Analysis of Nucleus Properties of the Enigmatic Comet 29P/Schwassmann-Wachmann 1

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ANALYSIS OF NUCLEUS PROPERTIES OF THE ENIGMATIC COMET 29P/SCHWASSMANN-WACHMANN 1

by

CHARLES ALFRED SCHAMBEAU
B.S. University of South Alabama, 2007
M.S. University of Alabama in Huntsville, 2009

A dissertation submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy
in the Department of Physics
in the College of Sciences
at the University of Central Florida
Orlando, Florida

Summer Term
2018

Major Professor: Yanga R. Fernández
ABSTRACT

We present results from a continuing effort to understand activity drivers for the enigmatic Comet 29P/Schwassmann-Wachmann 1 (SW1). SW1 has been of interest since its discovery almost 100 years ago because of its nearly continuous, quiescent activity beyond the water-sublimation line and its highly variable, outburst activity while receiving a nearly constant insolation due to its low eccentricity orbit. These characteristics make SW1 a useful target for investigating both distant cometary activity drivers and also cometary outburst behavior. We approach answering these questions through a detailed analysis of SW1; first by measuring nucleus properties required for a more accurate nucleus thermophysical modeling and second, by applying thermal modeling to replicate its activity. Our project began with an analysis of Spitzer Space Telescope infrared observations of SW1 from 2003. Coma removal techniques when applied to the images provided nucleus photometry measurements. Application of the Near Earth Asteroid Thermal Model (NEATM) to these measured photometry values resulted in an effective nucleus radius of $32.3 \pm 3.1$ km and a thermal beaming parameter of $1.14 \pm 0.22$. These results indicated that SW1 is one of the largest Jupiter Family Comets and also has a relatively smooth overall surface and/or a low thermal inertia. We next placed constraints on the nucleus’ spin state through analysis of evolution seen in the coma’s morphological structure through two sets of outburst coma observations. The first set analyzed are from the Kitt Peak 2.1-m telescope taken ~2 days after a major outburst in 2008. 3-D Monte Carlo coma modeling showed that the nucleus’ spin period is on the order of days and/or the spin pole orientation was along the Earth’s directions during observations. The second set are Hubble Space Telescope observations from 1996 taken ~15 hours after a major outburst. Modeling similarly showed a rotation period on the order of days. Due to the observing geometry differing between the 2008 and 1996 observations, we conclude the rotation period lower limit must be on the order of days even if the spin-pole direction was directed along the sub-Earth direction during one set
of observations. The nucleus properties measured or constrained by our project were incorporated into a thermophysical model to replicate the quiescent activity via the sublimation of the supervolatile species CO or CO$_2$. A progenitor nucleus was thermally evolved in SW1’s current orbit using different plausible nucleus interior compositional and layering schemes. We discuss results of this analysis and additionally possibilities for future thermal modeling efforts.
I dedicate this dissertation to my parents, Hope and Joel Schambeau.
ACKNOWLEDGMENTS

I would like to express my appreciation for the many individuals who encouraged and advised me during the research efforts of this dissertation. First, and foremost, I want to express gratitude to my advisor and committee chair, Dr. Yanga Fernández, for helping me to enroll in UCF’s Physics program and for accepting me into his research group. Thank you for the time you dedicated to teaching me planetary science and also for the opportunities you provided me during my graduate career. These experiences have enhanced my life in ways I couldn’t have imagined. To Dr. Nalin Samarasinha, thank you for your guidance while I navigated the ins and outs of graduate school and also for teaching me what it takes to succeed as an early career planetary scientist. Thank you also for the many Skype meetings over the years to discuss results from my research efforts. These meetings have given me examples of the critical analysis techniques that are necessary for confidence in one’s results. To Dr. Laura Woodney, thank you for your advice and the many trips to Kitt Peak to help with observations. It’s been a pleasure getting to know you and learning from you the skills of observational astronomy over the past few years. To Dr. Britt and Dr. Kokoouline, thank you for your input and guidance during my graduate research projects.

The UCF Planetary Science group has made my graduate experience all the more pleasurable. Akbar, Emily, Jenna, Mary, Tracy, and Zoe, your friendships have made my years of graduate school at UCF enjoyable. You all have encouraged me to excel and have inspired me to challenge myself by your good examples as early career researchers. I especially want to thank Jenna for the many great adventures during graduate school. I look forward to the adventures in store during the next chapter of our lives.

I also thank the many researchers outside of UCF that have given me guidance: Dr. Ellen Howell, Dr. Gal Sarid, Dr. Karen Meech, Dr. Maria Womack, and Dr. Matthew Knight.
Finally, I want to give my thanks to my family. Your unwavering support over the years of my academic endeavors has given me the confidence to continue when I had doubts. I couldn’t have done this without you. To my partner, Bob, I thank you for your support, patience, and understanding over the last two years of my PhD work. These years have been some of the most challenging of my life and I am grateful you were there by my side.
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CHAPTER 1: INTRODUCTION

