Modeling Pluto’s Light Curve in the Near Infrared: Implications for Observation Post New Horizons

by

Molly Kosiarek

B.S., Massachusetts Institute of Technology (2015)

Submitted to the Department of Earth, Atmospheric and Planetary Sciences
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at the

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June 2016

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Submitted to the Department of Earth, Atmospheric and Planetary Sciences on 13 May 2016, in partial fulfillment of the requirements for the degree of Master of Science in Earth, Atmospheric and Planetary Sciences

Abstract

The effects of volatile transport on Pluto’s surface on ground-based observations of Pluto’s light curve were studied. Due to Pluto’s eccentricity of 0.249, obliquity of 123 degrees, and atmosphere, the transfer of volatiles may cause global surface change over the course of Pluto’s orbit. Magellan visible and near infrared data were gathered one month before the New Horizons flyby in order to compare ground-based observing with spacecraft data. Furthermore, a model was created in order to predict how volatile transport will affect ground-based observations in the future. The near-infrared data show large scale surface composition as a function of longitude and confirm New Horizons’ compositional results. The model determines that the composition of the underlying layer on Pluto’s north pole can be determined by monitoring the J-Ks ratio, if the nitrogen ice currently located on the north pole is sublimated due to volatile transport. Therefore, ground based observing can monitor volatile transport and global surface changes can be monitored after the New Horizon’s flyby.

Thesis Supervisor: Amanda Bosh
Title: Senior Lecturer
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Contents

1 Introduction 15
  1.1 Motivation ............................................. 15
  1.2 Scientific Context ................................. 17

2 Magellan Near Infrared and Visible Data 31
  2.1 Magellan Data Observation Plan ......................... 31
  2.2 VisAO Data ........................................... 34
    2.2.1 Reduction of VisAO Data ......................... 34
    2.2.2 Analysis on VisAO Data .......................... 35
    2.2.3 Discussion of VisAO Data ......................... 35
  2.3 Clio Data ........................................... 38
    2.3.1 Summary of Clio Data ............................. 38
    2.3.2 Reduction of Clio Data ........................... 40
    2.3.3 Analysis of Clio Data ............................. 45
    2.3.4 Discussion of Clio Data ........................... 46

3 Pluto Infrared Light Curve Modeling 51
  3.1 Model Design .......................................... 51
  3.2 Model Test Cases ...................................... 53
  3.3 Modeling Surface Composition Evolution .................. 54
  3.4 Discussion of Model ................................... 59

4 Combined Discussion 61
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>B-V color light curve of Pluto and Charon from 1997 and 2002-2003.</td>
</tr>
<tr>
<td>1-2</td>
<td>Surface maps of Pluto and Charon as a function of longitude.</td>
</tr>
<tr>
<td>1-3</td>
<td>Comparison between data and geometry model for Pluto’s visual light curve amplitude.</td>
</tr>
<tr>
<td>1-5</td>
<td>Near-infrared spectra of Pluto and Charon at two different sub-observer longitudes from 2000.</td>
</tr>
<tr>
<td>1-6</td>
<td>Pluto climate models.</td>
</tr>
<tr>
<td>1-7</td>
<td>Maximum diurnal insolation versus Pluto atmospheric pressure.</td>
</tr>
<tr>
<td>1-8</td>
<td>Maps of volatile ices on Pluto’s surface from New Horizons.</td>
</tr>
<tr>
<td>1-9</td>
<td>Spectra of different areas on Pluto’s surface from New Horizons.</td>
</tr>
<tr>
<td>2-1</td>
<td>Example VisAO images of a reflected and a non-reflected Pluto and Charon.</td>
</tr>
<tr>
<td>2-2</td>
<td>VisAO photometry for each night between May 30th 2015 and June 3rd 2015.</td>
</tr>
<tr>
<td>2-3</td>
<td>Mean and standard deviation of the mean of VisAO photometry as a function of sub-observer longitude.</td>
</tr>
<tr>
<td>2-4</td>
<td>Filter curves for the J, H, and Ks filter on Clio.</td>
</tr>
<tr>
<td>2-5</td>
<td>Original and background-subtracted Clio images.</td>
</tr>
<tr>
<td>2-6</td>
<td>Clio photometry for each night between May 29th 2015 and June 3rd 2015.</td>
</tr>
</tbody>
</table>
2-7 Mean and standard deviation of the mean for the Pluto/Charon light curve over time in the J, H, and Ks filters. ........................................ 44
2-8 Total counts per pixel for each night on Clio. .............................. 45
2-9 Clio linearity correction for June 2nd and 3rd. ............................. 46
2-10 Mean and standard deviation of the mean for the Pluto/Charon light curve over sub-observer longitude in the J, H, and Ks filters. ........ 47
2-11 Filter differences in Pluto/Charon light curve over sub-observer longitude in the J, H, and Ks filters. ................................. 48
2-12 Conclusions from Clio filter transmission. ................................ 50

3-1 Model of Pluto’s surface composition. ........................................ 54
3-2 Reflectance spectra of nitrogen ice, methane ice, tholins, and water ice along with J,H, and Ks filters. ................................. 55
3-3 Test case: north pole facing Sun and Earth over a full rotation. ... 56
3-4 Test case: equator facing Sun and Earth over a full rotation. ......... 57
3-5 Light curve of case 1: static surface composition. ......................... 58
3-6 Amplitude of case 1: static surface composition. ........................ 59
3-7 Amplitude difference between the J and Ks filters for each of the five cases. .......................................................... 60

4-1 Modeling Pluto/Charon brightness ratio. ..................................... 62

A-1 Test case 1: light curve of a pure nitrogen ice Pluto over the next 50 years. .......................................................... 68
A-2 Test case 1: light curve of a pure nitrogen ice Pluto over the next 50 years at a constant Sun-Pluto and Earth-Pluto distance. ......... 68
A-3 Test case 2: light curve of a nitrogen ice Pluto with a methane "heart" over the next 50 years. ............................................ 69
A-4 Test case 2: light curve maximum and minimum over the next 50 years. 70
A-5 Test case 2: light curve of a pure nitrogen ice Pluto with a methane "heart" over the next 50 years at a constant Sun-Pluto and Earth-Pluto distance. ............................... 71
A-6 Test case 2: light curve of a pure nitrogen ice Pluto with a methane heart over the next 50 years at a constant Sun-Pluto and Earth-Pluto distance. ............................... 71
A-7 Test case 2: light curve amplitude over the next 50 years for a standard Sun-Pluto and Earth-Pluto distance. .......................................................... 72
A-8 Light curve of case 1: Pluto with a static surface composition. .... 73
A-9 Mean and amplitude of case 1: static surface composition. ........ 73
A-10 Light curve of case 2: five year nitrogen ice to tholin transition. . 74
A-11 Mean and amplitude of case 2: five year nitrogen ice to tholin transition. 74
A-12 Light curve of case 3: five year nitrogen to water ice transition. 75
A-13 Mean and amplitude of case 3: five year nitrogen ice to water ice transition. .......................................................... 75
A-14 Light curve of case 4: 50 year nitrogen ice to tholin transition. 76
A-15 Mean and amplitude of case 4: 50 year nitrogen ice to tholin transition. 77
A-16 Light curve of case 5: 50 year nitrogen ice to tholin transition. 77
A-17 Mean and amplitude of case 5: 50 year nitrogen ice to water ice transition. 78
A-18 Amplitude evolution for each of the five cases from 2015-2065. .... 78
A-19 Amplitude difference between the H and Ks filters for each of the five cases. .......................................................... 79
A-20 Amplitude difference between the J and H filters for each of the five cases. .......................................................... 79
List of Tables

1.1 Pressure at Reference Altitude in Pluto's Atmosphere 24
2.1 Magellan Infrared Data Collection 33
2.2 VisAO Image Quality 34
2.3 Magellan Near-Infrared Filters 38
2.4 J, H, and Ks Filter Transmission 48
2.5 Conclusions from Clio Filter Transmission 49
3.1 Vega Reference Flux 53
3.2 Model Case Descriptions 59
Chapter 1

Introduction

1.1 Motivation

The New Horizons spacecraft flew by Pluto in July 2015 and gathered detailed images and spectra of Pluto in order to study the current surface composition, atmosphere, and satellites. Pluto may have a global surface change in our lifetimes; therefore, it is important to use New Horizons's data not only to study the current surface properties, but also for future predictions. The major factors influencing Pluto's predicted global change are its high eccentricity, high inclination, and the freezing and sublimation temperatures of its surface and atmospheric components.

