Finally, we present our conclusions from this process and the next steps for continuing the development process in Section 7.5.

7.1 Introduction

The asteroid 99942 Apophis (originally 2004 MN₄) is one of 1,901¹ known potentially hazardous asteroids (its properties are summarized in Table 7.1). It’s believed to be in a slow tumbling rotation state and have an elongated shape with a mean diameter between 365 and 389 meters and a mass between 4.4 and 6.2 × 10¹⁰ kg (Müller et al., 2014). It precesses faster than it rotates, with periods of 27.38 ± 0.07 hrs and 263 ± 6 hrs respectively (Pravec et al., 2014). With a bond albedo between 0.10 and 0.17 and Sq spectral classification (resembling LL ordinary chondrite meteorites), Apophis shows a strong resemblance to Itokawa, the asteroid studied by JAXA’s Hayabusa mission (Pravec et al., 2014; Binzel et al., 2009). Apophis is currently in a slightly inclined Aten orbit with a period of 0.89 years.

Table 7.1: Summary of Apophis Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Diameter</td>
<td>365 – 389 m</td>
<td>Müller et al. (2014)</td>
</tr>
<tr>
<td>Mass Estimate</td>
<td>4.4 – 6.2 × 10¹⁰ kg</td>
<td>Müller et al. (2014)</td>
</tr>
<tr>
<td>Shape</td>
<td>Elongated, asymmetric, possibly bifurcated</td>
<td>Brozović et al. (2018)</td>
</tr>
<tr>
<td>Rotation State</td>
<td>Slow, tumbling</td>
<td>Müller et al. (2014)</td>
</tr>
<tr>
<td>Orbital Period</td>
<td>0.89 yrs</td>
<td>Pravec et al. (2014)</td>
</tr>
<tr>
<td>Rotation Rate</td>
<td>263 ± 6 hrs</td>
<td>Pravec et al. (2014)</td>
</tr>
<tr>
<td>Precession Rate</td>
<td>27.38 ± 0.07 hrs</td>
<td>Pravec et al. (2014)</td>
</tr>
<tr>
<td>Bond Albedo</td>
<td>0.10 – 0.17</td>
<td>Pravec et al. (2014)</td>
</tr>
<tr>
<td>Spectral Type</td>
<td>Sq-class</td>
<td>Binzel et al. (2009)</td>
</tr>
<tr>
<td>Meteorite Analog</td>
<td>LL ordinary chondrite</td>
<td>Binzel et al. (2009)</td>
</tr>
</tbody>
</table>

Most significantly, Apophis will be passing between 5.6 and 6.3 R⊕ of Earth’s center on Friday, April 13th, 2029. It is estimated that approaches this close by an objects this large occurs on average intervals of 800 years or more (Giorgini et al., 2008), making this a rare

¹This number was retrieved from NASA/JPL’s Center for Near Earth Object Studies (cneos.jpl.nasa.gov/stats/totals.html) and is accurate as of 4/27/18
event. Apophis’ 2029 close approach to Earth offers a unique opportunity to study ‘live’ how planetary tidal forces impact the shapes, spin states, surface geology, and internal structure of large asteroids.

In recent decades, our understanding of asteroids has been transformed from points of light to geological worlds owing to modern spacecraft exploration and state-of-the-art radar and telescopic investigations. Yet their internal geophysical structures remain largely unknown. Understanding the strength and internal integrity of asteroids is not just a matter of scientific curiosity, it is a practical imperative for advancing knowledge for planetary defense against the eventuality of an asteroid impact. Nature is providing the experiment for us in the form of Apophis’ 2029 approach to within about 30,000 km of Earth’s surface (passing inside Earth’s geosynchronous satellite ring). This rare event provides the opportunity for internal geophysical study as well as a chance to test current hypothesis on the effects of tidal forces on asteroids.

A growing body of theoretical studies (Farnocchia et al., 2015; Keane and Matsuyama, 2015; Nesvorný et al., 2005; Richardson et al., 1998; Scheeres et al., 2005, 2000; Souchay et al., 2014; Yu et al., 2014) and physical evidence (Binzel et al., 2010; Miyamoto et al., 2007), for tidal forces altering the shapes, spins, and surfaces of near-Earth asteroids all point to these Earth-asteroid interactions being as fundamental to the asteroid hazard problem as impact studies themselves. Numerical studies have predicted possible tidal distortion (Richardson et al., 1998) or small, localized landslides triggered by tidal interactions (Keane and Matsuyama, 2015; Yu et al., 2014) during Apophis’ close approach to Earth. Evidence of landslides have already been observed on the asteroid Itokawa (which is in the same spectral class as Apophis and has a similar bond albedo) (Miyamoto et al., 2007) and resurfacing from seismic shaking induced by tidal forces from near-planet encounters has been suggested as an explanation for the unexpectedly high number of ‘unweathered’ asteroids in the near-Earth object population (Nesvorný et al., 2005; Binzel et al., 2010).
There is a significant and growing body of evidence for Earth’s tidal effects influencing encountering objects, however there is still a great deal of uncertainty over the physical outcomes of such encounters. Studying in detail how Apophis responds to Earth’s tidal torques during its 2029 close approach will provide an unparalleled opportunity for interpreting strength and internal structure of a potentially hazardous asteroid, revealing the physical process of Earth-asteroid tidal interactions, and could potentially capture ‘live’ tidally induced activity occurring on the surface. These results would not only be a giant leap forward for asteroid science but would also improve our understanding of solar system formation and inform asteroid hazard assessment and mitigation strategies.

Within the context of it being unlikely that our spacefaring civilization would not mount an effort to take advantage of measuring and monitoring this extraordinary “natural experiment”, MIT’s 12.43/16.83 Space Systems Engineering during the Spring semester of 2017 designed the Surface Evaluation and Tomography (SET\(^2\)) mission. The SET mission uses a suite of high-heritage instruments mounted on a commercially available bus to study Apophis before, during, and after its 2029 close approach to the Earth. In addition to the scientific objectives surrounding the near-Earth approach, SET will also monitor and decode the coupling of rotation and thermal cycling resulting in Yarkovsky drift\(^3\).

An Apophis mission, like SET, also has great potential for engaging the public. The science objectives of SET, particularly its contributions to asteroid hazard assessment and mitigation strategies, are areas of research with great relevance to the general population. Additionally, Apophis will be visible to the naked eye during its 2029 encounter, which is certain to draw public interest and provide ample education and public outreach opportunities. The SET mission study performed at MIT has already gained public interest and

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\(^2\)The asteroid Apophis is named after the Egyptian god of chaos and evil. In Egyptian mythology, the god Set is sent on his solar boat to thwart Apophis.

\(^3\)Yarkovsky drift is caused by uneven temperatures across the surface of small (meter to ten-kilometer) objects resulting in changes to their orbits.
has been featured in several popular science publications including Astronomy\textsuperscript{4}, Space.com\textsuperscript{5}, SpaceFlight Insider.com\textsuperscript{6}, and MIT News\textsuperscript{7}, showing the potential an Apophis mission has to capture the public's attention.

While the SET mission as it was originally proposed is capable of fulfilling a robust set of science objectives, due to the time and resource constraints of the class, we were unable to identify a way of making the mission capable of directly studying tidally induced seismic shaking on Apophis. In this chapter, we perform the next iteration of the space mission engineering process and revisit this abandoned science objective, consider the motivation behind fulfilling it, and consider possible hardware options. We determine the best path forward is development of the "Smart Marbles" package, a network of uncoupled accelerometers that will be able to measure seismic shaking on Apophis with broad coverage and low cost and risk. If successful, "Smart Marbles" will not only allow the mission to address additional science goals related to seismic shaking, but it will also enhance its ability to address existing science goals.

7.2 The SET Mission

This section reviews the SET Mission as designed as part of MIT’s 12.43/16.83 Space Systems Engineering during the Spring semester of 2017 in order to provide context for the development of “Smart Marbles” (complete details can be found in MIT 12.43/16.83 Space Systems Engineering (2017)). A. Earle served as the Lead Project Scientist for this study. Here we show how Mission Objective 2 had to be modified because of the time and resource constraints of the class. The goal of this iteration of the space mission engineering processes is to restore this objective to fulfill its original goals and enhance the science outcome of the mission through development of new instrumentation, like the “Smart Marbles” package.

\textsuperscript{4}Nicole Kiefert. MIT students propose Apophis asteroid mission: After working hard to design a spacecraft, the students presented their ideas to NASA scientists. Astronomy.com. June 2017.
\textsuperscript{7}Meg Murphy. Project Apophis: Space Systems Engineering students design a close-range mission to a giant asteroid that will fly by Earth in 2029. MIT News. May 2017.
7.2.1 Mission Objectives

The SET Mission was designed around three mission objectives chosen to optimize the scientific impact of the mission as well as inform asteroid mitigation strategies (Table 7.2).