One overarching goal of astronomy is to understand the formation and evolution of Earth and the Solar System (SS). This goal requires understanding the compositional, dynamical, and thermophysical conditions of the protoplanetary disk, all of which could have been time dependent due to radial mass transport. Comets can help us achieve this understanding since their progenitors were the icy planetesimals that went into making the giant planets. They also represent material relatively little changed since the formation of our SS ∼4.5 Gyr ago. Their primordial, structural and compositional properties are linked to the conditions present in the early stages of our protoplanetary disk’s accretion (e.g. Weidenschilling 1997; Johansen et al. 2014). Material processing, most importantly heating from the Sun, has altered this material from its more pristine state. Thus a link must be established between the material observed today and the early more-pristine material which accreted into cometisemals. Orbital migration and scattering of the early comet populations has severed their direct link to the radially dependent conditions of the early SS (Tsiganis et al. 2005; Gomes et al. 2005; Morbidelli et al. 2005a; Levison et al. 2011). Resolving these dilemmas and linking our current comet populations to the progenitor comet populations both orbitally and compositionally is a multi-pronged effort well beyond the scope of one dissertation project. In this dissertation I address one component of this large astronomical puzzle: determining methods of measuring the compositional makeup of cometary nuclei through remote, primarily Earth-based, observations. My dissertation focuses on application of these methods to the Comet 29P/Schwassmann-Wachmann 1 (SW1).
Figure 1.1: HST observation of HR 4796A showing evidence for a circumstellar disk of material identified in the figure as “debris ring”, where the primary light of HR 4796A has been removed using a PSF template-subtracted coronagraphy technique (Schneider et al. 2018). Infrared spectroscopy using the NASA Infrared Telescope Facility and the Spitzer Space Telescope has measured a temperature of \(\sim 100\text{K}\) for the debris disk at a distance of 75 AU from the primary star. Spectral signatures of this material reflect those similar to reddened surfaces of cometary nuclei in our SS (Lisse et al. 2017). Image courtesy of NASA and the Space Telescope Science Institute (STScI).

1.1 Background and Scientific Motivation

Advances in our observational capabilities have allowed us to observe other planetary systems in the Milky Way like never before. For example, we are now able to detect the existence and composition of disks around both young and evolved stars elsewhere in our Galaxy; we can actually tell that there are stars in our neighborhood with dense asteroid and/or comet belts, some hundreds of times more massive than our own (e.g. Lisse et al. 2017; Mittal et al. 2015). Figure 1.1 shows a Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) image of the HR 4796 binary star system (Schneider et al. 2018), which has been detected to have a
disk of silicate material, around the HR 4796A primary star, compositionally similar to reddened material found in our SS’s comet population (Lisse et al. 2017). Additionally, results from the Kepler spacecraft and from ground-based observations (e.g. Gillon et al. 2017; Maxted et al. 2016) show that, in terms of exoplanets, there are many possible architectures to a system’s planetary layout. Presently, there are observational biases due to our limited capability of detecting smaller more-faint terrestrial-like planets, but with new observatories coming online over the next decade (e.g. the James Webb Space Telescope (JWST), Thirty Meter Telescope (TMT), and Giant Magellan Telescope (GMT)) we will gain a ten-fold improvement in detector resolutions to hunt for and characterize dim exoplanets next to or protoplanetary disks around their brighter parent star. The large diversity in exoplanetary systems and protoplanetary disks already detected and those potentially to be detected and characterized over the next several decades makes it vital to have a better understanding of our own SS and its formation. It is thus relevant to determine what our SS’s comet and asteroid populations tell us about our Galactic context.

1.1.1 Cometary Links to Solar System Formation

As was stated earlier, comets are some of the least processed material in our SS. If we can (1) verify that current cometary nuclei retain pristine material, (2) measure the compositional nature of this material, and (3) link current cometary orbital characteristics to their initial formation regions, we can provide necessary constraints for any potential SS formation model. Plausible formation models must reproduce the orbital characteristics and compositional nature of the current comet populations. In this dissertation, I focus on determining the feasibility of remote-sensing methods for measuring the compositions of cometary nuclei through an analysis of the comet SW1. I do not address in detail the necessary dynamical linkage which must be determined between current cometary orbital distributions and the progenitor orbital distributions present at formation of the SS. The modeling efforts required to represent the complex evolution of small bodies from their
original orbits is beyond the scope of my current work. I do present an introduction to the current layout of small icy bodies in the SS and their possible links to the early SS formation regions (e.g. Morbidelli et al. 2005b; Nesvorný et al 2017).

1.1.2 Comet Taxonomy

Comets historically have been classified by their orbital properties. While links between comets currently possessing similar orbital characteristics may imply a similar orbital history, and thus a similar formation region, there is no reason why this must be true. The complex nature of orbital dynamics over long time scales due to non-gravitational forces (e.g. orbital evolution due to activity) and gravitational interactions with the planets – especially Jupiter – can easily erase linkage between bodies once having similar starting regions. This process can also produce bodies with currently similar orbits that have reached these states through drastically different orbital histories and origins. This is mentioned to identify a fundamental weakness of classifying comets by their current orbital characteristics. However, it should be pointed out that until a better mechanism of classifying comets is devised, there is utility of such a dynamical classification scheme. In the following section, we discuss a taxonomy of comets determined by their current orbital properties.

A comet’s orbital period was one of the first methods used to classify comets. An orbital period of 200 years became the standard dividing line between two major groups of comets: long-period comets having periods longer than 200 years and short-period comets having periods shorter than 200 years (Duncan 2004). In the next two sections we describe sub-classification schemes for both groups. We spend more time explaining short-period comets due to their more relevant link to the work contained in this dissertation.
1.1.2.1 Long-Period Comets

Long-period comets (LPCs) are typically divided into two main types based on whether they have likely traveled into the inner SS before (i.e. to a heliocentric distance comparable to those of the planets): dynamically-new comets are experiencing their first inbound journey and returning comets have traveled into the inner SS before. The inverse of a LPCs’ semi-major axis before it enters the region of the SS where its gravitationally perturbed by interactions from the Planets $1/a_0$ is used to identify whether it is new, returning, or interstellar: $0 < 1/a_0 < 0.0001$ AU$^{-1}$ for new, $1/a_0 > 0.0001$ AU$^{-1}$ for returning, and $1/a_0 < 0$ AU$^{-1}$ for interstellar. Objects with a positive semi-major axis are most probably from the Oort Cloud (Oort 1950), to be discussed more in Section 1.1.3. While, interstellar objects have a pre-inner SS encounter semi-major axis $a_o$ which is negative, indicating these objects are not gravitationally bound to the Sun and are most likely of interstellar origin. A notable attribute of LPCs is their typically unstable orbits on timescale of a single close approach to the inner SS. LPCs experience major modifications in their orbital properties during the timeframe of a single orbital period due to gravitational interactions with the Sun and Planets and from non-gravitational forces (e.g. activity driven forces).