Pluto's orbital eccentricity of 0.2488 is higher than any other planet or dwarf planet in our solar system. Pluto varies between a distance of 29.66 AU to 49.31 AU from the Sun. At perihelion, Pluto receives three times the solar insolation as at aphelion (Spencer et al. 1997). This difference in solar insolation affects Pluto's temperature and its atmospheric properties (Earle and Binzel 2015).

Pluto's atmosphere was detected in 1988 by multiple occultation sites (Elliot et al. 1989, Millis et al. 1993). Pluto's atmosphere is made up of methane, nitrogen, and carbon monoxide (Owen et al. 1993, Cruikshank et al. 1976, and Fink et al. 1980). Pluto's surface is made up of pure methane ice, methane dissolved in nitrogen ice,

Due to the high volatility of nitrogen, Pluto’s nitrogen atmosphere is in vapor pressure equilibrium with surface ices. When the solar insolation decreases, the temperature on Pluto will also decrease and some of the atmospheric constituents could precipitate onto the surface. The atmospheric pressure would therefore decrease to maintain vapor pressure equilibrium, causing the atmosphere to contract (Hansen 2015). If the atmosphere begins to precipitate to the ground, the ground will have a fresh cover of ices. This new ice will increase Pluto’s albedo and thus decrease the planet’s temperature, which causes a snowball effect. The rest of the atmosphere should ‘snow out’ within a small time frame (Hansen 2015).

The fact that Pluto currently has a high albedo also supports the idea of volatile transport. On the surface, methane is converted into tholins on a hundred thousand year timescale, therefore there must be a redeposition/refreshing of the methane surface in order to maintain the high albedo of Pluto (Stern et al. 1988). Buratti et al. 2015 discusses the change in Pluto’s light curve over 2008-2014 and concludes seasonal transport of volatiles is currently occurring. By monitoring the surface composition, we may be able to see the deposition of ices and detect volatile transport. These analyses can be compared to occultation results on the atmospheric size.

In this thesis, I explore an observational approach to detecting Pluto’s expected changes over the coming decades. I first analyze Pluto and Charon data taken on the Magellan "Clay" telescope in order to compare ground-based observations with results from New Horizons’s close approach. I then discuss the model that I created to predict how Pluto’s light curve will change over the next 50 years due to volatile transport.
1.2 Scientific Context

Pluto’s surface and atmospheric composition and properties have been studied since its discovery through combined Pluto and Charon light curve analysis. In the 1980s, mutual eclipses between Pluto and Charon allowed detailed albedo maps of both bodies to be made. High spatial resolution data from Hubble advanced the resolution and accuracy of surface maps. Spectral analysis allowed surface compositional study, with the finding of nitrogen, methane, carbon monoxide, and tholins on the surface. Through stellar occultations the temperature and pressure structure of the atmosphere has been studied. In 2015, New Horizons flew past the Pluto system and gathered detailed information about Pluto’s surface and atmosphere.

Light Curve Analysis from 1960 to 2015

Pluto and Charon’s surface components have been studied from rotational light curve analysis. The Pluto system was initially observed unresolved in one light curve. Advancements such as the Hubble Space Telescope and Adaptive Optics make it possible to resolve Pluto and Charon, which are separated by a maximum of one arcsec. From the individual light curves, color information of Pluto and Charon as a function of longitude were determined.

From B-V measurements, Pluto is redder than Charon and has areas of varying amounts of red, whereas Charon does not have a statistically significant change in color at different longitudes (Buie et al. 1997, figure 1-1). The B-V values from Buie et al. 1997 are consistent with previous measurements from Binzel 1988 and Reinsch et al. 1994. Pluto’s light curve reddened between 1997 and 2002 (Buie et al. 2010a, figure 1-1). Also, Pluto’s light curve reddened between 2003 and 2008 (Buratti et al. 2015). This color change could be due to a widespread surface composition change.

A surface map of Pluto was created with Hubble data that show that the north
Figure 1-1: B-V color light curve of Pluto and Charon from 1997 and 2002-2003. Color measurements (points), color information from the difference between B and V Fourier series fits (solid blue line), two-term Fourier fit to the data (three-dot-dash orange line), measurements from Buie et al. 1997 (diamonds), and mean color from Buie et al. 1997 (dashed line) are shown. Note that Pluto has reddened between 2002 and 1997 and varies along longitude. In contrast, Charon has not changed in color and has a uniform color across all longitudes. Figure reproduced from Buie et al. 2010a.
pole area of Pluto has been brightening between 1990 and 2002 (Buie et al. 2010b, figure 1-1). This change could be due to an increased quality of data, surface composition evolution, or surface texture evolution (Buie et al. 2010b). The changes in Pluto’s light curve between the 1960s and 1990s can be explained by pure geometry change; however, light curve changes in the 2000s cannot be explained by the geometry change (Buratti et al. 2015, figure 1-3).

**Albedo Determination from Earth-Based Observations**

In 1989, the geometry of the Pluto system allowed Pluto and Charon to eclipse each other as viewed from Earth. These mutual eclipses allowed the surfaces of Pluto and Charon to be characterized as a function of latitude and longitude where previously only longitudinal studies were possible. These mutual eclipses also allowed Pluto and Charon to be studied separately before telescope capabilities were able to spatially resolve the two bodies. From 1954 to 1986 there were 14 eclipse events (Buie et al. 1992).

From these mutual events, Buie et al. 1992 found that the surface of Pluto has a bright north pole region, a darker equatorial region and an even brighter south pole region (figure 1-1). There is also a large dark region near the equator at 100 degrees longitude which matches the low points in the rotational light curves. Overall, Charon is darker than Pluto (figure 1-1).

**Surface Composition**

Identification and analysis of features in Pluto and Charon’s spectra can give compositional information about these bodies. For example, identifying individual absorption lines can determine composition and looking at line depths can suggest amounts of a certain compound. Similarly, broad-band photometry in the infrared can give information about the longitudinal location of these compounds on both Pluto and Charon.
Figure 1-2: Surface maps of Pluto and Charon as a function of longitude. Top map is V data from Buie et al. 1992 based on mutual event and light curve data. Second and third maps are from 1994 from Hubble Space Telescope data (Faint Object Camera). Fourth map and final map shows the B and V map respectively, from Hubble Space Telescope data (Advanced Camera for Surveys). These maps show brightening of the north pole area of Pluto. Figure reproduced from Buie et al. 2010b.
Figure 1-3: Comparison between data (points) and geometry model (solid line) for Pluto's visual light curve amplitude. From the 1950s until 2000 the amplitude change is dominated by geometry change as is seen by the good agreement between the data and geometry model. After 2000 the amplitude change may be dominated by surface changes. Figure reproduced from Buratti et al. 2015.
Figure 1-4: Low resolution spectra of Pluto and Charon in the near-infrared from 1987-1992. a) spectra of Pluto and Charon from 1987 data. b) comparisons between Roush et al. 1996, Bosh et al. 1992, and Marciais et al. 1992. Note how Charon has a lower albedo than Pluto for most wavelengths. Figure reproduced from Roush et al. 1996.

Charon was predicted to have water ice at all longitudes from analysis of the difference in albedo of different wavelengths (Buie and Shriver 1994, Nakamura et al. 2000, figure 1-4). Nitrogen ice, methane ice, and carbon monoxide ice were detected on Pluto by comparing the K band spectrum with reflectance models (Nakamura et al. 2000, figure 1-5). Numerically, Pluto’s surface is covered with 37% methane, 42% methane diluted with nitrogen, 21% tholins, and less than 6% pure nitrogen ice (Olkin et al. 2007).