Mission Objective 1: General Characteristics

The first mission objective encompasses the surface geology and mapping goals of the mission. It includes characterizing Apophis' bulk properties, including: mass, volume, bulk density, surface topography and composition. It also improves upon ground-based measurements of Apophis' shape, size, spin state, and rotation rate. The designed investigation starts with an initial survey before Apophis' close approach to Earth, continues throughout the flyby event and concludes with a survey after the event (see subsection 7.2.3 for more details). By observing these properties before, during, and after Apophis' close approach to Earth the SET mission looks for signs of tidally induced deformation or seismic resurfacing, as well as changes in spin state or rotation rate. A detailed study of Apophis' surface geology and composition will also help with understanding its geologic and dynamical history.

Mission Objective 2: Internal Structure

The second SET mission objective focuses on understanding the internal structure of Apophis through characterization before and after the asteroid’s close approach to Earth. The strength and cohesion of the interior can be determined from observations of Apophis’ interior structure and how it responds to the tidal torques from the Earth encounter event. This information is useful for general asteroid studies and has implications for impact scenario modeling and planetary defense.

Originally the SET mission's original concept sought to monitor Apophis' interior structure and any tidally induced seismic activity throughout its close approach to Earth. However, due to the time and resource constraints of 12.43/16.83 Space Systems Engineering, it was ultimately decided to remove “during” from this mission objective and settle for just taking interior measurements before and after the encounter. This limits the science of the mission to monitoring seismic activity strong enough to induce observable surface changes.
or changes to the organization of the interior structure. The goal of the “Smart Marbles” package (Section 7.4) is to allow seismic measurements (and thus inference of the interior structure) throughout the encounter phase of the mission to enhance the science outcomes of the mission and better understand how tidal torques effect potentially hazardous asteroids.

Mission Objective 3: Orbit Characterization

The final SET mission objective focussed on studying the process of Yarkovsky drift. Post-encounter the spacecraft continues to monitor Apophis until the next ground tracking opportunity in 2036. These synoptic measurements of position, rotation, and thermal emission are intended to decode the coupling of rotation and thermal cycling resulting in Yarkovsky drift. This can not only improve the future orbit determination for Apophis, but it can also improve orbit determination for other potentially hazardous asteroids.

7.2.2 Instrumentation and Spacecraft Overview

The original design for the SET mission includes four scientific instruments for fulfilling the mission objectives and science goals. The mission design provides a robust instrument suite, while keeping cost and risk low, by choosing heritage instruments (with instruments based on those flown on or designed for New Horizons, OSIRIS-REx, Mars Reconnaissance Orbiter, and the Lucy Mission). A heritage bus was also chosen, with the selection of the LEOStar-3 bus for the spacecraft (Figure 7.1). The LEOStar-3 is manufactured by Orbital ATK and was used for the Dawn and Deep Space 1 missions. The nominal instrument suite is described below and each instrument’s contributions to fulfilling the science goals of the is summarized in Table 7.2.

LOng Range Reconnaissance Imager (LORRI)

The first instrument designed to start science operations at Apophis is LORRI, the LOng Range Reconnaissance Imager. LORRI is based on the instrument by the same name flown on New Horizons (and planned for the Lucy mission), and consists of a 20.8 cm Ritchey-Chrétien telescope with a $1,028 \times 1,028$ pixel panchromatic CCD imager, giving it a $0.29^\circ \times 0.29^\circ$
Table 7.2: Original Science Traceability Matrix for the SET Mission to Apophis

<table>
<thead>
<tr>
<th>Top Level Mission Requirement</th>
<th>Science Goal</th>
<th>Science Measurement Requirement</th>
<th>Primary Instrument</th>
<th>Secondary Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.O.1 - Characterize Apophis' shape, size, density, surface topography and composition, rotation rate, and spin state</td>
<td>Surface Mapping (before, during, and after Earth encounter)</td>
<td>Survey Apophis' surface structure and shape to learn about geology of mid-sized (100's of meter diameter) asteroids</td>
<td>LORRI</td>
<td>Ralph-MVIC (pan)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LORRI/Ralph LEISA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Survey Apophis' shape before and after encounter to determine the impact of tidal torque on an asteroid's shape</td>
<td>Ralph-MVIC (pan)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measure Apophis' spin state and rotations rate before and after encounter to understand how tidal torques impact the dynamics of a potentially hazardous asteroid</td>
<td>Ralph-MVIC (pan)</td>
<td>LORRI/Ralph LEISA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Image Apophis' surface before, during, and after the encounter at sufficient resolution to observe possible land slides and other surface responses to tidal torques</td>
<td>LORRI</td>
<td>Ralph-MVIC (pan)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Map Apophis' surface with filters to allow for color imaging and broad band spectroscopy</td>
<td>Ralph-MVIC (color)</td>
<td>Ralph-LEISA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectral mapping of Apophis' surface to look at compositional heterogeneities and better refine Apophis' spectral class with higher resolution and broader wavelength coverage than achievable with ground-based observations</td>
<td>Ralph-LEISA</td>
<td>Ralph-MVIC (color)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Perform surface composition and color surveys both before and after encounter to look for tidally induced resurfacing</td>
<td>Ralph</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>During encounter observe Apophis' surface with color filters at sufficient time and spatial resolution to observe tidally induced resurfacing</td>
<td>Ralph-MVIC (color)</td>
<td>Ralph-LEISA</td>
</tr>
<tr>
<td>M.O.2 - Characterize internal structure before and after near-Earth event</td>
<td>Internal Structure</td>
<td>Map Apophis' interior (before and after encounter) to interpret the strength and internal structure of a potentially hazardous asteroid</td>
<td>RRT</td>
<td></td>
</tr>
<tr>
<td>M.O.3 - Characterize Apophis' orbit, accounting for the influencing factors of the Yarkovsky Effect</td>
<td>Yarkovsky Effect</td>
<td>Post-encounter monitoring to decode the coupling of rotation and thermal cycling resulting in Tarkovsky drift</td>
<td>TES</td>
<td>LORRI/Ralph</td>
</tr>
</tbody>
</table>

Science Measurements Objectives highlighted in blue are significant for understanding how a potentially hazardous asteroid responds to tidal torques.

field of view (Cheng et al., 2008). During the approach phase LORRI is designed to be the first instrument to resolve Apophis and take images to improve upon ground-based measurements of Apophis’ rotation rate, spin state, and shape while also monitoring the area around the asteroid for potential hazards. Once the spacecraft is in orbit around the asteroid, LORRI becomes responsible for high-resolution surface imaging, with an expected resolution of 0.0099 m/pixel at a distance of 2 km from the surface.
The Ralph instrument also has heritage on New Horizons and Lucy and consists of a panchromatic and color imager (MVIC) and a spectral imager (LEISA). Chapter 2 of this thesis presented some of the results from the New Horizons version of this instrument.

**Multi-spectral Visible Imaging Camera (MVIC)** consists of 7 independent CCD arrays on a single substrate to produce panchromatic and colored images. Each CCD has a $5.7^\circ \times 0.037^\circ$ field-of-view, but they are able to produce images with a much wider field-of-view by operating in time delay integration (TDI) mode (Reuter et al., 2008). Once SET is in orbit, MVIC becomes responsible for the broad panchromatic imaging, color and broad band spectrometry mapping. These maps can be used to look for evidence of seismic resurfacing induced by tidal torques from the Earth.

**Linear Etalon Imaging Spectral Array (LEISA)** is a wedged filter infra-red spectral imager that creates spatially resolved spectral maps. LEISA is a scanning imaging instrument, that makes use of a special filter over which the wavelength varies in one direction (Reuter et al., 2008). For SET the plan is to have
LEISA cover the 0.45 – 4.0\(\mu m\) wavelength range, with a spatial resolution of 60.8\(\mu rad\) and a 0.9° x 0.9° field-of-view. LEISA can map the surface composition of Apophis, search for compositional heterogeneities, and reveal surface composition changes triggered by Apophis’ tidal interaction with the Earth.