1.1.2.2 Short-Period Comets

Short-period comets (SPCs) have relatively stable orbits when compared to LPCs, although their orbital elements can change due to gravitational perturbations from the planets, most notably from Jupiter. While the orbits themselves may change due to these interactions, there is a parameter which tends to be nearly-conserved over long timeframes. This nearly constant parameter, called the Jupiter Tisserand Parameter $T_J$, is defined as:

$$T_J = \frac{a_J}{a} + 2\sqrt{\frac{a}{a_J}(1 - e^2) \cos i.}$$  \hspace{1cm} (1.1)
In the equation $a_J$ is the semi-major axis of Jupiter, $a$ is the comet’s semi-major axis, $e$ is the comet’s eccentricity, and $i$ is the comet’s inclination. $T_J$ is used as a classification metric for comets (e.g. Levison 1996). A plot of $T_J$ vs. $a$ for all known SPCs as of February 2018 is shown in Figure 1.2. The figure implies a natural grouping of comets, which is used for further classification of SPCs. The classification scheme of Levison (1996) and Duncan et al. (2004) is as follows: Halley Type comets (HTCs) have $T_J < 2$, Jupiter-Family comets (JFCs) have $2 < T_J < 3$, and Chiron or Encke Types have $T_J > 3$ (additionally, Chiron Types have $a > a_J$ and Encke Types have $a < a_J$). The comet of primary interest for this dissertation, SW1, has a $T_J = 2.99$ and is classified using the above definition as a JFC. Figure 1.2 helps to visualize the main populations of SPCs by their orbital properties. Halley Types are also referred to as nearly-isotropic comets (NICs) because of their nearly isotropic distribution of inclinations (Levison et al. 1996). Ecliptic comets, defined as having $T_J > 2$, typically have low inclinations and include JFCs, Chiron Types, and Encke Types. The differences in inclination values for NICs and Ecliptic comet populations hint at two distant, cold-storage reservoirs believed to be the source regions for both populations, the Oort Cloud and Scattered Disk, which will be described in the next section.

Furthermore, Chiron Types are thought to be an evolutionary stage between Scattered Disk objects (to be discussed in Section 1.1.3.2) and JFCs. Encke Types compromise evolutionary stages of JFCs, which have had their orbits modified so that they are no longer on Jupiter crossing orbits (i.e. $a < a_J$), and also include Main-Belt comets (MBCs). MBCs are dynamically distinct from comets and are believed to be icy asteroids that exhibit activity through events such as impacts exposing subsurface ices and are not phenomenologically similar to comets (Jewitt et al. 2015).
Figure 1.2: Plot of Jupiter Tisserand Parameter ($T_J$) vs. $a$ for short-period comets. Due to the nearly-conserved nature of the Tisserand parameter, bodies on the diagram move mostly horizontally. The main orbital populations: nearly-isotropic comets with $T_J < 2$ (including Halley Types) and ecliptic comets with $T_J > 2$ (including JFCs, Chiron Types, and Encke Types) are believed to originate from two dynamically separate reservoirs. SW1 is identified on the plot by a red star. Also, identified is the semi-major axis of Jupiter, because of its gravitational influence on cometary orbits. The plot is similar to Figure 1.3 from Rickman (2018) and includes orbital elements obtained from the NASA Jet Propulsion Laboratory Small-Body Database Search Engine.
1.1.3 Source Regions for Comet Populations

In the simplest terms there are two hypothesized source regions for the current comet populations (Rickman 2018): (1) the Oort Cloud is the source region for the nearly-isotropic comets (identified with LPCs and Halley Types) and (2) the Scattered Disk is the source of ecliptic comets (identified with JFCs, Chiron Types and Encke Types). At this time there is only indirect evidence for the existence of the Oort Cloud. There may be a primordial link between the two source regions, but there are clear differences in terms of orbital properties between comets arriving in the inner SS from either of the two reservoirs (Rickman 2018). Figure 1.3 shows the theoretical structure of both reservoirs and Figure 1.4 shows a theoretical linkage between the cometary source regions and the current comet populations. Both populations are members of a larger group of objects called trans-Neptunian objects (TNOs) which have a semi-major axis larger than Neptune.
1.1.3.1  The Oort Cloud

The Oort Cloud is a theorized spherical distribution of small bodies orbiting the Sun having an inner boundary of thousands to tens of thousands of AU and an outer boundary possibly around 100,000 AU. These boundaries are inferred from the orbits observed for incoming LPCs through dynamical modeling of trial Oort cloud populations and the calculated flux rates for incoming LPCs produced by these models (Oort 1950; Dones et al. 2004; Rickman 2018). Gravitational
perturbations from passing stars and galactic tides are responsible for placing Oort Cloud objects on inbound LPCs orbits. The introduction to the Oort Cloud is brief because the comet of interest for this dissertation is a JFC and believed to have originated in the Scattered Disk.