The detection of hydrated ammonia and crystalline water ice on the surface of Charon poses a mystery about Charon’s surface (Cook et al. 2007). Crystalline water ice is created when water ice is heated to 78 K and has a lifetime of tens of millions of years, which means that Charon must have some way to replenish this ice. Possible processes are cryovolcanism, impact gardening, or a process that brings annealed ice to the surface, with cryovolcanism being the most likely (Cook et al. 2007). No
Figure 1-5: Near-infrared spectra of Pluto and Charon at two different sub-observer longitudes from 2000. The spectrum were normalized to 1 at 2.19 microns. Nitrogen ice, methane, and carbon monoxide were detected on the surface of Pluto. Figure reproduced from Nakamura et al. 2000.
cryovolcanism was detected by New Horizons; therefore the source of this crystalline ice is still unknown.

Atmospheric information of Pluto and Charon from Stellar Occultations

The atmosphere of Pluto has been studied through stellar occultations since it was first detected in 1988 (Elliot et al. 1989). The atmosphere is made up of nitrogen, methane, and carbon monoxide (Owen et al. 1993, Cruikshank et al. 1976, and Fink et al. 1980). The atmosphere is in vapor pressure equilibrium with the surface. If the nitrogen frost temperature increases by a factor of 1.5, the atmospheric pressure would double (Olkin et al. 2007). There are hazes in the atmosphere, which may be related to the production of tholins (Gulbis et al. 2015). A compilation of the surface pressures found by subsequent stellar occultations is located in table 1.1 (Adapted from Earle and Binzel 2015).

Table 1.1: Pressure at Reference Altitude in Pluto’s Atmosphere

<table>
<thead>
<tr>
<th>Date</th>
<th>Pressure at 1275 km ($\mu$ bar)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988 June 9</td>
<td>0.83 ± 0.11</td>
<td>Elliot and Young (1992)</td>
</tr>
<tr>
<td>2002 August 21</td>
<td>1.76 ± 0.51</td>
<td>Elliot et al. (2003)</td>
</tr>
<tr>
<td>2006 June 12</td>
<td>1.86 ± 0.10</td>
<td>Young et al. (2008)</td>
</tr>
<tr>
<td>2007 March 18</td>
<td>2.03 ± 0.2</td>
<td>Person et al. (2008)</td>
</tr>
<tr>
<td>2007 July 31</td>
<td>2.009 ± 0.09</td>
<td>Olkin et al. (2015)</td>
</tr>
<tr>
<td>2008 August 25</td>
<td>4.11 ± 0.54</td>
<td>Buie et al. (2009)</td>
</tr>
<tr>
<td>2009 April 21</td>
<td>2.59 ± 0.09</td>
<td>Young et al. (2009)</td>
</tr>
<tr>
<td>2010 February 14</td>
<td>1.787 ± 0.076</td>
<td>Young et al. (2010)</td>
</tr>
<tr>
<td>2011 June 23</td>
<td>2.0 ± 0.1</td>
<td>Person et al. (2013) and Bosh et al. (2015)</td>
</tr>
<tr>
<td>2013 May 4</td>
<td>2.7 ± 0.2</td>
<td>Olkin et al. (2015)</td>
</tr>
<tr>
<td>2015 June 29</td>
<td>2.21 ± 0.04</td>
<td>Bosh et al, submitted</td>
</tr>
</tbody>
</table>

The atmosphere nearly doubled in pressure between 1989 and 2003 (Elliot et al. 2003), which may be explained by volatile transport between the surface and the atmosphere. Between 2002 and 2006, the atmosphere had remained relatively constant except for the disappearance of the atmospheric extinction (Person et al. 2013). Evidence for atmospheric haze was again seen in 2015 (Bosh et al., submitted).
atmosphere has a thermal inversion, since the half-light temperature is higher than the surface temperature. This temperature inversion allows many of the volatiles to exist in both the atmosphere and surface at the same time. Future occultations could help differentiate between volatile transport models and determine whether Pluto’s atmosphere collapses as it moves away from the Sun.

**Pluto Volatile Transport and Climate Models**

Transport of Pluto’s surface volatiles will occur since Pluto has an atmosphere that is in vapor pressure equilibrium with the surface and can redistribute materials from warmer areas to colder areas throughout Pluto’s orbit. There are a variety of models, from pole source and sink models to complete atmospheric freeze-out models. The critical parameters in these models include the thermal inertia of the surface, the total abundances of volatiles, and amounts of these compounds on the surface and in the atmosphere. As volatile transport occurs, the most reflective areas will be the coldest, and will therefore be covered in more fresh ice renewing the high albedo. The warmest areas will not have new ice coverage, lowering the albedo due to the transformation from methane ice to tholins, and will continue to increase in temperature. This affect will create large scale bright and dark patches. These patches can be used to study the local surface temperature as the brighter patches will reflect more sunlight and therefore be colder, whereas the darker patches will absorb more sunlight and be warmer.

Pluto has considerable methane on its surface; therefore it should have a low albedo since methane reacts with energetic particles and creates a complex carbon (tholins) with a low albedo (Stern et al. 1988). The average photolysis rate of methane is $1 \times 10^8$ cm$^{-2}$ sec$^{-1}$, which sums to $2 \times 10^{-5}$ g cm$^{-2}$ over each orbit. The timescale to produce an optically thick coating is a hundred thousand years; therefore, without any resurfacing, Pluto should have an albedo of less than 0.1. However, the average albedo on Pluto is 0.55, which suggests that methane is being replenished
by the transport of volatiles through the atmosphere (Stern et al. 1988). Models predict that Pluto’s light curve should vary throughout Pluto’s orbit due to the solar insulation differences (Stern et al. 1988). Some of these variations include a distinct change occurring between 7 and 17 years after perihelion. The phase lag is associated with the thermal inertia of the surface components.

New Horizons data can be used in order to further shape climate models. For example, Young (2013) modeled volatile transport over Pluto’s orbit as a function of thermal inertia, emissivity of the surface components, and bolometric hemisphere albedo (figure 1-6). Some cases resulted in a north polar ice cap in 2015, whereas others predicted that volatile transport would have already transferred these ices to colder areas on Pluto. New Horizon’s findings, such as the northern nitrogen ice pole, can be used to further narrow down the possible cases.

Due to volatile transport, the polar caps may completely sublimate and be re-deposited over the course of Pluto’s orbit (Hansen et al. 2015). Their model also predicts that the atmosphere will not collapse by the New Horizons’s flyby in 2015 with an atmospheric pressure between 0.3 and 3.2 Pascals (best match is 2.4 Pa); this result conflicts with Olkin et al. (2013), who predicts that the atmospheric pressure does not vary throughout Pluto’s orbit. Future occultations will be important to further differentiate among climate models.

Insolation affects the surface temperature, which should in turn affect the atmospheric pressure (Earle and Binzel 2015). Over the course of Pluto’s orbital history, the longitude of perihelion varies through 360 degrees over 3.7 million years and the obliquity varies through 23 degrees over 3 million years (Dobrovolskis and Harris 1983). The sub-solar latitude varies between nearly -60 degrees and 80 degrees throughout Pluto’s orbit (Earle and Binzel 2015). There is a possible correlation between maximum insolation and atmosphere pressure (Earle and Binzel 2015, figure 1-7). If this is a causal relationship, the atmospheric pressure should peak in 2017.
Figure 1-6: Pluto climate models. Each circle represents Pluto at a different place in its orbit, the bar represents the rotational axis. Polar caps are shown with a lighter color. The plots show geometric albedo and surface pressure over the Pluto-year. Figure reproduced from Young 2013.
Figure 1-7: Maximum diurnal insolation versus Pluto atmospheric pressure. There may be a causal relationship between the maximum insolation and atmospheric pressure. Figure reproduced from Earle and Binzel 2015.

and then decrease until aphelion. Occultations near and directly after 2017 will be important to detect this peak and subsequent decrease in atmospheric pressure.
New Horizons Findings

New Horizons flew by Pluto in July 2015 and gathered detailed images and spectra. These data are being sent back to the Earth in small batches as New Horizons continues through the Kuiper Belt. A number of summary papers were published in March 2016 covering the initial results from New Horizons. Moore et al. (2016) discusses the geology of Pluto and Charon. Gladstone et al. (2016) discusses the atmosphere of Pluto. Weaver et al. (2016) discusses the smaller satellites of Pluto. Grundy et al. (2016) discusses the surface compositions across Pluto and Charon. Bagenal et al. (2016) discusses Pluto’s interactions with solar wind, energetic particles, and dust.