**Radio Reflection Tomography Instrument (RRT)**

The RRT instrument designed for SET consists of a 10 m dipole antenna and electronics box for signal generation and power amplification, it is based on SHARAD instrument flown on the Mars Reconnaissance Orbiter (Putzig et al., 2009). The antenna is to be folded for launch and then deployed using the elastic properties of the encasing tube. The instrument maps the internal structure by recording the echoes of transmitted low-frequency radio waves and using them to measure differences in dielectric properties of materials in the asteroid. The RRT instrument will have a transmission frequency of 20 MHz and a bandwidth of 5 MHz. This bandwidth is designed to provide a spatial resolution of approximately 20 m (assuming a refractive index similar to Itokawa). This resolution is sufficient for detecting fragments roughly the size of the Chelyabinsk meteoroid (which struck Russia in 2013), which is significant from a planetary protection perspective.

**Thermal Emission Spectrometer (TES)**

TES is based on the OTES instrument flown on OSIRIS-REx and consists of a telescope, interferometer assembly, electronics, and support structure (Christensen et al., 2017). The instrument achieves its spectral range by implementing an interferometer, beam splitter, and moving mirror assembly. TES operates in the spectral range of 6 – 100 \(\mu m\) to map mineralogical and thermophysical properties. At a distance of 2 km from the surface its single detector with a 8 \(\mu rad\) field-of-view can see an area roughly 16m x 16m. TES can provide insight into Apophis’ mineralogy, globally map the material distribution, and determine regolith physical properties based on diurnal temperature measurements (Christensen et al., 2017). By combining thermal measurements from TES with imaging and ground-based radar...
tracking we will be able to better understand the coupling of thermal cycling and rotation which results in Yarkovsky drift. This can not only improve future predictions for Apophis’ orbit, but can also inform predictions for other potentially hazardous asteroids.

### 7.2.3 Concept of Operations

The SET mission concept has a six week launch window starting in August of 2026 (with a back-up launch window in August of 2027). The concept of operations, including rough instrument usage plan, is outlined in Figure 7.2. The instruments are planned to be turned on and calibrated as the spacecraft leaves the Earth’s sphere of influence and uses solar electric propulsion to gradually change planes and match its orbit with Apophis’. The spacecraft will rendezvous with Apophis at its aphelion in March 2028, giving it more than a year to complete its initial survey of Apophis. Once the initial survey is complete the spacecraft transfers to a leader-follower configuration 20 km ahead of Apophis before its close approach to Earth on April 13th, 2029. This position provides favorable viewing geometry while also keeping the spacecraft at a safe distance during the close approach to Earth. After the Earth flyby event the spacecraft performs another survey before entering the long term observation phase. The spacecraft continues to formation fly with Apophis for at least 7 years to study the Yarkovsky effect before finally performing an exit burn to leave Apophis’ sphere of influence and enter its own heliocentric orbit (compliant with planetary protection constraints).

### 7.3 Trade Space for Measuring Surface Activity

For this thesis work, the objective is to enhance the original SET mission design (proposed by MIT’s 12.43/16.83 Space Systems Engineering) with the addition of an instrument to study seismic effects and interior structure during Apophis’ close approach to Earth. Taking this next step requires defining alternative mission concepts (and then evaluating them). After considering both contact and non-contact options, including both pre-existing technology (with novel implementation in some cases) and concepts that are still under de-
After defining and evaluating alternative mission concepts, we determined that while the “Smart Marbles” concept still has a low technology readiness level (TRL) rating by NASA standards and requires further testing and development, it shows the most promising science possibilities while still keeping risk and cost low and the data rate manageable. There is also a clear path forward for further research and development that fits within the timeline necessary to be spaceflight ready in time for a mission like SET to study the 2029 Apophis close-approach (see subsection 7.4.3 and Earle et al. (2017a)).

Figure 7.2: Proposed timeline of operations for the SET mission (Image credit: Max Vanatta and MIT 12.43/16.83 Space Systems Engineering (2017))
Table 7.3: Trade Space for Measuring Surface Activity. “TRL” refers to NASA’s technology readiness levels (see Appendix B for more details). “I.S.C.” is for instantaneous surface coverage possible during the encounter phase of the mission. “M.D.O.” means manageable data output, indicating whether or not the amount of data produced could easily be stored on the spacecraft and sent back to Earth.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Risk</th>
<th>TRL</th>
<th>I.S.C.</th>
<th>M.D.O.</th>
<th>Other Concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRT/RTT</td>
<td>Low</td>
<td>9</td>
<td>n/a</td>
<td>Yes</td>
<td>Can’t observing during the encounter</td>
</tr>
<tr>
<td>Imaging Options</td>
<td>Low</td>
<td>9*</td>
<td>&lt; 50%</td>
<td>No</td>
<td>*Cameras like this have flown before, but not used in this way</td>
</tr>
<tr>
<td>Lander/Rover</td>
<td>High</td>
<td>9</td>
<td>Minimal</td>
<td>Yes</td>
<td>Low success rate, high cost, requires multiple units, political concerns</td>
</tr>
<tr>
<td>Doppler Laser Vibrometer</td>
<td>Low</td>
<td>1</td>
<td>Minimal</td>
<td>Yes</td>
<td>Still a long way from being flight ready</td>
</tr>
<tr>
<td>“Dumb Marbles”</td>
<td>Low</td>
<td>9*</td>
<td>&lt; 50%</td>
<td>No</td>
<td>Requires better imaging, runs into same problems as imaging options</td>
</tr>
<tr>
<td>*Artificial markers like this have been implemented before, but not for seismic studies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Smart Marbles”</td>
<td>Low</td>
<td>2</td>
<td>100%</td>
<td>Yes</td>
<td>Needs further development and testing</td>
</tr>
</tbody>
</table>

7.4 “Smart Marbles”

Now that we have determined that “Smart Marbles” appear as a promising path forward for enhancing the scientific capabilities of an Apophis mission, like SET, here I revisit the science motivation for their development and further constrain the objectives and rational for their design. From here we can begin formulating a preliminary design and determine how it fits in with the rest of the SET mission design. We consider both how resources would be needed to allocate the new instrumentation as well as how it would be able to enhance the mission objectives and science outcomes of the mission.

7.4.1 Science Motivation

There is currently a large and growing body of evidence for seismic shaking and tidal interactions from close encounters with planets effecting the surface evolution of asteroids, however these processes are still not well understood (e.g. Scheeres et al., 2015; Murdoch et al., 2015, and references therein). The primary science objective of “Smart Marbles”
is to provide a method of studying these effects, particularly in the context of the 2029 close-approach of Apophis, with better coverage, lower-cost, and lower-risk than traditional landing packages.

Previous space missions that have studied asteroids in detail have provided a wealth of new data to suggest seismic shaking occurs on asteroids and effects their surface evolution. Thomas and Robinson (2005) provided the first evidence for seismic shaking as an asteroid surface shaping process, when they suggested it as a mechanism for explaining the varying crater densities observed an Eros. Specifically, they showed the formation of a relatively young crater had resulted in the removal of craters up to 0.5 km over almost 40% of Eros’ surface within a particular straight line distance through the asteroid to the crater site (and that these erasures could not be explained by burial by ejecta). Since then additional evidence for seismic movement of regolith has been observed on Eros and other bodies, for example signs of movement of material away from topographic highs on Eros and signs of regolith migration on Lutetia (Murdoch et al., 2015, and references therein). The distribution of craters and surface material on Itokawa (which shows has a similar albedo, size, and spectral class as Apophis) also shows evidence of regolith migration and crater removal from seismic shaking (Miyamoto et al., 2007; Murdoch et al., 2015).

According to Nesvorný et al. (2005), near-Earth asteroids undergo planetary encounters more frequently than mutual collisions, suggesting tidal effects may play a substantial role in the evolution of these bodies. Binzel et al. (2010) and Nesvorný et al. (2010) have both suggested that seismic processes induced by recent planetary encounters may account for the presence of ‘unweathered’ Q-type asteroids. In a most extreme case, the effects of planetary tidal interactions were directly observed in the early 1990’s when the comet Shoemaker-Levy 9 was pulled apart (and later impacted) Jupiter (Weaver et al., 1994, 1995). In addition to observational evidence, simulations have also shown the potential for tidal forces to impact near-Earth asteroids. Richardson et al. (1998) showed that Earth’s tidal forces can distort
and disrupt Earth crossing asteroids with weak, ‘rubble-pile’ structures. Simulations also suggest near-Earth encounters may account for the odd shapes and rotation rates of some near-Earth asteroids (Bottke et al., 1999).