Figure 1.4: Diagram representing one current theory of the dynamical linkage between the reservoirs (Oort Cloud and Scattered Disk) and the current populations of comets with regards to an object’s aphelion distance (Q) and perihelion distance (q). The figure labeling is as follows: OC (Oort Cloud), SD (Scattered Disk), CEN (Centaur), JF (Jupiter-Family), HT (Halley Type comet), LP (Long-period comet), and New (Dynamically-new comet). The dashed dividing lines indicate there is more uncertainty in the heliocentric distances associated with the population orbital boundaries. Figure is modeled after a similar image in Rickman (2018).
The existence of a larger population of low-inclination small bodies beyond the orbit of Neptune was speculated by Edgeworth (1949) and Kuiper (1951) because of the observed mass deficit identified at the time for heliocentric distances larger than $\sim 30$ AU. Although Pluto (discovered in 1930) and one of Pluto’s moons Charon (discovered in 1978) had been known about for many years, this TNOs population in modern terms was detected and verified with the discovery of 15760 Albion, formerly 1992 QB$_1$ (Jewitt & Luu 1993) in 1992. The TNOs population is divided into many sub-populations based on orbital properties. For this dissertation, I am particularly concerned with one sub-population called the Scattered Disk because it is believed to be the source region of the JFCs (Duncan & Levison 1997; Morbidelli & Brown 2004; Duncan et al. 2004). This collection of bodies has semi-major axis values larger than 30 AU and, more importantly, are on orbits that are (or have been) “scattered” by close gravitational interactions with Neptune (Morbidelli & Brown 2004; Rickman 2018). There is considerable complexity associated with the structure and evolution of the Scattered Disk itself, but the important component for this dissertation is that JFCs are hypothesized to be bodies which have migrated from their longterm cold storage in the Scattered Disk to more interior regions of the SS where heating from the Sun causes significant volatile-driven activity (e.g. gas and dust emission from the comet’s nucleus). Observations of these active comets allows an increased ability to investigate the chemical and structural makeup of these primitive bodies, aiding our overall goal of understand the orbital and compositional linkage of comets to the conditions during the early stages of SS formation.

The pathway from Scattered Disk object to JFC is believed to involve a gravitational cascade of interactions between the object and the giant planets. These gravitational interactions result in transient orbits (on the order of millions of years) with higher eccentricities, allowing the object’s orbit to cross the next interior giant planet’s orbit (Duncan & Levison 1997; Duncan et al. 2004).
The longterm net gravitational interaction is stochastic and can result in an increase or decrease of the object’s perihelion distance. Objects which experience a net decrease in perihelion, eventually reaching a perihelion interior to that of Jupiter’s orbit, achieve the designation of JFC. The intermediate stages of this migration, between Neptune and Jupiter, occupy a space called the Centaur region, with one formal definition of this region given by Jewitt (2009): (1) perihelion distance and semi-major axis satisfying $a_J < q < a_N$ and $a_J < a < a_N$, where $a_J = 5.2$ AU and $a_N = 30.0$ AU are the semi-major axes of Jupiter and Neptune and (2) the object is not in a mean-motion 1:1 resonance with a planet. The comet SW1 is a member of this Centaur population and in the next section I explain why investigating it and other objects in this transitional region are important for our overall understanding of the SS.

1.1.3.3 Significance of Understanding the Centaur-to-Jupiter Family Transition Region

Historically, cometary research has focused on observational studies of active JFCs residing in the inner SS (interior to $\sim 3$ AU) where the sublimation of water ice is the dominant activity driver (Festou et al. 2004; Rickman 2018). Observations indicate the active lifetimes of JFCs actually often start when they are still in the Centaur region (Mazzotta Epifani et al. 2007; Jewitt 2009; Meech et al. 2009), yet, the transition from Centaur to JFC happens in a region too cold for water sublimation to be the driver of the activity (Meech & Svoren 2004). The presence of cometary activity beyond the historically—and possibly erroneously—established 3AU water-sublimation line has been well documented (Meech & Svoren 2004; Meech et al. 2009; Kelley et al. 2013), but our understanding of this distant cometary activity is incomplete, limiting our ability to fully understand the transition region from the outer to inner SS. Activity in this region, if present, is likely not driven by the sublimation of water ice. Of the volatile species that may become active at these distances, CO and CO$_2$ are likely causes because of their cosmogonical abundances and low sublimation temperatures (Womack et al. 2017; Bauer et al. 2015; Ootsubo et al. 2012; Reach et
al. 2013). But, there are concerns as to whether these ices can survive in the near-surface regions of small bodies residing in the Scattered Disk for the lifetime of the SS (Meech & Svoren 2004). The crystallization of amorphous water ice (AWI) leading to the release of gases formerly trapped in the AWI pore structure has been proposed as an alternative activity driver (Prialnik et al. 2004; Meech et al. 2009). Determination of which activity driver or combination of activity drivers is currently ongoing informs us of the compositional nature of the nucleus, which as mentioned earlier holds information about the primordial constituents of our SS. There are many open-ended questions regarding the transitional Centaur region which when answered will help to inform our understanding of the SS’s formation. The following is a list of current questions regarding the Centaur-to-Jupiter family transition region:

- Why are some Centaurs active and others not (Jewitt 2009; Bauer et al. 2013)? Is this due to primordial composition differences, or, is the dichotomy primarily linked to the orbital histories of active and inactive Centaurs?

- Is there a relationship between nucleus size and observed activity? Are the majority of Centaurs active, but we only detect activity in the larger end members of the population because of their larger relative active areas yielding a mass loss rate high enough for detectable activity?

- What is the complete picture of the Centaur size distribution (Stansberry et al. 2008; Bauer et al. 2013) and how does it compare to the size distributions of other small-body populations (e.g. JFCs, Jupiter Trojans, Scattered Disk objects)? Does the Centaur size distribution differ from the JFCs, reflecting the former representing a group that has undergone less mass loss due to their relatively lower activity levels? If Centaurs follow a different distribution than JFCs does that imply the Centaur size distribution is more reflective of the distribution for the Scattered Disk?
• How do we distinguish a Centaur experiencing its first inbound journey from the Scattered Disk, where presumably it should contain more preserved volatile material, from one that has previously experienced time as a JFC, where there should be a depletion of its volatile inventory, and been scattered by Jupiter back into the Centaur region for a second time? Would these dynamical differences explain observations of active and inactive Centaurs?

• What are the surface properties of the Centaur population (e.g. albedo, composition, and surface roughness) and how do they compare with other populations?

• Are hypervolatiles such as CO and/or CO$_2$ still present in ice form near the surfaces of nuclei, representing surviving ices from its initial formation, or, if there are icest produced from a freezing of gases released from deeper interior portions of the nucleus. The determination of hypervolatile ice survival gives indications of the bodies formation temperature and also the thermal history of the body.