Grundy et al. (2016) confirmed that nitrogen, carbon monoxide, and methane are all located on Pluto’s surface (figure 1-8). The methane absorption is particularly strong in Tombaugh Regio, in Tartarus Dorsa, Lowell Regio, and south of Cthulhu Regio. Nitrogen ice could be the dominant surface component. Nitrogen absorption is strongest in craters, and in Sputnik Planum. Water ice and tholins are also located on Pluto’s surface, these components are not volatile at Pluto’s surface temperatures and pressures (figure 1-9).

As New Horizons’s data are analyzed, there will be more accurate surface compositions and distributions that can be used to constrain future volatile transport models on Pluto. Future ground-based observing will be needed in order to analyze the validity of these new models and to monitor volatile transport on Pluto.
Figure 1-8: Maps of volatile ices on Pluto’s surface from New Horizons. Brighter colors mean more absorption. The lower images show the absorption overlaid on the surface features. Figure reproduced from Grundy et al. 2016.

Figure 1-9: Spectra of different areas on Pluto’s surface from New Horizons. a) the north pole. b) strong nitrogen and weak water ice absorption. c) al-Idrisi Montes, similar to b without water ice. d) water ice and weak methane absorption. e) Sputnik Planum with methane, nitrogen, and carbon monoxide ice absorptions. f) weak water and hydrocarbon absorptions. Figure reproduced from Grundy et al. 2016.
Chapter 2

Magellan Near Infrared and Visible Data

2.1 Magellan Data Observation Plan

Images of Pluto and Charon were taken by Dr. Bosh from May 28th to June 3rd 2016 on the Magellan "Clay" Telescope at Las Campanas Observatory. Images were taken using Adaptive Optics (AO) in the J, H, and Ks filters using Clio and in the I, Z, R, and Open filters using VisAO. A summary of all observations can be found in Table 2.1. Since Pluto has a 6.4 day rotation period, six nights of data were taken in order to sample all longitudes of Pluto.

This run was plagued by persistent clouds and high winds. As the Magellan AO system does not use laser guide stars, Pluto was used as the AO guide star (Morzinski et al. 2014). AO was used in order to clearly separate Pluto and Charon. However, due to the high winds, the motion of the images made it difficult for the AO system to "lock". This resulted in an incomplete AO correction and a lower Strehl ratio. For photometry, a high Strehl ratio is not needed as long as Pluto and Charon are separated; however, Pluto and Charon were not fully separated. For the photometry, I ideally would have used apertures that were 1.4 times the full-width half-max (FWHM) (AstroImageJ Software). However, this size aperture intersected
both Pluto's and Charon's point-spread functions. I used an aperture size of 0.823 times the FWHM for the Clio photometry and equal to the FWHM for the VisAO photometry in order to avoid contaminating the photometry.
<table>
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<th>Camera</th>
<th>Filter</th>
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<td>wind speed &gt;35m/s = dome shut</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>05/29/15</td>
<td>patchy clouds</td>
<td>Clio</td>
<td>K</td>
<td>22</td>
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<td></td>
<td></td>
<td>VisAO</td>
<td>Z</td>
<td>61</td>
</tr>
<tr>
<td>05/30/15</td>
<td>good seeing</td>
<td>Clio</td>
<td>K</td>
<td>63</td>
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<td>H</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>J</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VisAO</td>
<td>Open</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Z</td>
<td>45</td>
</tr>
<tr>
<td>05/31/15</td>
<td>0.7&quot; seeing</td>
<td>Clio</td>
<td>K</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>J</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VisAO</td>
<td>I</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Z</td>
<td>8</td>
</tr>
<tr>
<td>06/01/15</td>
<td>0.5&quot;-0.6&quot; seeing</td>
<td>Clio</td>
<td>K</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>J</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VisAO</td>
<td>Open</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Z</td>
<td>32</td>
</tr>
<tr>
<td>06/02/15</td>
<td>slight clouds, wind gusts (11m/s), seeing 0.6-0.7</td>
<td>Clio</td>
<td>K</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>J</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VisAO</td>
<td>Open</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Z</td>
<td>57</td>
</tr>
<tr>
<td>06/03/15</td>
<td>scattered clouds, 0.5-0.7&quot; seeing</td>
<td>Clio</td>
<td>K</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>J</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VisAO</td>
<td>Open</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Z</td>
<td>22</td>
</tr>
</tbody>
</table>
2.2 VisAO Data

2.2.1 Reduction of VisAO Data

The 96/4 Window beamsplitter was used to split the light for each image into the AO wavefront sensor and the VisAO detectors. This beamsplitter creates a 'ghost' image that is brighter but out of focus than the target image (Jared Males, personal communication). Therefore, each image had the potential to have a reflected Pluto and Charon and a non-reflected Pluto and Charon. A summary of image quality is in Table 2.2 below. Example images containing each type of Pluto and Charon are shown in Figure 2-1.

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Filter</th>
<th># of Images</th>
<th># Reflected Pluto’s</th>
<th># Pluto</th>
<th># Charon</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/29/15</td>
<td>Z</td>
<td>61</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>05/30/15</td>
<td>Open</td>
<td>54</td>
<td>50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>26</td>
<td>24</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>22</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>45</td>
<td>44</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>05/31/15</td>
<td>I</td>
<td>50</td>
<td>50</td>
<td>46</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>15</td>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>06/01/15</td>
<td>Open</td>
<td>44</td>
<td>42</td>
<td>42</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>26</td>
<td>22</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>22</td>
<td>19</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>32</td>
<td>22</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>06/02/15</td>
<td>Open</td>
<td>29</td>
<td>24</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>31</td>
<td>23</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>76</td>
<td>63</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>57</td>
<td>49</td>
<td>49</td>
<td>0</td>
</tr>
<tr>
<td>06/03/15</td>
<td>Open</td>
<td>75</td>
<td>34</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>50</td>
<td>28</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>30</td>
<td>11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>22</td>
<td>14</td>
<td>14</td>
<td>0</td>
</tr>
</tbody>
</table>
It would be ideal to use the non-reflected Pluto and Charon for photometry, however this was not possible due to the large number of datasets that do not have the non-reflected images. Thus, I performed photometry on all of the reflected Pluto and Charon data; a complete graph is shown in figure 2-2.

2.2.2 Analysis on VisAO Data

I then found the mean and standard deviation of the mean for each of the groups of same-filter images. The total light curve, with different colors for each filter, is shown in figure 2-3.

Due to the large error bars on each datapoint on the VisAO graph, I was unable to make any robust conclusions. With a higher signal-to-noise value we could compare the amplitude of individual filter light curves to past papers, such as Buratti et al. 2015, in order to track changes. In the future, I suggest to use a brighter guide star so that the 50/50 beamsplitter can be used in order to increase the signal-to-noise of the VisAO data.