Thus far most of what we know about the effects of tidal forces and seismic shaking on asteroids is based on simulations and observational evidence suggestive of these processes having occurred. The 2029 close approach of Apophis provides us with a ‘live’ experiment by which to test and constrain our theories and dramatically improve our understanding of near-Earth asteroids and the processes that shape them. There is currently much speculation about what could happen during Apophis’ close approach to Earth. Keane and Matsuyama (2015) and Yu et al. (2014) both predicted that landslides on Apophis would most likely be small, localized events widely distributed across the surface of Apophis. Observing these events would provide useful constraints on this mechanism and the bulk properties of regolith. More recent work by Brozović et al. (2018) suggest Apophis may have a bi-oblate shape with higher angles of repose than the convex shape assumed for the previous work, which could show more dramatic changes than previously predicted. It has also been suggested that Earth’s tidal torques may change Apophis’ rotation rate and spin state during its 2029 close-approach (Souchay et al., 2014).

The SET mission was designed to study the 2029 close-approach of Apophis as efficiently as possible using pre-existing hardware. High resolution, color, and spectral imagers will be able to detect changes to Apophis’ surface composition and geology induced by the encounter, and the RRT instrument will be able to map the interior structure before and after the encounter and look for major changes. Given that the field-of-view is limited by illumination and spacecraft viewing geometry it is unlikely that the imaging instruments will be able to observe landslides or other small scale changes in action. The existing instrument suite offers robust science capabilities and will be able to answer many important science questions related to potentially hazardous asteroids and near-planet encounters however it will not be able to directly measure seismic shaking. Taking seismic measurements at many
points on the surface of a near-Earth asteroid like Apophis would provide information about the asteroid’s internal structure, porosity, properties of its regolith, and would constrain the effects of tidal torques on near-Earth objects. All areas of research that are of great scientific interest as well as important for informing potentially hazardous asteroid mitigation strategies. For this reason we set out to develop the “Smart Marbles” package to provide a low-risk, low-cost, high spatial coverage method for studying seismic shaking on small, airless, planetary bodies.

7.4.2 Science Objectives and Rationale

Ultimately the development of ‘Smart Marbles’ will require dedicated, detailed simulations, but for our preliminary design we derive our science objectives based on previous planetary seismology experiments and simulations.

A network of several planetary seismometers were placed on the Moon during the Apollo program and have been used to determine the timing and location of moon-quakes, the internal structure of the Moon, and the properties of each layer (Goins et al., 1981; Nakamura and Koyama, 1982). Thus far the Apollo lunar seismometers are the only planetary instrument to record seismic data with clear evidence of an interior signal, however seismometers have been deployed on Mars in the past and the Mars InSight mission plans to deploy a seismic package that has shown a great deal of success during testing on Earth (Panning et al., 2015). Viking 2 was equipped with a 3-axis, short period seismometer, which was unsuccessful in obtaining measurements pertaining the Mars’ interior but was able to determine that the natural background noise on Mars was low, with the primary source being wind (something we will not need to contend with on airless bodies like Apophis), it also determined the noise could be reduced by a factor of $10^3$ on future missions by removing the seismometer from the lander (Anderson et al., 1977).

While seismometers are yet to be deployed on asteroids a slew of concept studies and mission proposals have supported their feasibility and scientific impact (e.g. Scheeres et al., 2003; Pavone et al., 2013; Anderson et al., 2014; Murdoch et al., 2014). Murdoch et al. (2014)
found that the seismic signal from an asteroid being struck at 6 km/s by a 10 g impactor was dominated by waves in the 10–100 Hz range. Richardson et al. (2004) also studied simulated impact induced seismic shaking (on asteroids with diameters between 1 – 100 km) and found seismograms generally had frequency spectrum between 1 – 100 Hz with a peak between 10 – 20 Hz. Walker et al. (2006) demonstrated that tools presently exist to make seismology a method of determining interior discriminating information for irregular bodies, in their simulations they successfully used seismology to distinguish between different geometries and identify major features (such as regions and sound speeds).

On Earth there is already some precedence for using uncoupled accelerometer networks to detect seismic activity, in particular using the accelerometers in smartphones and computers to determine the time and location of seismic events (Kong et al., 2016; Han et al., 2017). However, in addition to designing an accelerometer instrument that can survive the space environment, launch, and deployment, a slew of other concerns arise when considering the use of uncoupled seismometers on airless, low-gravity bodies like Apophis. The acceleration due to gravity on kilometer sized asteroids (slightly larger than Apophis) if they have an elongated shape can be on the order of $10^{-2} - 10^{-4}$ m/s$^2$ with variations of a factor of 2 across the asteroid’s surface (Tancredi et al., 2012), making it difficult to predict exactly what ‘Smart Marbles’ will encounter at Apophis given the current level of uncertainty in Apophis’ shape. Furthermore, Tancredi et al. (2012) found that a particle layer shocked from below would produce the lift of particles at the surface, which can acquire vertical velocities comparable to the surface escape velocity in very low-gravity environments. Given the uncertainty over exactly how Apophis will respond to Earth’s tidal torques we can not completely rule out the possibility of surface instruments being lofted (or less likely, completely ejected). This is one of the motivations for the redundancy of the ‘Smart Marbles’ package, if one or even several marbles are lofted or ejected it will not compromise the science goals of the mission. Additionally, lofted ‘marbles’ are not a lost cause. Tracking the ballistic path of such marbles can determine the strength of the seismic wave which caused the movement (Scheeres et al.,
2015). However, we still acknowledge this is an area of concern that warrants further detailed study (particularly before making a final decision about the form the ‘Smart Marbles’ will take).

Based on previous planetary seismic studies and simulations we have determined a preliminary set of science objectives for the “Smart Marbles” package that will be refined with further dedicated modeling. Currently, “Smart Marbles” are being designed to measure accelerations up to $0.5m/s^2$ with a sensitivity of $0.0001m/s^2$ and frequency range of $1–100\ Hz$. This covers the range of seismic activity we might expect to see on an asteroid like Apophis and provides sufficient sensitivity to differentiate interior structures and properties.

### 7.4.3 “Smart Marbles” Design Overview

The ‘Smart Marbles’ package is still under development and the complete details of the design plan can be found in Earle et al. (2017a). Here we provide a quick overview of the current design for context. The goal of the ‘Smart Marbles’ project is to provide scientific capabilities that are not possible with non-contact remote sensing instruments while offering broader coverage, lower risk, and a more cost efficient design than previously flown landing packages. This is accomplished by leveraging simplicity and redundancy. Each individual marble is based on a simple design with simple components (in some cases implemented in innovative ways), making them cost efficient to design and build and low risk to operate. Deploying 10’s to 100’s of marbles provides better coverage than traditional landing packages and further decreases the risk. Marbles will be equipped with both marble-to-marble and marble-to-spacecraft communications capabilities (adding another layer of redundancy) so the failure of a single component (or even a whole marble) will have minimal effect the data quality and ability to accomplish mission objectives.

For the purposes of Earle et al. (2017a) three different architecture concepts are under consideration: spheres, beanbags, and cubes (Figure 7.3). All three architectures share several common components and specifications. They all include a battery for power, controller, and communications (both marble-to-marble and marble-to-spacecraft). Given the uncer-
Architecture Concepts To Be Investigated

Spherical Marble Concept
- Simplicity of form allows the marbles to easily act as markers of known physical properties even if the electronics go dead.
- Rigid overall form allows for a single accelerometer package to be used.

Pros:
- The rigid marble could bounce off hard portions of the asteroid (the portions giving the best seismic readings).

Cons:
- The rigid marble could bounce off hard portions of the asteroid (the portions giving the best seismic readings).

Beanbag Concept
- Beanbag form dampens the impact and would inelastically absorb the majority of the impact forces damping the amplitude of each successive bounce.
- Heritage from Hayabusa II markers.
- Sensors rest directly on the surface.
- Mass is adjustable with type and quantity of 'beans'.

Pros:
- The dampening means multiple accelerometers must be used.

Cons:
- The damper means multiple accelerometers must be used.

Unfolding Cube Concept
- The solar cells could allow for 1000+ hours of operations.
- The large surface area can reduce the chances the sensors are knocked off the surface.
- Large unfolded area could be infused with a longer antenna.

Pros:
- Deployment can be risky.
- Dust can cover and reduce the solar cell efficiency.
- This architecture is far more complex than the beanbag or spherical marble.

Cons:
- The rigid marble could bounce off hard portions of the asteroid (the portions giving the best seismic readings).

Figure 7.3: Architecture concepts being considered for 'Smart Marbles'. Further details about each of these architectures can be found in Earle et al. (2017a) (Image credit: Max Vanatta).