In this dissertation, I presents results from a series of investigations which will help to address many of the above questions through a deeper understanding of the distantly-active and transition-region object 29P/Schwassmann-Wachmann 1.

1.2 Comet 29P/Schwassmann-Wachmann 1

SW1 was discovered on November 15, 1927 by Arnold Schwassmann and Arno Arthur Wachmann at the Hamburg Observatory, in Bergdorf, Germany while undergoing an outburst and reaching a magnitude of $\sim 13.5$. The comet has been of interest since its discovery because of the unique orbital properties and activity patterns it possesses when compared to other comets. In this section these unique properties are presented, explaining why a more detailed understanding of SW1 is warranted.
1.2.1 Orbital Properties

SW1 is currently in a nearly circular orbit just outside the orbit of Jupiter, with eccentricity $e = 0.04$ and semi-major axis $a = 6.0$ AU. At the time of this work, it possesses the third lowest eccentricity of known comets (NASA, Jet Propulsion Laboratory’s Small-Body Database Search Engine). Table 1.1 provides a more complete list of SW1’s orbital elements obtained from the International Astronomical Union’s Minor Planet Center (IAU, MPC). Figure 1.5 shows orbital diagrams of SW1 for UT 2018, March 8 acquired from the NASA, Jet Propulsion Laboratory Small-Body Database Browser, which emphasize its low eccentricity and low inclination orbit. The orbital region of SW1 is chaotic (Carusi et al. 1995), where dynamical simulations constrain the half-life for orbits similar to SW1’s at $\sim 300$ years (Horner et al. 2004) and a time before being expelled into interstellar space by Jupiter on the order $\sim 10^5$ years (Neslusan et al. 2017). SW1’s orbital properties classify it as a JFC using the definitions provided in Section 1.1.2.2 and additionally as a Centaur using the definition of Jewitt (2009). Historically, SW1 has been referred to as a JFC, but orbitally it is more closely representative of a Centaur. It is also believed that SW1 is less thermally evolved than most JFCs due to its relatively large perihelion distance. This dissertation often refers to SW1 as a JFC, but this is only because of the historical context and it shouldn’t distract from SW1’s Centaur classification.
Figure 1.5: Orbital diagrams for SW1 showing the configuration of the inner Solar System on March 8, 2018. The top panel is a bird’s-eye view looking down the north ecliptic pole and the bottom panel shows a view looking along the vernal equinox. These diagrams highlight the low eccentricity and low inclination nature of SW1’s orbit. A cyan curve indicates the portion of the orbit above the ecliptic plane and likewise a blue curve indicates the portion below. Diagrams were obtained from the NASA Jet Propulsion Laboratory Small-Body Browser. Images courtesy of NASA/JPL-Caltech.
Table 1.1

Summary of SW1’s Orbital Elements Obtained from IAU, MPC

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>Date of Perihelion Passage</td>
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</tr>
<tr>
<td>q, Perihelion Distance</td>
<td>5.766822 AU</td>
</tr>
<tr>
<td>a, Semi-Major Axis</td>
<td>6.002614 AU</td>
</tr>
<tr>
<td>i, Orbital Inclination</td>
<td>9.36833°</td>
</tr>
<tr>
<td>e, Orbital Eccentricity</td>
<td>0.0430316</td>
</tr>
<tr>
<td>P, Orbital Period</td>
<td>14.79 years</td>
</tr>
<tr>
<td>n, Mean Daily Motion</td>
<td>0.06662625°/day</td>
</tr>
</tbody>
</table>

1.2.2 Activity of SW1

SW1’s activity patterns are unique among the JFCs and Centaur populations, especially in context with its orbital properties. To begin, SW1 is characterized by a nearly continuous, moderately-variable activity outside of the region of efficient water-sublimation. The majority of observed comets experience an appreciable change in activity around this canonical 3-AU water-sublimation line due to the activation or cessation of water-ice sublimation. As mentioned earlier the bulk composition of cometary volatile material is theorized to be mostly water ice, which has been observationally supported by numerous remote-sensing and spacecraft-visited in-situ measurements. Thus the ∼3-AU activation region for cometary activity makes sense. Of course there are the usual exceptions to the rules, with SW1 being a good example of cometary activity outside of the region dominated by water-ice sublimation. This distant cometary activity raises the question as to what is(are) their source(s) of activity? Does SW1 contain higher concentrations of supervolatile species (e.g. CO and CO$_2$), or, does it contain near-surface amorphous water ice whose amorphous-to-crystalline phase transition potentially releases supervolatile gas species trapped
in the amorphous water ice pore structure? This fundamental compositional difference between comets observed to be active and not be active outside the water-sublimation line is of interest to our understanding of early SS formation models. Does the compositional difference originate from the time of cometesimal accretion or is it the result of material evolution during different orbital or collisional histories between individual cometary nuclei? A better understanding of SW1’s distant activity is useful for helping to address the questions posed in Section 1.1.3.3 relating to the distantly active comets, which for various reasons (most importantly their smaller nucleus size and smaller total amount of activity) are more challenging to observe.