2.2.3 Discussion of VisAO Data

Buratti et al. (2015) finds an amplitude of 0.09 ± 0.03 magnitudes over a full rotation period in the V filter in 2014. I used an average V magnitude of 15.17 for Pluto and 17.05 for Charon to convert the magnitudes to Pluto/Charon brightness ratio in order to estimate the expected amplitude of the Magellan VisAO light curve (Buratti et al. 2015). I calculated a value of 0.47 ± 0.06 Pluto/Charon brightness ratio as the amplitude, this value is significantly less than the error bars and scatter on figure 2-3, therefore the scatter that I see in my light curve is noise and not the rotation of Pluto.
Figure 2-1: Example VisAO images of a reflected and a non-reflected Pluto and Charon. The background has around 400 counts per pixel and the Pluto and reflected Pluto areas have around 500 counts per pixel.
Figure 2-2: VisAO photometry for each night between May 30th 2015 and June 3rd 2015. Open = green, I = blue, R = red, Z = black.
2.3 Clio Data

2.3.1 Summary of Clio Data

The Mauna Kea Observatories (MKO) J, H, Ks filters were chosen for Clio since they overlap with some major absorption lines of Pluto’s surface components. These filters also avoid many of the major water absorption lines in Earth’s atmosphere. The wavelength range and transmission of these filters are shown in figure 2-4 and summarized in table 2.3.

Table 2.3: Magellan Near-Infrared Filters

<table>
<thead>
<tr>
<th>Filter</th>
<th>Left Bound (microns)</th>
<th>Right Bound (microns)</th>
<th>Average Transmission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>1.17</td>
<td>1.34</td>
<td>87</td>
</tr>
<tr>
<td>H</td>
<td>1.49</td>
<td>1.78</td>
<td>95</td>
</tr>
<tr>
<td>Ks</td>
<td>2.00</td>
<td>2.30</td>
<td>91</td>
</tr>
</tbody>
</table>

(b) Filter curve for the J filter on Clio (Joyce, R, Kitt Peak National Observatory, 2013).

Figure 2-4: Filter curves for the J, H, and Ks filter on Clio.
2.3.2 Reduction of Clio Data

All data were reduced and analyzed using AstrolmageJ and MATLAB. To reduce the data, I first subtracted off the sky brightness in order to see Pluto and Charon in the images. The sky, telescope, and dome all add signal to each frame in the infrared. This "sky" brightness in the near infrared is around 70 times brighter than Pluto and Charon. The telescope was moved side to side every few images ("dithering") to subtract off the sky brightness post-imaging, resulting in a Pluto-dominated image. I grouped the images of Pluto in one dither with the previous dither position and pairwise subtracted them to result in background-subtracted images. An original image and a sky-subtracted image are shown in figure 2-5.

Next, I performed photometry on all of the sky-subtracted infrared images using AstrolmageJ. The plot for each night is shown in figure 2-6. Pluto and Charon are semi-resolved due to the AO. Since there were no photometric standard stars in the field, I have shown relative brightness between Pluto and Charon.

Charon has no detectable atmosphere; therefore, the surface features should change on a geological timescale (Gladstone et al. 2016). Pluto has an atmosphere, as a result, Pluto is able to change on a much faster timescale. Thus, Charon can be used as a "standard" for short timescales. This comparison is useful for the times where observational constraints, such as field of view size, prevent standard stars from being observed. Charon’s albedo is lower than Pluto’s at most wavelengths between 0.8 and 2.4 micrometers, which lowers it’s contribution to the spectrum. However, between 1.72 to 1.79 micrometers and 2.18 to 2.4 micrometers, Charon is brighter than Pluto and therefore that area is most likely to show contamination from Charon (Fink and DiSanti, 1988, Doute et al., 1999, Buie and Grundy, 2000 and Grundy and Buie, 2002).

Furthermore, the surface of Charon is fairly uniform in comparison to Pluto. Water ice has been detected on Charon’s surface from it’s spectrum (Marcialis et al.
Figure 2-5: Original and background-subtracted Clio images. Note the scale bar for each image. The sky is around 27,000 counts whereas Pluto is a couple hundred counts.
The distribution of water ice is likely a uniform distribution across the surface which will result in a fairly flat infrared light curve (Buie and Shriver 1994). The geometric albedo of the surface is less than Pluto’s average albedo and not wavelength dependent (Tholen et al. 1987). The reflectance is nearly uniform and is likely neutral in color from 0.4 to 2.5 microns (Binzel 1988, Olkin et al. 1993, Stern and Tholen 1997, Grundy et al. 2016). Therefore, the contributions from Charon should affect each sub-observer longitude uniformly.

I then found the mean and error of the mean for each of the images taken with the same filters each night. The total light curve is shown in figure 2-7.
Magnitude of Pluto/Charon on May 30th 2015

Days since May 29th 2015 UT

Clio photometry of May 29th UT

Magnitude of Pluto/Charon on June 1st 2015

Days since May 29th 2015 UT

Clio photometry of June 2nd UT

Figure 2-6: Clio photometry for each night between May 29th 2015 and June 3rd 2015. Green points are J, red points are H, and blue points are Ks.
Figure 2-7: Mean and standard deviation of the mean for the Pluto/Charon light curve over time in the J, H, and Ks filters. Green points are J, red points are H, and blue points are Ks.
Figure 2-8: Total counts per pixel for each night on Clio. The jumps refer to a gap of observation time. The change in pixel counts over time is due to cloud movement over the night.

### 2.3.3 Analysis of Clio Data

Due to the high variation of cloud cover during the observations, I checked the linearity of the images for each night. The full plot of total image counts is shown in figure 2-8. The change in total counts over the course of each night is primarily due to cloud cover movement. As more clouds arrived, the sky got brighter and therefore contributed more counts per pixel. The jumps in the curve show a gap in time.

CLIO's linear regime is below 27,000 counts per pixel. Two of the nights had counts higher than 27,000 counts per pixel. I used the linearity correction shown below in equation 2.1 to convert the recorded number of counts to actual number of counts (Morzinski et al. 2015).

\[ y = 112.575 + 1.00273x - 1.4077 \times 10^{-6}x^2 + 4.5905 \times 10^{-11}x^3 \]  \hspace{1cm} (2.1)

Figure 2-9 shows the recorded counts and the actual counts calculated by the
Figure 2-9: Clio linearity correction for June 2nd and 3rd. The difference between the recorded and actual counts is at most a 0.387% difference.

The linearity correction equation. The difference between the recorded counts and actual counts is at most a 0.387% difference. This difference fits well into my error bars shown above in figure 2-7. This difference is therefore not significant and I used the uncorrected values for my analysis.

Finally, I used the sub-observer longitude given by JPL Horizons to convert the x-axis from time to sub-observer longitude in order to compare my data to images taken by the New Horizons spacecraft (NASA JPL Horizons, figure 2-10).

2.3.4 Discussion of Clio Data

The J, H, and Ks filters each contain different absorption lines for Pluto’s surface components. Looking at one filter individually can reveal a small amount of information about the surface composition. Each filter will collect a different amount of light depending on the composition of the reflecting surface. The fraction of light re-
Figure 2-10: Mean and standard deviation of the mean for the Pluto/Charon light curve over sub-observer longitude in the J, H, and Ks filters.
Figure 2-11: Filter differences in Pluto/Charon light curve over sub-observer longitude in the J, H, and Ks filters.

Reflected back from Pluto, depending on the surface compassion and filter transmission, is shown in table 2.4. Comparing each filter to the other two can provide additional compositional information. For this section, I am assuming that Pluto is made up of only nitrogen ice, methane, tholins, and water ice. These are the four primary compounds on Pluto’s surface (Grundy et al. 2016). The filter differences for the Clio data are shown in figure 2-12

<table>
<thead>
<tr>
<th></th>
<th>J</th>
<th>H</th>
<th>Ks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Ice</td>
<td>0.65</td>
<td>0.71</td>
<td>0.68</td>
</tr>
<tr>
<td>Methane Ice</td>
<td>0.54</td>
<td>0.49</td>
<td>0.34</td>
</tr>
<tr>
<td>Tholins</td>
<td>0.38</td>
<td>0.44</td>
<td>0.40</td>
</tr>
<tr>
<td>Water Ice</td>
<td>0.52</td>
<td>0.29</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 2.4: J, H, and Ks Filter Transmission
There is an overall downward brightness trend between 0 and 200 degrees in longitude and an overall upward trend from 200 to 360 degrees in longitude. From the J filter, the composition that would result in the brightest surface would be nitrogen ice, then methane ice, then water ice, and finally tholins. Since the 20 degrees longitude has the highest brightness ratio, the side of Pluto facing the Earth at a sub-observer longitude of 20 degrees is not primarily made up of tholins. Similarly, the side of Pluto facing the Earth at a sub-observer longitude of 270 degrees longitude is not made up of primarily nitrogen ice. For the H filter, the highest point at 20 degrees longitude means that side of Pluto is not primarily water ice, and the lowest point confirms that the side of Pluto at 270 degrees longitude is not made up of primarily nitrogen ice. The highest point in Ks confirms that the 20 degree longitude side is not primarily water ice. The lowest point in Ks at 180 degrees longitude shows that that side is not made primarily of nitrogen ice. A tabular view of this discussion can be seen in table 2.5 and a pictorial view can be seen in figure 2-12.