In all cases we expect each individual marble to be about 2 – 5 cm in diameter (diameter of closed cube) and have a mass of roughly 100 – 500 g. The small size and mass of each individual unit makes it possible to adapt the total volume and mass of the system based on the scientific needs of the mission and resource availability. Given that Apophis makes repeated close-approaches to Earth (with the next one predicted for 2036) substantially disrupting its...
orbit carries significant risk (and potential political ramifications) if it is perturbed onto a path that intersects Earth’s orbit. Even assuming the maximum mass of 500 g and a package of 500 units, the total mass being deployed at Apophis would be about 250 kg, which is only $4 \times 10^{-9}$ of Apophis’ mass. Furthermore this mass would be soft landed, and distributed across Apophis’ surface, further minimizing the influence on Apophis’ orbit. This is a “worst case scenario” given that we will most likely use fewer marbles and the mass estimate used here is the upper limit (this total mass is also well above the current payload mass limit for the SET mission).

The exact architecture will be determined through further development and refinement of mission objectives in order to more precisely weigh the pros and cons of each option. For example, refined knowledge of power needs, battery capabilities, and accelerometer costs will inform decisions. Spheres require the fewest accelerometers per marble, making them the best choice if accelerometer price becomes a driving factor. Cubes have the largest surface area making them best suited for the addition of solar panels if necessary (and giving them the largest surface contact area). Beanbags are simple, have some heritage with the Hayabusa mission (Yoshimitsu et al., 2009), and are best suited for absorbing the impact but require several accelerometers and would be difficult to outfit with solar panels.

### 7.4.4 Mission Integration

Now that we have determined the measurements objectives for “Smart Marbles” and developed a preliminary design concept, the next step is to consider how the package will fit into the SET mission, including how resources will be allocated to support it as well as how it will impact the potential science outcome of the mission.

First we consider the available resources on the SET mission to support “Smart Marbles”. The current concept of operations (see subsection 7.2.3) has the spacecraft arriving at Apophis more than a year before the close approach to Earth. Currently the pre-encounter observing plan includes ample margin (on the order of several months), some of which can be used for “Smart Marbles” deployment. Even if the “marbles” are soft landed (using only
the acceleration from Apophis' gravity field) from the larger orbital distance of 2 km, it will only take about 11.5 hrs for a "marble" to make it from the spacecraft to Apophis, so the several months of margin available should be more than enough time for deployment.

We also must consider how much room is available on the spacecraft to accommodate the "Smart Marbles" package, both in terms of volume and mass. The current design uses less than half the available volume for the science payload, with room for additional instrumentation of about 112 cm × 112 cm × 64 cm in volume. With the worst case scenario of each "marble" occupying a 10 cm × 10 cm × 10 cm area, this would place a limit of around 725 "marbles". However, slight reductions in radius or improved packing (for example if each "marble" is a sphere instead of a cube) would make is possible to fit thousands of marbles. Mass will most likely be a more limiting factor than volume. Currently, the spacecraft can accommodate an additional 69.5 kg of scientific instrumentation. This means the spacecraft could accommodate between 140 and 700 "marbles" depending on the mass of the final design. However this does not account for the mass of the container and launch mechanism, so more realistic upper limit is probably around 500 marbles. Assuming Apophis is spherical, this would mean an average distance of about 28 m between "marbles" (with only 100 "marbles" deployed this would increase to 62 m). This preliminary analysis suggests the "Smart Marbles" package will be able to achieve sufficient surface coverage while remaining within the resource availability of the originally proposed SET mission, thus not requiring significant modification or redesign of the original mission.

While "Smart Marbles" will not require the design of the spacecraft or concept of operations to be substantially redesigned, they will have a significant impact on the scientific outcomes of the mission. Table 7.4 shows how "Smart Marbles" would enhance the Science Traceability Matrix (Tables 7.2) for the SET mission, by both adding the potential for new science goals as well as enhancing the missions ability to fulfill preexisting science measurement objectives. Most notably, M.O. 2 has been rewritten to not only include "during" (the original motivation for this project) but also include characterizing the seismic response
Table 7.4: Updated Science Traceability Matrix (original shown in Table 7.2) for the SET Mission to Apophis enhanced by the addition of “Smart Marbles”

<table>
<thead>
<tr>
<th>Top Level Mission Requirement</th>
<th>Science Goal</th>
<th>Science Measurement Requirement</th>
<th>Primary Instrument</th>
<th>Secondary Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.O.1 - Characterize Apophis’ shape, size, density, surface topography and composition, rotation rate, and spin state</td>
<td>Surface Mapping (before, during, and after Earth encounter)</td>
<td>Survey Apophis’ surface structure and shape to learn about geology of mid-sized (100’s of meter diameter) asteroids</td>
<td>LORRI</td>
<td>Ralph-MVIC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Survey Apophis’ shape before, during, and after encounter to determine the impact of tidal torque on an asteroid’s shape</td>
<td>Ralph-MVIC/“Smart Marbles”</td>
<td>LORRI/Ralph LEISA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measure Apophis’ spin state and rotations rate before and after encounter to understand how tidal torques impact the dynamics of a potentially hazardous asteroid</td>
<td>Ralph-MVIC</td>
<td>LORRI/Ralph LEISA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Image Apophis’ surface before, during, and after the encounter at sufficient resolution to observe possible land slides and other surface responses to tidal torques</td>
<td>LORRI/“Smart Marbles”</td>
<td>Ralph-MVIC(pan)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Map Apophis’ surface with filters to allow for color imaging and broad band spectroscopy</td>
<td>Ralph-MVIC(color)</td>
<td>Ralph-LEISA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectral mapping of Apophis’ surface to look at compositional heterogeneities and better refine Apophis’ spectral class with higher resolution and broader wavelength coverage than achievable with ground-based observations</td>
<td>Ralph-LEISA</td>
<td>Ralph-MVIC(color)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Perform surface composition and color surveys both before and after encounter to look for tidally induced resurfacing</td>
<td>Ralph</td>
<td>Ralph-LEISA/“Smart Marbles”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>During encounter observe Apophis’ surface with color filters at sufficient time and spatial resolution to observe tidally induced resurfacing</td>
<td>Ralph-MVIC(pan)</td>
<td>Ralph-LEISA/“Smart Marbles”</td>
</tr>
<tr>
<td>M.O.2 - Characterize Apophis’ orbit, accounting for the influencing factors of the Yarkovsky Effect</td>
<td>Seismic Shaking</td>
<td>Measure seismic shaking before, during, and after the near-Earth event with sufficient sensitivity and coverage to differentiate interior structure and properties and determine significance of tidal interactions for evolution of a PHA</td>
<td>“Smart Marbles”</td>
<td>“Smart Marbles”</td>
</tr>
<tr>
<td></td>
<td>Internal Structure</td>
<td>Map Apophis’ interior to interpret the strength and internal structure of a potentially hazardous asteroid</td>
<td>RRT</td>
<td>“Smart Marbles”</td>
</tr>
<tr>
<td>M.O.3 - Characterize Apophis’ orbit, accounting for the influencing factors of the Yarkovsky Effect</td>
<td>Yarkovsky Effect</td>
<td>Post-encounter monitoring to decode the coupling of rotation and thermal cycling resulting in Yarkovsky drift</td>
<td>TES</td>
<td>LORRI/Ralph</td>
</tr>
</tbody>
</table>

Science Measurement Requirements highlighted in blue are significant for understanding how a potentially hazardous asteroid responds to tidal torques.

Changes made possible by the “Smart Marbles” package are highlighted in purple, with specific changes to Science Measurement Requirements written in bold font.
to tidal torques. By landing “Smart Marbles” on Apophis’ surface before the encounter to acquire baseline measurements we will be able to determine if and at what distance range tidal torques induce seismic shaking on Apophis. Additionally, “Smart Marbles” will be able to enhance the science outcomes of some of the imaging goals. The network aspect of “Smart Marbles” means that in addition to providing seismic information they will also be able to provide measurements pertaining to Apophis’ shape, and track if and how it changes during the near-Earth encounter. The surface motion data provided will also enhance our understanding of the physical processes at work if landslides or resurfacing is observed by the imaging and spectral instruments.

7.5 Conclusions and Future Work

This chapter reviewed the SET mission and performs the next iteration of the space mission engineering process to both advance the mission design and serve as an opportunity to learn about the early stages of the NASA mission lifecycle. We identified the need for the mission to include instrumentation capable of directly measuring tidally induced seismic shaking and determined that existing hardware could not meet the scientific needs of the mission while also keeping the cost and risk reasonable. This served as our motivation for developing the “Smart Marbles” package, a network of uncoupled accelerometers designed to measure seismic shaking at a lower cost and with less risk than traditional landing packages. Based on previous studies of planetary seismology we were able to determine this concept is feasible and formulate a preliminary set of design requirements. If “Smart Marbles” are successfully developed they will not only allow the SET mission to fulfill additional science goals, they will also enhance its ability to address existing science goals, like understanding the mechanism behind tidally induced resurfacing if it occurs.