Figure 1.6: Plot showing CO-production rate measurements of SW1 from the literature (Senay & Jewitt 1994; Crovisier et al. 1995; Graham & Womack 1995; Festou et al. 2001; Gunnarsson et al. 2008; Paganini et al. 2013; Womack et al. 2017). All production rates are from measurements of the CO $J = 2 - 1$ transition at 230 GHz except for the Paganini et al. (2013) measurement which is based on infrared observations.
It was observationally determined through mm-wavelength observations of the CO $J = 2 − 1$ rotational transition at 230 GHz that SW1’s nearly continuous activity, often called its quiescent activity, is driven primarily by the release of CO from its nucleus (Senay & Jewitt 1994), but the mechanism(s) of releasing a large amount of CO gas has(have) not been definitively established. Infrared spectroscopy of CO in SW1’s quiescent coma established that CO is the parent molecule driving the activity and the inner CO coma’s temperature is $\sim 5$ K (Paganini et al. 2011). CO-production rate measurements have been consistently made over the past two decades, with Figure 1.6 showing published CO-production rate measurements to date Senay & Jewitt 1994; Crovisier et al. 1995; Graham & Womack 1995; Festou et al. 2001; Gunnarsson et al. 2008; Paganini et al. 2013; Womack et al. 2017). Variations in the reported CO-production rates could be the result of activity variability, but they also could represent scatter in measurements due to different model techniques used between the groups publishing production rates. The rates published by Womack et al. (2017) represent a set of published rates using consistent modeling assumptions that show scatter on the same order of magnitude seen between measurements made from the different groups, which supports the claim that variability in measurements is reflective of inherent activity variability for SW1. Surface temperatures calculated to be present on SW1 using simple surface boundary-condition thermal models (e.g. Chapter 2) are too high for the existence of CO on or near the surface to drive activity. Recent modeling efforts suggest the CO coma is the result of gas released from the pores of amorphous water ice during the exothermic amorphous-to-crystalline phase transition (Womack et al. 2017). More modeling and analysis is necessary to conclusively determine the true nature of SW1’s activity driver(s).

There have been limited numbers of detections for other neutral gas species in the coma of SW1: H$_2$O was detected at a rate of $6.3 \times 10^{27}$ molecules/second at $R_H = 6.2$ AU (Ootsubo et al. 2012) and CN was detected with a production rate of $8.0 \times 10^{24}$ molecules/second at $R_H = 5.8$ AU (Cochran & Cochran 1991). The detection of HCN from the *Herschel Space Observatory* has
been reported as an Asteroids, Comets, Meteors 2014 meeting abstract (Bockelee-Morvan et al. 2014), but no production rates have been published to date in the literature from this detection. CO$_2$ has not been detected, but there is an upper-limit estimate from the Akari Space Observatory of $< 0.35 \times 10^{27}$ molecules/second (Ootsubo et al. 2012) and observations from the Spitzer Space Telescope which did not detect any CO$_2$ emission (Woodney et al. 2008). The CO$^+$ ion has been detected since the early 1980s (Cochran et al. 1982), with recent measurements of the $[\text{N}_2^+] / [\text{CO}^+] = 0.01$ ion-production rate ratio indicating a cold ($\sim 25$ K) formation region for SW1 (Ivanova et al. 2018).

Gas production rates for other distantly active comets and Centaurs ($R_H > 5.0$ AU) are limited due to their large heliocentric and geocentric distances combined with limitations inherent to currently available observatories. For example, there are CO-production rate measurements in the literature for only three other objects at similar distance as SW1: 2060 Chiron, 60558 Echeclus, and comet Hale-Bopp (Drahos et al. 2017; Womack et al. 2017; Weirzychos et al. 2017). Gaining compositional mass fraction measurements for more bodies in this distant population is necessary if we want to investigate for statistically significant trends in this populations and what information it may reveal about nuclei compositions.

Another interesting component of SW1 involves its quiescent activity being punctuated by short-term increases in dust activity. These episodic, possibly quasi-periodic events called outbursts, result in dust-production rate increases typically of several orders of magnitude (Trigo-Rodriguez et al. 2010; Kossacki and Szutowicz 2013; Gronkowski 2014; Miles et al. 2016a). The exact length of time for the increased nucleus activity (i.e. outburst duration) is unknown, but the ejected dust coma often persists for several days to possibly weeks. Figure 1.7 shows a sample of SW1’s magnitude measurements for the time period between 2008 and 2018 acquired from the IAU Minor Planet Center. The magnitude measured is directly linked to the cross-sections of dust grains present in the coma during the time of observations. The CO-production rate measurements shown
in Figure 1.6 display scatter, but it is uncertain whether the variability seen is representative of CO-production rates during quiescent and outburst phases of activity or if the scatter in CO-production rates is representative of the variability in CO-production rates inherent during the quiescent activity alone. The outburst nature of SW1’s activity raises the question: with a seemingly stable thermal environment due to the low eccentricity orbit why would the nucleus experience frequent excursions from a steady state of activity?

Figure 1.7: Photometry of SW1 highlighting its activity variability. The plot shows reported nucleus photometry values obtained from the IAU Minor Planet Center from 2008 through April 2018. For comparison, the red line represents the photometric behavior of SW1 assuming an insolation driven activity and corrections for changes in geocentric distance. SW1’s activity is seen to be consistently variable during the ten years included in the plot, with reported magnitudes ranging between (11, 18.8).
1.2.3 SW1 Nucleus Properties

A historical account of nucleus properties (e.g. nucleus size, surface roughness, thermal inertia, and nucleus spin state) for SW1 will be introduced in Chapters 2 and 3 of this dissertation.

1.3 Dissertation Outline

The unique properties of SW1 described in this introductory chapter highlight why it is an excellent target for continued investigation. The remainder of this dissertation describes a research project with the goal of a better understanding of what causes the enigmatic activity of SW1 through a thermophysical modeling effort of its nucleus. While the final understanding of “what drives SW1’s quiescent and outburst activity” isn’t answered with this dissertation, this work sets the stage for future efforts to gain a deeper understanding of SW1, and in the process a better understanding of other distantly active small bodies.