Table 2.5: Conclusions from Clio Filter Transmission

<table>
<thead>
<tr>
<th>J</th>
<th>H</th>
<th>Ks</th>
<th>J-H</th>
<th>H-K</th>
<th>J-K</th>
<th>conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>not T*</td>
<td>not W*</td>
<td>not W</td>
<td>N* or T</td>
<td>any</td>
<td>N or T</td>
</tr>
<tr>
<td>70</td>
<td>not all N</td>
<td>not all N</td>
<td>not all N</td>
<td>N or T</td>
<td>any</td>
<td>N or T</td>
</tr>
<tr>
<td>130</td>
<td>not all N</td>
<td>X</td>
<td>not all N</td>
<td>X</td>
<td>X</td>
<td>some M* or W</td>
</tr>
<tr>
<td>180</td>
<td>X</td>
<td>X</td>
<td>not N</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>270</td>
<td>not T</td>
<td>not W</td>
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<td>N or T</td>
<td>any</td>
<td>N or T</td>
</tr>
<tr>
<td>320</td>
<td>not all N</td>
<td>not all N</td>
<td>not all N</td>
<td>N or T</td>
<td>any</td>
<td>N or T</td>
</tr>
</tbody>
</table>

In conclusion, the large scale composition of Pluto can be currently determined by ground-based observations. As Pluto undergoes possible volatile transport, near-infrared ground-based observations can determine longitudinal compositional information. Therefore, we can monitor Pluto's surface compositions as these changes occur in order to learn more about what types of volatile transport are occurring on Pluto's surface.
Figure 2-12: Conclusions from Clio filter transmission. The top image is the mean and standard deviation of the mean for each night of Clio data with derived compositional information written on the graph. The bottom image is from NASA New Horizons, the compositional data overlaid are from Grundy et al. 2016. The similarities between the information derived from the graph and from New Horizons shows that large scale surface composition features on Pluto can be detected from the ground.
Chapter 3

Pluto Infrared Light Curve Modeling

3.1 Model Design

Since Pluto may undergo a global surface change in the near future and we will not have another flyby, it is important to predict the changes as viewed from the Earth through simulations. I created a model that produces a light curve of what you would see if you observed Pluto from the ground in the J, H, and Ks filters for a full rotational period. I chose these filters for many of the same reasons that Dr. Bosh observed Pluto in these filters. They overlap with some major absorption lines of the molecules that make up Pluto’s surface composition. Also, these filters avoid many of the major water vapor lines in Earth’s atmosphere. Finally, sufficient light is emitted by the Sun at these wavelengths to reflect off of Pluto back to the Earth to result in a high enough signal to noise using large ground-based telescopes. I used the specifications for the MKO J, H, and Ks filters in this code. The filter transmissions are shown in Chapter 2 in figure 2-4.

For this model, the user specifies Pluto’s surface composition, the observable latitude range on Pluto, and the observation frequency. The model iterates through the surface in latitude-longitude blocks and produces a J, H, and Ks light curve over the sub-observer latitude by assuming each filter is a rectangular filter with a given center, width, and maximum throughput (specified in table 2.3).
**Model Equations**

The flux in a particular wavelength from a particular area segment of Pluto is calculated by:

\[ F_{\lambda,a} = t_r * s_p(\lambda) * s_o(\lambda) * a(lat, long) * \cos(lat - \alpha) * |\cos(1/2(\beta - long)| \]  

(3.1)

Where \( F_{\lambda,a} \) is the flux from a small area of Pluto for a particular wavelength, \( t_r \) is the transmission of the filter, \( s_p(\lambda) \) is the albedo for a particular composition at the particular wavelength, \( s_o(\lambda) \) is the solar spectrum value for the particular wavelength at a specific Sun-Pluto distance of \( 4.905 \times 10^{12} \) meters and an Earth-Pluto distance of \( 4.792 \times 10^{12} \) meters. \( a \) is the area of a latitude-longitude square at a particular latitude and longitude in meters\(^2\). \( \cos(lat - \alpha) \) and \( |\cos(1/2(\beta-long)| \) are both terms to correct for how much light is reflected towards the observer from the latitude-longitude square, where \( lat \) is the latitude of the square, \( long \) is the longitude of the square, \( \alpha \) is the sub-observer latitude and \( \beta \) is the sub-observer longitude.

The \( F_{\lambda,a} \) is then summed over the wavelengths in a particular filter and summed over the visible hemisphere of Pluto to result in the total flux received:

\[ F = \sum_{0}^{a_p} \sum_{f_{low}}^{f_{high}} F_{\lambda,a} \]  

(3.2)

Where \( F \) is the total flux, \( a_p \) is the visible area of Pluto, \( f_{low} \) is the lower bound of the filter and \( f_{high} \) is the upper bound of the filter. The flux is then converted to magnitudes, using Vega as a standard star (table 3.1) in the equation below:

\[ m_{pluto} - m_{vega} = -2.5 \times \log_{10} \frac{F_{pluto}}{F_{vega}} \]  

(3.3)

52
Table 3.1: Vega Reference Flux

<table>
<thead>
<tr>
<th>Filter</th>
<th>Isophotal Wavelength* (μm)</th>
<th>Reference Flux* (W m⁻² μm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>1.250</td>
<td>3.01×10⁻⁹</td>
</tr>
<tr>
<td>H</td>
<td>1.644</td>
<td>1.18×10⁻⁹</td>
</tr>
<tr>
<td>Ks</td>
<td>2.149</td>
<td>4.35×10⁻¹⁰</td>
</tr>
</tbody>
</table>

*(Tokunaga and Vacca 2005)

Model Parameters

For simplicity, I assume that Pluto is uniformly covered in pure nitrogen ice except for its two largest surface components, informally named Tombaugh Regio (the "heart") and Cthulhu Regio (the "whale") (figure 3-1). The heart is a rectangle from 40 to -10 degrees of latitude and 160 to 220 degrees of longitude. The whale is a rectangle from 20 to -15 degrees of latitude and 15 to 160 degrees of longitude. The heart is assumed to be pure methane ice and the whale is made up of tholins. The reflectance spectra used are shown in figure 3-2. I assume that the illumination percentage of Pluto's Earth-facing hemisphere is 100%. Since Pluto is significantly further from the Earth and Sun than the Earth and Sun are from each other, the fraction of Pluto illuminated by the sun nearly matches the section of Pluto viewed by the earth. For reference, of the Earth-facing hemisphere, the fraction illuminated by the Sun is 99.991% to 99.993 over the course of May 29th to June 3rd 2015 (NASA JPL Horizons).

3.2 Model Test Cases

In order to test this model, I have graphed the J, H, and Ks magnitudes as a function of longitude for the two extremes - where the sub-observer latitude is 0 degrees (pole-facing) and 90 degrees (equator-facing) while Pluto stays at a constant Sun-Pluto and Earth-Pluto distance (figure 3-3 and 3-4).

When the pole is directly facing the Earth and Sun there is no rotation curve since no features are rotating in or out of view. When the equator is directly facing the
Figure 3-1: Model Pluto’s surface composition. White is nitrogen ice, light grey is methane ice, dark grey are tholins.