Now that we’ve done a basic feasibility study of “Smart Marbles” and identified the scientific motivation for their further development, the next major step in the development process is performing simulations to model exactly how uncoupled accelerometers will respond in a
low gravity environment like the surface of Apophis, and refine the design requirements that need to be met to achieve the desired scientific outcomes of measuring seismic waves and inferring interior structure. These simulations will also inform decisions related to architecture, size, weight, power, and coverage (in terms of number of “marbles” deployed) and allow the next iteration of defining and allocating system requirements. The first step will be simulating how “marbles” respond to seismic shaking, including determining the conditions under which they may be lofted or ejected from the surface given the low-gravity of asteroid surfaces. The next step will be adding complexity to the model to determine the sensors’ sensitivity to discerning interior structure and effective coverage limits of each individual “marble”. Simulations of impact induced seismic shaking on asteroids have already been performed by Murdoch et al. (2014) and Richardson et al. (2004). Walker et al. (2006) demonstrated that tools presently exist to make seismology a method of determining interior discriminating information for irregular bodies, in their simulations they successfully used seismology to distinguish between different geometries and identify major features (such as regions and sound speeds). The scientific potential of “Smart Marbles” is not restricted to an Apophis mission, they could be used on any airless planetary body to study seismic shaking, whether it be tidally or impact induced.
Appendices
Appendix A

Calculating Pluto’s Obliquity Variations using Dobrovolskis et al. (1997)

The purpose of this appendix is to give a detailed description of how we calculate Pluto’s eccentricity, angle from perihelion (or true anomaly), and sub-solar latitude over long timescales for use in the insolation calculations described in subsection 3.2 and used throughout the Pluto sections of this thesis. These calculations are based on the equations presented in Dobrovolskis et al. (1997), referred to herein as “Dobro”. We also compare the assumed physical parameters used by Dobro with the precise results of New Horizons and their effect on the timescales discussed in Chapters 3, 4, 5, and 6.

The equations lend themselves to working in terms of eccentric anomaly ($E$), so the first step is to determine the eccentric anomaly range over which you want to calculate the parameters and the step size (which varies based on how the total time over which the calculations are going to be run). Once the eccentric anomalies have been determined, they can be used to calculate the approximate times ($\tau$) over which the parameters will be calculated using:

$$\tau = E \times (T/360.)$$ (A.1)
Where $T$ is the orbital period of Pluto in Earth years. Next we use Dobro’s equation 12 to define and calculate $\psi$, a parameter that will be used throughout these computations:

$$\psi = 72.8^\circ + 91.0^\circ \tau_{\text{myrs}}$$  \hspace{1cm} (A.2)

Where $\tau_{\text{myrs}}$ is $\tau$ converted to millions of years. From here we can calculate the eccentricity of Pluto’s orbit ($e$) using equation 8 from Dobro:

$$e = 0.244 + 0.022 \cos(\psi) + 0.0005 \cos(3\psi)$$  \hspace{1cm} (A.3)

Next we calculate the mean anomaly ($M$), which is derived from the eccentric anomaly and eccentricity, using:

$$M = E - e \sin(E)$$  \hspace{1cm} (A.4)

Mean anomaly is the angle from perihelion which a body would have if it moved in a circular orbit, with constant speed, in the same orbital period as the actual body in its elliptical orbit. It is mathematically convenient since it varies linearly with time, and is used here to determine the time ($t$) steps that will be used for the rest of the calculations:

$$t = M(T/360.)$$  \hspace{1cm} (A.5)

The next step is to use the eccentric anomaly and eccentricity to calculate the true anomaly ($\nu$), which is the angle at the primary focus between the direction of perihelion and the object’s position, and is given by:

$$\nu = 2 \arctan \left( \sqrt{\frac{1+e}{1-e}} \tan \frac{E}{2} \right)$$  \hspace{1cm} (A.6)
At this point we have the eccentricity \((e)\) and angle from perihelion \((\nu)\) of Pluto for all of our times \((t)\), the last thing we have to calculate is the sub-solar latitude as a function of time. To do this, first we calculate the longitude of Pluto’s spin angular momentum vector \((\phi)\) using Dobro’s equation 20:

\[
\phi = 19.5° + 130.2°t_{\text{myrs}}
\]  

(A.7)

where \(t_{\text{myrs}}\) is the times \(t\) converted to million years. From \(\phi\) the component of Pluto’s unit spin vector aligned toward Pluto’s orbit normal \((Z)\) can be calculated using Dobro’s equation 23:

\[
Z = -0.442 - 0.184 \sin \phi
\]  

(A.8)

The obliquity of Pluto \((\theta)\) is simply \(\arccos Z\) by equation 15 in Dobro. Next we recalculate \(\psi\), this time using \(t\) instead of \(\tau\). We use \(\psi\) and \(\phi\) to calculate the angle between the longitude of perihelion and the vernal equinox \((X)\) from Dobro’s equation 24:

\[
X = \phi - 24.0° \sin \psi
\]  

(A.9)

Finally we can calculate the sub-solar latitude \((\delta)\) as a function of time using \(\nu\), \(X\), and \(Z\) which have all been calculated as functions of time \(t\):

\[
\delta = \arcsin \left( \sqrt{1 - Z^2} \sin (\nu - X) \right)
\]  

(A.10)

Now that we have Pluto’s eccentricity \((e)\), angle from perihelion \((\nu)\), and sub-solar latitude \((\delta)\) all as functions of our set of times \((t)\) we are able to use the equations from Levine et al. (1977) to calculate insolation incident on the top of Pluto’s atmosphere as a function of time and latitude (as described in subsection 3.2).
Note that between these two sets of calculations we switch some of our parameter symbols so that the equations stay consistent with how they were originally published. In particular the angle from perihelion is represented by $\nu$ in this appendix and $\theta$ in subsection 3.2, and in this appendix $\phi$ is used to represent the longitude of Pluto’s spin angular momentum vector, but in subsection 3.2 it represents the latitude for which the insolation is being calculated.

Table A.1: Comparison of Pluto system parameters used in Dobrovolskis et al. (1997) and reported in Stern et al. (2015)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pluto mass</td>
<td>$m_p$ (g)</td>
<td>$1.27 \times 10^{25}$</td>
<td>$1.303 \times 10^{25}$</td>
<td>2.6</td>
</tr>
<tr>
<td>Charon Mass</td>
<td>$m_c$ (g)</td>
<td>$1.5 \times 10^{24}$</td>
<td>$1.587 \times 10^{24}$</td>
<td>5.6</td>
</tr>
<tr>
<td>Pluto Radius</td>
<td>$R_p$ (km)</td>
<td>1,180</td>
<td>1,187</td>
<td>0.6</td>
</tr>
<tr>
<td>Charon Radius</td>
<td>$R_c$ (km)</td>
<td>620</td>
<td>606</td>
<td>2.3</td>
</tr>
<tr>
<td>Semi-major Axis</td>
<td>$a$ (km)</td>
<td>19,405</td>
<td>19,596</td>
<td>1.0</td>
</tr>
<tr>
<td>Principle moments</td>
<td>$A$</td>
<td>$7.329 \times 10^{30}$</td>
<td>$7.577 \times 10^{30}$</td>
<td>3.3</td>
</tr>
<tr>
<td>of inertia</td>
<td>$B = C$</td>
<td>$5.187 \times 10^{32}$</td>
<td>$5.508 \times 10^{32}$</td>
<td>6.0</td>
</tr>
<tr>
<td>Precessional</td>
<td>$H$</td>
<td>0.493</td>
<td>0.493</td>
<td>0.000</td>
</tr>
<tr>
<td>Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is also worth acknowledging that these calculations are from Dobrovolskis et al. (1997), which is now more than two decades old and based on work originally presented in Dobrovolskis and Harris (1983). During that time our knowledge of the Pluto system has improved dramatically. However the differences between the values used for Dobrovolskis et al. (1997) and those reported in Stern et al. (2015) are minimal (Table A.1), with a difference of less than 1% for the semi-major axis of Charon’s orbit and Pluto’s radius, and a difference of less than 3% for Charon’s radius and the combined mass of the two. The differences in these measured parameters result in differences of roughly 3% and 6% for the moment of inertia along the semi-major axis through the center of both bodies ($A$) and the moments of inertia through along the axes perpendicular to $A$ ($B$ and $C$), respectively. Where $A$, $B$, and $C$ are defined as:

$$A = 0.4m_p R_p^2 + 0.4m_c R_c^2$$  \hspace{1cm} (A.11)
Despite these small differences the precession constant, $H$, which is defined as:

\[ H = \frac{C - A}{2C} \]  

is the same for both the values presented in Dobrovolskis et al. (1997) and Stern et al. (2015).