The outline of this dissertation is as follows: Chapter 2 contains details of an analysis of Spitzer Space Telescope observations of SW1, measuring properties of SW1’s nucleus. We discuss details of constraining the nucleus’ spin state through analysis of coma morphology in Chapter 3. Two sets of SW1 outburst dust-coma observations were modeled with a 3-D Monte Carlo coma modeling routine to place constraints on the nucleus’ spin state. Chapter 4 includes details of thermophysical modeling of SW1’s nucleus to establish activity drivers for both the quiescent and outburst activity. And, finally, in Chapter 5 I describe possibilities for future research efforts to better understand SW1.
As mentioned in Chapter 1, knowledge of a comet nucleus’ size is important for nucleus thermophysical modeling. Measuring nuclear properties of active comets is hindered by the presence of emission from the gas and dust contained in the coma. For an accurate assessment of the thermal radiation emitted by SW1’s nucleus, allowing measurements on the nucleus’ size, the coma flux must be modeled and removed. This process is one of painstakingly and meticulously comparing the residuals of an image, with a model coma removed, to a point-spread function (PSF) of the optical system used for the observations. It should be pointed out that for most comet observations, the nucleus is unresolvable in the image and its contribution to the image is a PSF. Thus, using a scaled PSF as a measure for the flux contribution is warranted. The software used for this modeling was developed by Fernández (1999) and is based on the technique described by Lamy and Toth (1995) and used many times since then (e.g., Lamy et al. 2006, 2011; Fernández 1999, 2013; Kelley et al. 2013), in particular, to correctly predict the sizes of nuclei before their flyby by spacecraft (Lamy et al. 1998; Fernández et al. 2003; Lisse et al. 2009).

The size distribution of the Centaur population is still an area of ongoing research and is not well-determined. Due to their large heliocentric distances, size measurements are challenging. A radius range of 0.89 km to 230.5 km has been observed for Centaurs by Bauer et al. (2013) using infrared observations from the WISE spacecraft and a range of 2 km to 41 km has been observed for Centaurs showing activity by Jewitt (2009) using optical observations, assuming a geometric albedo of $p_R = 0.1$. The first discovered Centaur 2060 Chiron has a $210^{+11}_{-10}$ km diameter (Fornasier et al. 2013). Where does SW1 lie in this distribution? Several groups past and present have studied SW1 in order to measure properties of the comet’s nucleus. Due to the continuous activity of SW1 producing a persistent coma, direct measurements of the nucleus are currently unattainable. Further, observational measurements of SW1 are hindered by its large heliocentric
distance. Radius measurements of SW1 show a large range: 20.0 ± 3.0 km (Cruikshank & Brown 1983), 8.6 ± 0.1 km (Meech et al. 1993), 27.0 ± 5.0 km (Stansberry et al. 2004), 18.7^{+5.7}_{-5.9} km (Stansberry et al. 2008), and 23± 6.5 km (Bauer et al. 2013). This large spread of radius values shows our lack of knowledge of basic physical properties of SW1’s nucleus.

Using Spitzer thermal images we have made an attempt at constraining the nucleus’ effective radius, infrared beaming parameter, and albedo. This is a reanalysis of Spitzer data used by Stansberry et al. (2004; 2008) for their estimates. The work presented here uses a more careful method of accounting for coma flux measurements and their removal from images for nucleus photometry measurements. The organization of this chapter is as follows: Section 2.1 gives an overview of the 2003 Spitzer observations of SW1. The coma modeling and removal procedure is described in Section 2.2, along with an application of a Near Earth Asteroid Thermal Model (NEATM, Harris 1998) to the extracted nuclear infrared photometry measurements described in Section 2.3. Section 2.4 shows improvements to the initial NEATM with the inclusion of IRS Blue Peak-Up observations. The chapter is concluded in Section 2.5 with an overview of the results and their implications on the thermal evolution experienced during the dynamical evolution of SW1.

2.1 Spitzer Observations of SW1

The work presented in this section was previously published as “A new analysis of Spitzer observations of Comet 29P/Schwassmann-Wachmann 1” by Schambeau et al. in Icarus, 260, pp. 60-72.

Spitzer observations of SW1 were acquired on UT 2003 November 21, 23, and 24 during the In-Orbit Checkout (IOC)/Science Verification (SV) period (Werner et al. 2004). Table 2.1 gives the details of each set of observations (similar to Table 2 from Stansberry et al. 2004). All three
instruments on Spitzer were used for the observations: Infrared Array Camera (IRAC) (Fazio et al. 2004), Infrared Spectrograph (IRS) (Houck et al. 2004), and Multi-band Imaging Photometer for Spitzer (MIPS) (Rieke et al. 2004).

Table 2.1

<table>
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<th>Instrument</th>
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<th>Epoch</th>
<th>Band</th>
<th>$t_{\text{exposure}}$</th>
<th>$\Delta$</th>
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<tr>
<td>IRS</td>
<td>6068992</td>
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<td>SL1 (7.4-15.4 $\mu$m)</td>
<td>122</td>
<td>5.54</td>
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<td>70.0</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Unique integer number that identifies a Spitzer Astronomical Observation Request (AOR).
$^b$ Day of 2003 November, UT at beginning of observations.
$^c$ Imaging wavelength ($\mu$m) or spectral band.
$^d$ Total exposure time per pixel for each image frame, seconds.
$^e$ SW1–Spitzer distance (AU). Heliocentric distance was 5.73 AU, solar phase angle was 10.0° and the tracking rate was 8".6 hr$^{-1}$.

2.1.1 IRAC

The Infrared Array Camera (IRAC) is a multi-channel infrared camera capable of imaging in 3.6, 4.5, 5.8 and 8.0 $\mu$m bands. A detailed description of the IRAC can be found in the IRAC Handbook (IRAC Instrument and Instrument Support Teams 2013). Each band images a field of view (FOV) of $5.2' \times 5.2'$ and a pixel scale of 1.2"/pixel.
Figure 2.1: (a) 5.8 $\mu$m and (b) 8.0 $\mu$m combined and calibrated images centered on SW1. Each has a FOV of $1.01' \times 1.01'$ and equatorial north is up and east is to the left. The solar direction is identified by the yellow arrow and SW1’s skyplane projected heliocentric velocity by the red arrow. The scale bar at the bottom right of (a) shows a distance of 20'' and the circle in the top left of the images represents the size of the PSF’s first minimum. A star’s diffraction spike artifact is clearly seen in the 5.8 $\mu$m image and partially visible in the 8.0 $\mu$m image.