Earth and Sun the rotation curve has the maximum amplitude since both the heart and whale are rotating in and out of view over the course of one rotation period. The magnitude and amplitude vary between filters due to the difference in reflectance of Pluto’s surface components in each filter.

3.3 Modeling Surface Composition Evolution

I modeled Pluto’s J,H,K light curve moving forward through the next 50 years, with five different surface composition changes. Case 1 is the control and has a static surface composition. Figure 3-5 shows the light curve for Pluto in J,H,Ks over the next 50 years with a static surface composition. All variations in the light curve are due to the geometry changing (specifically, the change in sub-Earth latitude of Pluto). The distance is fixed at the current Pluto-Sun and Pluto-Earth distance, since the distance change dominates the light curve evolution. This dependence is further described in
Figure 3-2: Reflectance spectra of nitrogen ice, methane ice, tholins, and water ice along with J,H, and Ks filters. J, H, and Ks filter bounds are shown in green, red, and blue respectively. Adapted from Clark et al. 1986 using Grundy et al. 2016 and Olkin et al. 2007.
Test Case: Pole facing Sun and Earth

Figure 3-3: Test case: north pole facing Sun and Earth over a full rotation.
Test Case: Equator facing Sun and Earth

Figure 3-4: Test case: equator facing Sun and Earth over a full rotation.
Appendix A. The light curve amplitude first decreases and then increases due to the change of sub-observer latitude, which is clearly shown in figure 3-6.

Since Pluto’s North Pole is permanently facing the Sun in this part of its orbit, the ice located on the sun-facing pole will likely sublimate and migrate to the sun-opposing pole (A. Earle personal communication, Young 2013). The pole is currently composed mainly of nitrogen, and is assumed to be pure nitrogen in my model. I have defined the north pole to be from 90 to 60 degrees on Pluto with respect to it’s spin axis and south pole to be from -60 to -90 degrees. When the nitrogen ice sublimates and migrates to the opposite pole, it will uncover underlying material. The underlying material is likely either tholins or water ice. Water ice is the bedrock on Pluto and therefore could be the material underneath the nitrogen ice (Grundy et al. 2016). Tholins are produced from solar interactions with surface ices over time.
Tholins are older material, so it is also possible that the surface ice layer of Pluto is overlying tholins. I modeled five different cases, described in table 3.2. Full graphs for each case are located in Appendix A.

Table 3.2: Model Case Descriptions

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Pole Layer</th>
<th>Timescale of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nitrogen Ice</td>
<td>No Change</td>
</tr>
<tr>
<td>2</td>
<td>Tholins</td>
<td>Fast - 5 years</td>
</tr>
<tr>
<td>3</td>
<td>Water Ice</td>
<td>Fast - 5 years</td>
</tr>
<tr>
<td>4</td>
<td>Tholins</td>
<td>Slow - 50 years</td>
</tr>
<tr>
<td>5</td>
<td>Water Ice</td>
<td>Slow - 50 years</td>
</tr>
</tbody>
</table>

3.4 Discussion of Model

Similar to the Clio data analysis performed in Chapter 2, examining the difference in amplitude between different filters can reveal the most information. Water ice has weak absorption in the J band, moderate absorption in the H band, and strong absorption in the Ks band. It is useful to calculate the J-Ks amplitude in order to
Figure 3-7: Amplitude difference between the J and Ks filters for each of the five cases.

As we can see from figure 3-7, these cases can be differentiated by amplitude alone. Volatile transport, specifically the underlying material on Pluto’s north pole, can be studied by observing the J-Ks amplitude of Pluto’s light curve. The amplitude difference for a water ice pole layer is much larger than the amplitude difference for tholins. If this sublimation does occur, the underlying material can be differentiated by the J-Ks amplitude change.
Chapter 4

Combined Discussion

The final step to my analysis was to use the model that I created in order to produce the light curve observed from Clio. Pluto was modeled with the two main surface features, the heart and the whale. The surface compositions were determined from figure 1-9. Curve e) was used for the heart, curve f) for the whale, and curve a) for the rest of the surface. The Charon spectrum used as the composition for the entire body was adapted from Olkin et al. (2007) by adding 0.13 to the albedo at all wavelengths in order to shift the model to a similar brightness range as the data. The J, H, and Ks Pluto/Charon brightness ratio light curve is shown in figure 4-1.

There are a number of similarities between the model light curve and the Clio light curve. The differences between the J and H can be used to show the tholins around 80 degrees in longitude. The increase in J relative to H and Ks around 200 degrees suggests methane or water ice as those two compounds have a higher J transmission. The brighter portions of both light curves is between 20 and 100 degrees longitude. And finally, the dimmer portions of both light curves is between 180 and 280 degrees longitude.

The major differences between the model light curve and the Clio light curve are around 20 degrees, 180 degrees and 300 degrees. At 20 degrees, the brightness ratio in Ks is much lower in the model than in the data. I used one spectra of Pluto's
Figure 4-1: Modeling Pluto/Charon brightness ratio. Note the similarities between the model (open circles) and Clio data (stars). For example, around 20 degrees longitude, the J curve is lower than H suggesting Nitrogen or Tholins. Also, the brighter portions of the light curve are from 20 to 100 degrees longitude. Conversely, the model Ks curve has a lower amplitude than the Clio data Ks curve.
pole for the entire background of Pluto, which is not fully accurate as there are small surface compositional changes. These small surface compositional changes will likely affect areas dominated by nitrogen ice the most since nitrogen ice produces a small signal in reflectance spectra. Around 180 degrees the model Ks curve is also shown to have a lower amplitude than the data, however this area is hard to diagnose since there is data on only one filter. Lastly, around 300 degrees the ordering of the J, H, and Ks data curves from brightest to dimmest is not the same as the model curves. This could be related to the difference at 20 degrees since both of these areas are dominated by nitrogen ice.

Overall, two major factors for these differences are the model input parameters and Pluto’s complexity. The model assumed only two large scale surface features. However, upon further inspection, the heart has two distinct light curves. The left side of the heart is a majority methane and matches the curve that I used for this model. The right side of the heart has a light curve (curve d) in figure 1-9 that is closer to the tholin’s light curve than the left side’s light curve. This addition could affect the ratios between the filters. Also, as was mentioned previously, the background composition of Pluto varies across the surface which has not been taken into account. Finally, Charon’s surface composition was assumed to be equal to one spectrum adapted from Olkin et al. 2007. This spectrum was created from a darkened water ice model in order to remove the Charon component from combined Pluto-Charon data. I increased the albedo of Charon’s spectrum by 0.13 in order to shift the model to the brightness range of the data. This was a non-physical change; however, Charon was only used as a standard object in order to analyze the Pluto data. Charon’s spectrum does affect the results of the model; therefore, Charon spectra published by New Horizons will increase the accuracy of this model.

However, it is important to note that Pluto is made up of more than nitrogen ice, tholins, methane ice, and water ice (Grundy et al. 2016). The other compounds, such as carbon monoxide ice, may also affect the light curve in ways that were not
considered in this thesis. Also, the composition of each particular area are not pure compounds. Many areas have a mixture of multiple compounds which increase the difficulty of this qualitative analysis. As further New Horizons's data is analyzed and published, there may be more quantitative data on the specific compositions for each area published, which would allow a quantitative analysis of the Clio light curve. Furthermore, a model with a smaller surface feature resolution that included small-scale features would increase the accuracy of these results.
Chapter 5

Conclusion

5.1 Magellan Data

I calculated the Pluto to Charon brightness ratio in the J, H, and Ks filters as a function of sub-observer longitude using data from May 28th 2015 to June 3rd 2015. By looking at the trends in each of the filters, as well as the J-H, H-Ks, J-Ks values at each sub-observer longitude, I was able to infer the surface composition of Pluto. As a result, the side of Pluto centered on 20 degrees in longitude is mainly nitrogen ice. The side of Pluto centered on 70 degrees is nitrogen ice with an addition of tholins. The side of Pluto centered on 130 degrees is nitrogen ice with tholins and an addition of a more absorptive material, likely methane ice. The side of Pluto centered on 180 degrees has a large amount of the more absorptive material, likely methane ice. The side of Pluto centered on 270 degrees has an increased amount of nitrogen ice. The side of Pluto centered on 320 degrees is mainly nitrogen ice. This is in agreement with New Horizons's surface component mapping (Grundy et al. 2016).