The precession constant is a dimensionless measure of the planets oblateness used to predict long-term behavior, for Pluto it is determined mostly by the large aspect ratio of the system (thus was accurate before other parameters of the system were well known). From $H$ we can calculate $\alpha$ using equation 2 in Dobro:

\[ \alpha = \frac{3n^2}{2N} (1 - e^2)^{-3/2}H \]  

where $n$ is Pluto’s orbital mean motion around the sun and $N$ is Pluto’s rotation rate (or Charon’s mean motion rate). Alpha then gives us the change in Pluto’s obliquity ($\theta$) and angular momentum vector ($\phi$) over time using Dobro’s equations 13 and 14:

\[ \frac{d\theta}{dt} = -\sin i \cos \phi \left( \frac{d\Omega}{dt} \right) + \sin \phi \left( \frac{di}{dt} \right) \]  

\[ \frac{d\phi}{dt} = -\alpha \cos \theta - \cos i \left( \frac{d\Omega}{dt} \right) + \sin i \sin \phi \cot \theta \left( \frac{d\Omega}{dt} \right) + \cos \phi \cot \theta \left( \frac{di}{dt} \right) \]  

where $i$ is the inclination and $\Omega$ is the longitude of the ascending node. From here Dobro converts to cartesian coordinates (to make integrating more efficient). The derivatives in cartesian coordinates (according to Dobro’s equations 16, 17, and 18) are:

\[ \left( \frac{dX}{dt} \right) = \alpha YZ + Y \cos i \left( \frac{d\Omega}{dt} \right) - Z \sin i \left( \frac{d\Omega}{dt} \right) \]  

\[ \left( \frac{dY}{dt} \right) = -\alpha XZ - X \cos i \left( \frac{d\Omega}{dt} \right) + Z \left( \frac{di}{dt} \right) \]  

\[ \left( \frac{dZ}{dt} \right) = \alpha XYZ - Y \cos i \left( \frac{d\Omega}{dt} \right) + Z \left( \frac{di}{dt} \right) \]
\[
\left( \frac{dZ}{dt} \right) = X \sin i \left( \frac{d\Omega}{dt} \right) - Y \left( \frac{di}{dt} \right)
\]  
(A.19)

By integrating and then using equation Dobro’s equation 20 (Equation A.7 above) and equation 19 \( (\theta = 115.5^\circ + 11.8^\circ \sin \phi) \) we get Dobro’s equation 21 (A.9 above), 22 \( (Y = 0.884 \sin(19.5^\circ + 130.2^\circ t) - 0.088) \), and 23 (equations A.8 above). Pluto’s eccentricity, and Pluto and Charon’s orbital mean motions were well known at the time of Dobro’s calculations, and updates to the system’s parameters provided by Stern et al. (2015) have not changed the value of \( H \) thus changes to \( \alpha \) and the dependent equations above are negligible. Furthermore since we are looking at long term trends, tiny variations in the orbit (if they occurred) would not have a significant impact on our results.
Appendix B

Detailed Exploration of the Trade Space for Measuring Surface Activity

Before designing the “Smart Marbles” concept described in Chapter 7, we considered several alternative architectures to try to search for signs of tidally induced seismic activity during Apophis’ close approach to Earth. In addition to considering the scientific potential of each concept we also considered factors such as risk, cost, technology readiness level (TRL), and whether or not the date rate was manageable. We employed NASA’s standards for determining the technology readiness level of each concept (Figure B.1). Most of the options we considered already had heritage and a TRL of 9, however we also considered some other technologies that are still early in their development and yet to be space flown. Our assessment of risk encompassed factors including success of previous missions using similar technology, the level of difficulty associated with operating the instrumentation (and landing if applicable), and the likelihood and science impact of component failures.

Through this analysis and consideration of the entire trade space for measuring surface activity, we ultimately determined that “Smart Marbles” warranted further development because of their high scientific potential in a low cost, low risk package.
Figure B.1: NASA’s Technology Readiness Level (TRL) definitions. A TRL number is obtained once the description in the diagram has been achieved. (Image credit: NASA)

B.1 RRT/RTT

For the purpose of the SET Mission designed by the 12.43/16.83 Space Systems Engineering Spring 2017 class, a Radio Reflection Tomography (RRT) instrument was selected to measure the interior structure of Aphophis before and after its close approach to the Earth. This sort of instrument offers several advantages for measuring interior structure but also has limitations which ultimately lead to redefining the science mission objectives for the SET Mission for the purposes of 12.43/16.83 Space Systems Engineering
RRT (Radio Reflection Tomography) and RTT (Radio Transmission Tomography) instruments send radio waves towards an object and then measure the reflection (RRT) or transmission (RTT) of the waves after they have interacted with the object. Using inversion and modeling techniques the received signal can be used to determine the complete 3-D interior structure of an asteroid. Simulations indicate this technique is sensitive to interior cracks, void spaces and variations in composition and density of the interior for a wide range of target structures (however it is not sensitive to whether block interstices are void or regolith filled) (Safaeinili et al., 2002; Grimm et al., 2015). Since RRT instruments are measuring reflections, the transmitter and receiver can both be mounted on the same spacecraft. The simplicity and cost savings of only requiring a single spacecraft was a major motivation in selecting an RRT instrument instead of an RTT instrument for the SET Mission. However, it is worth acknowledging that Grimm et al. (2015) found the use of two spacecraft and RTT capabilities has been shown to dramatically improve the recovery of subsurface structure. That study also found that the velocity model has to be close to the true distribution to focus the echo on the boundaries of the internal blocks (something we will discuss more at the end of this subsection).

Both RRT and RTT instruments have successfully been flown on planetary missions (qualifying them as TRL 9 by NASA standards). The COmet Nucleus Sounding Experiment by Radio Transmission (CONSORT) instrument (RTT) on the Rosetta Mission made use of transmitters and receivers on both the Rosetta spacecraft and the Philae lander. Comet 67P, the target of the Rosetta Mission, has a radius of roughly ten times that of Apophis. Propagation through the smaller lobe of the nucleus was successfully achieved and analysis showed a decrease in the dielectric constant with depth, most likely from a decrease in the dust-to-ice ratio or increase in porosity (Ciarletti et al., 2015). RRT instruments have been used at Mars, including Mars Reconisicence Orbiter’s (MRO) SHAllow RADar (SHARAD) instrument and its predecessor, the Mars Advanced Radar for Subsurface and
Ionosphere Sounding (MARSIS) instrument on Mars Express. SHARAD made use of a wider transmission band width to achieve higher resolution to profile subsurface ice layers down to hundreds of meters in the Martian subsurface (Seu et al., 2007).

For the SET Mission, as described in MIT 12.43/16.83 Space Systems Engineering (2017), an RRT instrument is planned, that will have a transmission frequency of $20MHz$ and a bandwidth of $5MHz$. For a reflective index similar to Itokawa this would result in a spatial resolution of roughly $8.5m$, and worst case scenario a resolution of $20m$. In addition to its proven heritage, one benefit of using an RRT instrument on a mission to Apophis is that it is not dependent on seismic activity to determine interior structure, so in the event that tidal forces from the Earth are not strong enough to trigger seismic events on Apophis it will still be possible to learn about Apophis’ interior structure. However, it is expected to take about 30 days to fully map the interior of Apophis. The field-of-view, spatial and time resolution of an RRT instrument are not sufficient to measure seismic effects from tidal forces, thus the RRT will not be able to accomplish the same science goals as the proposed “Smart Marbles” concept. The two would have compliment each other nicely on an Apophis mission, since the RRT could provide interior structure information regardless of the results of the tidal interaction and the “Smart Marbles” package can provide information about tidal interactions, and assuming seismic activity does occur, could provide guidance for the RRT models to focus the echo boundaries.

B.2 Imaging Options

For imaging options we consider using a high-frequency, high-resolution camera mounted on a spacecraft like SET, as well as Earth-based radar (which can achieve higher spatial resolution than Earth-based imaging). The obvious appeal of these options is that they do not require any physical contact with the asteroid, making them lower cost and lower risk than any kind of landing package. In the case of Earth-based radar observations the necessary equipment already exists and does not require a spacecraft mission. However this option does
depend on the necessary facilities remaining operational until 2029 or new comparable (or better) facilities being online by then. A high-frequency, high-resolution imaging instrument on a mission like SET could study Apophis’ surface during its close approach to Earth and look surface changes, while it would require a spacecraft it would also be able to achieve much higher spatial and time resolution than Earth-based radar observations.