I calculated the Pluto to Charon brightness ratio in the V, R, I, Z and Open bands as a function of sub-observer longitude using data from May 29th 2015 to June 3rd 2015. The data had too low of a signal-to-noise ratio for further analysis.

In the future I recommend taking multiple filters of data each night. The J-H,
J-Ks, and H-Ks analysis increased the reliability of the conclusions. Studying the differences between the filters results in more information than considering filters individually. I would also recommend not using Pluto as a guide star, since this choice requires the use of the 96/4 beamsplitter in order for the AO system to have sufficient light. The split beam results in too low of signal-to-noise ratio to detect the rotation curve of Pluto in the VisAO dataset. Also, the AO system has limited success with a fourteenth magnitude guide star, especially in windy or cloudy weather.

5.2 Model

I created a model that produces the J, H, and Ks broad-band rotational light curve as a function of sub-observer longitude for Pluto for a variety of surface compositions. As Pluto moves away from the Sun in its orbit, there is likely to be large volatile transport between the atmosphere and the surface or between warmer and colder areas on Pluto’s surface. I modeled the transport of nitrogen ice from the north pole to the south pole uncovering either water ice or tholins over a timescale of both five years and 50 years. These cases can be differentiated by their J-Ks amplitudes. I suggest to compare future observations to these predicted light curves in order to determine the underlying layer of Pluto’s pole and determine the timescale of the sublimation.

In the future I recommend comparing near-infrared data of Pluto with this type of model in order to figure out if and what type of volatile transport is occurring on Pluto. The model can be calibrated with observational data in order to monitor surface changes as a function of longitude. Furthermore, as sub-observer latitude changes, there is a glimpse into the latitude distribution of ices.
Appendix A

Model Cases

A.1 Test Cases

Test Case 1

To test the model I first modeled Pluto covered in only nitrogen ice. The J, H, and Ks light curve over sub-observer longitude for the next 50 years is shown in figure A-1.

The evolution of the light curve in figure A-1 is due to Pluto’s orbital mechanics: Pluto is moving further away from the Sun and from Earth and therefore the light curve gets fainter in all wavelengths. Then, I modeled the light curve as a function of sub-observer longitude over the next 50 years using a constant Pluto-Sun distance and Pluto-Earth distance, shown in figure A-2.

Since Pluto is currently modeled as being covered with only one surface component, nitrogen ice, the sub-observer latitude should not affect the light curve, resulting in a flat light curve in all of the filters.
Figure A-1: Test case 1: light curve of a pure nitrogen ice Pluto over the next 50 years.

Figure A-2: Test case 1: light curve of a pure nitrogen ice Pluto over the next 50 years at a constant Sun-Pluto and Earth-Pluto distance.
Test Case 2

The next test case consists of an entirely nitrogen Pluto except for one rectangular area of pure methane ice representing the "heart" on Pluto's surface. The light curve for test case 2 is shown in figure A-3.

This light curve has a large amplitude due to the heart rotating in and out of the viewing field. Methane ice reflects less light than nitrogen ice in the J, H, and Ks filters, which lowers the magnitude of Pluto when the heart is in view. The amplitude of the light curve in each filter is different due to the different absorption bands in each filter. The Ks filter has the largest methane absorption line area, and therefore the amplitude of the K filter is the most affected by the addition of the heart. To better understand the change of amplitude as a function of time, I have plotted the amplitude of the J, H, and Ks light curves as a function of year in figure A-4.

The overall downward trend in figure A-4 is due to Pluto moving away from the
Figure A-4: Test case 2: light curve maximum and minimum over the next 50 years. The error bars refer to the amplitude of each light curve, the datapoints are the average apparent magnitude.

Sun and Earth. In order to better see the light curve changes due to Pluto’s sub-observer latitude change and surface component change, I modeled the light curves with the current distance as this static distance. Figure A-6 below shows the light curve as a function of sub-observer latitude for standard distance over the next 50 years and figure A-7 below shows the amplitude of the light curves for a standard distance over the next 50 years.

As is evident from figure A-7, the amplitude changes over time most clearly show the light curve changes due to the surface component changes.
Figure A-5: Test case 2: light curve of a pure nitrogen ice Pluto with a methane "heart" over the next 50 years at a constant Sun-Pluto and Earth-Pluto distance.

Figure A-6: Test case 2: light curve of a pure nitrogen ice Pluto with a methane heart over the next 50 years at a constant Sun-Pluto and Earth-Pluto distance. An offset of 0.1 has been added to H and an offset of 0.27 has been added to Ks to better see the change.
Figure A-7: Test case 2: light curve amplitude over the next 50 years for a standard Sun-Pluto and Earth-Pluto distance.

### A.2 Case 1 - 5

Case 1 depicts Pluto’s predicted light curve with no surface change (figure A-8. All changes in the light curve are due to orbital geometry. The mean and amplitude of the light curve over time is shown in figure A-9.

Case 2 depicts how the light curve would change if the nitrogen ice sublimated off of Pluto’s north pole over the course of five years and exposed underlying tholins (figure A-10). The mean and amplitude of the light curve over time is shown in figure A-11.

Case 3 depicts how the light curve would change if the nitrogen ice sublimated off of Pluto’s north pole over the course of five years and exposed underlying water ice (figure A-12). The mean and amplitude of the light curve over time is shown in figure A-13.
Figure A-8: Light curve of case 1: Pluto with a static surface composition.

Figure A-9: Mean and amplitude of case 1: static surface composition. The error bars refer to the amplitude of each light curve, the datapoints are the average apparent magnitude.
Figure A-10: Light curve of case 2: five year nitrogen to tholin transition.

Figure A-11: Mean and amplitude of case 2: five year nitrogen to tholin transition. The error bars refer to the amplitude of each light curve, the datapoints are the average apparent magnitude.
Figure A-12: Light curve of case 3: five year nitrogen to water ice transition.

Figure A-13: Mean and amplitude of case 3: five year nitrogen to water ice transition. The error bars refer to the amplitude of each light curve, the datapoints are the average apparent magnitude.
Figure A-14: Light curve of case 4: 50 year nitrogen ice to tholin transition.

Case 4 depicts how the light curve would change if the nitrogen ice sublimated off of Pluto's north pole over the course of 50 years linearly and exposed underlying tholins (figure A-14). The mean and amplitude of the light curve over time is shown in figure A-15.

Case five depicts how the light curve would change if the Nitrogen sublimated off of Pluto’s North Pole over the course of 50 years linearly and exposed underlying water ice (figure A-16). The mean and amplitude of the light curve over time is shown in figure A-17.

In order to more easily view the amplitude change over time for each of the cases, I have plotted the amplitude only for each of the five cases (figure A-18). Compositional information can also be determined by studying the differences between filters. H-Ks amplitude difference for each of the five cases shown in figure A-19. J-H amplitude difference for each of the five cases shown in figure A-20.
Figure A-15: Mean and amplitude of case 4: 50 year nitrogen ice to tholin transition. The error bars refer to the amplitude of each light curve, the datapoints are the average apparent magnitude.

Figure A-16: Light curve of case 5: 50 year nitrogen ice to tholin transition.
Figure A-17: Mean and amplitude of case 5: 50 year nitrogen ice to water ice transition. The error bars refer to the amplitude of each light curve, the datapoints are the average apparent magnitude.

Figure A-18: Amplitude evolution for each of the five cases from 2015-2065. The symbol refers to the case number: case 1 is stars, case 2 is plus signs, case 3 is circles, case 4 is triangles, and case five is x shapes.
Figure A-19: Amplitude difference between the H and Ks filters for each of the five cases.

Figure A-20: Amplitude difference between the J and H filters for each of the five cases.
Bibliography