Earth-based radar observations have already been used to constrain Apophis’ shape, size, and spin state, and Apophis will be observable from Goldstone from mid-March to mid-April of 2029 and from Arecibo starting April 14th, 2029 (the day after Apophis’ close approach to Earth) and continuing until late-May (Brozović et al., 2018). By transmitting using the 34m DDS-13 antenna at Goldstone it will be possible to image Apophis to 1.875 meters/pixel in 2029 (Brozović et al., 2018). These observations would make it possible to look for changes in Apophis’ spin state, by comparing measurement from before and after close approach, and would be able to look for changes in Apophis’ shape and surface morphology to several meters scale. This method is also limited by its field of view, since only one side of Apophis is visible from Earth at a time. While these observation do offer promising scientific results (Brozović et al., 2018), they can not compete with the resolution possible from spacecraft-based imaging, and will not be able to directly measure seismic activity like “Smart Marbles”. For these reasons we find Earth-based radar to be worthwhile scientific pursuit, both in its own right and as a compliment to a spacecraft mission, but it is unable to address the science questions we plan to explore with “Smart Marbles”.

A high-frequency, high-resolution imager on a mission like SET would be able to observe Apophis’ surface with higher spatial and time resolution than ground-based radar. However, like ground based observations it is limited by its field of view, assuming a mission with a single spacecraft it would only be able to view about half of Apophis’ surface at a time (potentially even less depending on the geometry of the spacecraft, asteroid, and sun). Another major limitation of this method is the high data volume it produces. We start by estimating the data output of an instrument with resolution and an observing cadence that would not
be sufficient to measure seismic activity itself, but would be able to observe its side effects, like localized landslides, regolith sorting, and changes to shape and surface topography, in detail. To accomplish this we would need a resolution of around $0.1 \text{ m/pixel}$ and a CCD of roughly $5,000 \times 5,000 \text{ pixels}$ to be able to image the full disc at the same time. This estimate is based on Apophis’ long axis having a lower bond of 450 meters (Brozović et al., 2018) and assuming moderately good position knowledge and spacecraft pointing. With a sensitivity of $8 \text{ bits/pixel}$ each image would be $0.2 \text{ Gbits}$. We assume an observing cadence of $5 \text{ images/second}$ (given that we are only looking for the side effects of seismic activity, not the waves themselves) over the 30 hr encounter phase of Apophis’ close approach to the Earth (which only spans the length of time the Apophis is within 1 lunar distance of the Earth). This would produce roughly 108 $\text{Tbits}$ of data, two orders of magnitude more than the 3 $\text{Tbits}$ of storage planned for the SET mission (which would also be needed to store data from other instruments and spacecraft housekeeping data). Not only would the spacecraft need to be able to store that much data but at some point it would need to be sent back to Earth. Using a Ka-band communications, and assuming a downlink speed of $6 \text{ Mbps}$, a reasonable estimate for a distance of 0.15 $\text{AU}$ (Slobin, 2015), it would take more than 200 days worth of dedicated downlink time to transfer that much data to Earth. This time could be dramatically reduced using laser communications, which could cut the downlink time to around 100 hours, but currently have no deep space heritage (NASA, 2015). This shows that high-frequency, high-resolution imaging options are plagued by three major challenges (1) creating a large format CCD with fast read out times, (2) storing very large quantities of data on the spacecraft, and (3) downlinking such a large quantity of data. In addition to these major design challenges such an instrument would have a limited field of view and would not be able to directly detect seismic activity, only its consequences (assuming tidal forces are substantial enough to trigger such effects). Given the challenges associated with designing and operating a high-frequency, high-resolution imager and the limited scientific payoff, we chose to not pursue this option any further.
B.3 Lander/Rover

Among the mission architectures explored in 12.43/16.83 Space Systems Engineering was the possibility of including a landing package or rover with a seismometer as part of the SET Mission. While the scientific potential of such packages is promising, they tend to be very high cost and high risk, with a less than 30% success rate for launched seismometers (Lognonné, 2005, and references therein). It is also difficult to couple a seismometer to a planetary surface (Goldstein et al., 2006), adding to the cost, risk, and complexity of such missions. Numerical computations based on the asteroid Eros show seismology can differentiate interior structures in small bodies, however it requires measurements from multiple points on the object’s surface (Walker et al., 2006). In addition to not providing enough data to infer interior structure, a single seismometer has the potential to miss events since waves do not propagate well through regolith (Purnell, 1986) and surface changes on Apophis are expected to be small, localized events (Yu et al., 2014; Keane and Matsuyama, 2015). Additionally, landing anything of substantial mass on the asteroid, that could conceivably perturb its orbit, poses political concerns given how close it comes to the Earth at regular intervals. Anything that could increase the risk of future impacts or alter where impacts occur would have major political, ethical, and planetary defense ramifications.

B.4 Laser Doppler Vibrometer

In addition to the heritage based options described above we also explored the possibility of studying Apophis’ surface during its close approach to Earth using Laser Doppler Vibrometers, technology not yet used in spaceflight. Laser Doppler Vibrometers measure the doppler shifts a laser beam reflected of a surface to determine the motion of the surface. This technique is appealing for studying Apophis since it does not require physical contact with the asteroid’s surface (thus making it simpler and lower risk than landing packages) and ideally would be able to measure seismic vibrations at several points on the asteroid’s surface (which could then be used to infer interior structure).
Laser Doppler Vibrometers have been developed for applications such as non-destructive testing of aircraft parts (Kilpatrick and Markov, 2008) and buried land-mine detection (Lal et al., 2006). However, these instruments offer a limited field-of-view (and being mounted on the spacecraft further restricts the field-of-view to the spacecraft facing side of Apophis) and their high sensitivity and precise nature pose serious challenges for becoming flight qualified and successfully operating on a spacecraft. While further development of this technology could one day make it more spaceflight compatible, given the current challenges it is unlikely it would be ready for mission use by the mid 2020’s (when an Apophis bound mission would need to launch to observe Apophis during the 2029 close approach to Earth).

B.5 “Dumb Marbles”

In addition to the “Smart Marbles” package we also considered whether or not we could go even simpler (and cheaper) and deploy a collection of highly reflective objects of known mass, shape, volume, and surface friction across the surface of Apophis, without any instrumentation or communication capabilities. We would try to study Apophis’ surface changes and seismic activity through imaging of the “Dumb Marbles”. The properties of asteroid regolith are still not well understood and the dynamics of granular material in the small-body gravitational environment is vital for interpreting their surface geology (Murdoch et al., 2015). We would attempt to gain a better understanding of the surface processes on Apophis (as well as seismic activity and thus internal structure) by deploying 10’s to 100’s of easily observable test “particles” of known properties across its surface. There is some technological precedence for this, the Hayabusa mission deployed a highly reflective target marker on the asteroid Itokawa. However, Hayabusa’s target marker served as an artificial landmark and was used purely for navigation and spacecraft guidance purposes (Yoshimitsu et al., 2009).

The SET mission as proposed in MIT 12.43/16.83 Space Systems Engineering (2017) will carry an instrument modeled after the LORRI instrument on New Horizons and Lucy for its high resolution imaging. As it currently stands this is the instrument best suited
for monitoring the “Dumb Marbles” once they have been deployed on Apophis’ surface, thus the spatial resolution and time between LORRI images sets the limit on the spatial and frequency resolution limits on this package. At a distance of 2 km (the spacecraft distance planned for the surveys of Apophis’ surface before and after its close approach to Earth) LORRI will be able to observe Apophis’ surface at a resolution of 0.0099 m/pixel. However, at this distance LORRI is only able to image a fraction of Apophis’ surface at a time, thus limiting the effective spatial coverage of the hardware package. During the actual encounter phase, the spacecraft will be in a leader-follower configuration with the asteroid at a distance of 20 km, giving LORRI much lower spatial resolution (but better coverage).

In addition to the limited coverage and resolution, the imaging speed of LORRI is too slow to measure seismic vibrations, it would only be capable of witnessing their effects, like landslides. Trying to modify or replace LORRI to improve coverage, resolution, or imaging frequency will quickly run into the same challenges encountered with high-resolution, high-frequency imaging options (described in subsection B.2).

While there are some scientific benefits to having test “particles” of known properties deployed on an asteroid, the limited spatial and time resolution and coverage possible with simple “marbles” (incapable of taking their own measurements and communicating with the parent spacecraft) makes the potential science, particularly in terms of measuring seismic activity (and inferring internal structure), minimal. “Smart Marbles” will also serve as test “particles” of known properties, but with the addition of accelerometers and communications capabilities will be able to fulfill more science objectives.
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