The IRAC was used in high dynamic range (HDR) mode during the observations. Unfortunately, a star was close to SW1 in the FOV producing a diffraction spike in the images. This rendered the 3.6 $\mu$m and 4.5 $\mu$m observations useless other than to acquire upper limit photometry. Of importance is the identification of SW1 in the 5.8 $\mu$m band, which had not been used in the previous analysis (Stansberry et al. 2004). The 5.8 and 8.0 $\mu$m observations entailed acquiring five 30 second exposures of SW1. The software MOPEX (MOsaicking and Point-source EXtraction, Makovoz et al. 2012) was used to calibrate and stack the basic calibrated data images (BCDs) acquired from the Spitzer Heritage Archive, generated from version S18.25.0 of the Spitzer pipeline. The final stacked, calibrated, and cropped 5.8 $\mu$m and 8.0 $\mu$m images are shown in Figure 2.1. Each image has an effective exposure time of 150 seconds.
In the 5.8 $\mu$m image, SW1 was identified close to the mentioned diffraction spike. A broad diffuse coma was not observed in this band. On the other hand the 8.0 $\mu$m image shows traces of a diffuse extended coma in the northeast and southeast region of the image. The diffraction spike is also in this region, but was suppressed using correction techniques described in the IRAC Handbook.

2.1.2 IRS

Spectra of SW1 were obtained with the IRS operating in the Long-Low order 1 (LL1: 19.5-38.0 $\mu$m), Long-Low order 2 (LL2: 14.0-21.3 $\mu$m), and Short-Low order 1 (SL1: 7.4-14.5 $\mu$m). The analysis of IRS spectra was performed by a collaborator and is not included in this dissertation. The reader is referred to Schambeau et al. (2015) for details of the analysis.

2.1.3 MIPS

The Multiband Imaging Photometer for Spitzer (MIPS) is an infrared imager with 24.0, 70.0, and 160.0 $\mu$m bands. A detailed summary of MIPS can be found in the MIPS handbook available through the Spitzer Heritage Archive (MIPS Instrument and Instrument Teams 2011). SW1 was observed in all three bands, but only recovered in the 24.0 $\mu$m and 70.0 $\mu$m images. Observations with MIPS involved scanning a large region around SW1, which resulted in most pixels in the mosaic having an $\sim$66 second exposure for the 24.0 $\mu$m and $\sim$40 second exposure for the 70.0 $\mu$m image. These images, after MOPEX mosaicking and calibration, can be seen in Figure 2.2, each having an 8.0'$\times$8.0' FOV. Figure 2.3(a) shows the full 24 $\mu$m mosaic of SW1 along with intensity contours showing the coma shape and structure. This figure can be related to Stansberry et al. (2004) Figure 1, but we have oriented the images with Equatorial North up as opposed to Ecliptic North. Also, Figure 2.3(b) shows the 24 $\mu$m image with a $1/\rho$ profile removed ($\rho$ is the skyplane projected cometocentric distance) similar to Figure 2 in Stansberry et al. (2004).
MIPS mosaicked images are notorious for image artifacts in the final MOPEX generated mosaic. Each of these image artifacts are described in detail in the MIPS handbook, along with correction algorithms to mitigate their impact on the final mosaic. Processing for the 24 $\mu$m image involved applying a median time filter per pixel, which removed the long lived dark latent artifacts caused by sources with brightness greater than 50 Jy being imaged after the last array annealing, but before the SW1 observations. The 70 $\mu$m image suffered from artifacts resulting from slow response variations on the array leading to streaks and stim latents due to the stim flashes used to measure the slow response of the array. Two correction algorithms were implemented on the Basic Calibrated Data (BCD) before mosaicking which improved the quality of the final image: high-pass median time filter per pixel and column median value subtraction. Traces of a “jail-bar” artifact can still be seen in Figure 2.2(b).
Figure 2.3: (a) 24 µm MIPS mosaic of SW1 showing contours to highlight the coma and tail shape. The mosaicked image has dimensions of (17' × 52'). The contour levels of the image are 0.2, 0.5, 1.0, 2.5, 5.0 and 10.0 MJy/sr. (b) 1/ρ removed 24.0 µm image similar to Stansberry et al. (2004) Figure 2 (lower left) panel, which shows enhancement in the south-east region produced by the single jet observed in the 2004 analysis. It should be noted that this jet-like feature is due to solar radiation pressure and not from rotation as was previously believed (Stansberry et al. 2004).

2.2 Coma Removal and Nucleus Photometry

2.2.1 IRAC

The modeling and removal of the coma from a comet’s image is not a straightforward procedure or “one size fits all” technique that can be applied to comet observations. Each image must be analyzed to determine a modeling and removal method best suited for a successful point source
extraction. Two modeling techniques were found to be necessary for the Spitzer images: a scaling of a system PSF for the 5.8 \(\mu\)m and 8.0 \(\mu\)m images and a more complex coma modeling routine for the 24.0 \(\mu\)m and 70.0 \(\mu\)m bands. Each method will be described in detail in the following paragraphs. Both have been tested with synthetic comet images to verify coma removal capabilities.

For the 5.8 \(\mu\)m and 8.0 \(\mu\)m images, shown in Figure 2.1, there was not sufficient flux from the coma to produce a usable coma model. In addition, the removal of the diffraction spike from the images resulted in an artifact that interfered with any coma flux present. This method involved first finding the pixel location of the comet’s centroid and choosing this to be the location of the nucleus. Next, a PSF was centered on this location and scaled to match the level of the comet’s flux. Initially, a PSF generated from the program STINYTIM (Krist 2006) was used for this procedure, but it was found that this PSF did not represent well the structure observed in the comet’s image or field stars also in the image. One of the field stars from each band, sufficiently distant from the diffraction spike, was used to represent the PSF. SW1 was moving slow enough during each image’s exposure that the projected distance traveled was less than a pixel, which was approximately 4800 km/pixel.

Once the PSF was scaled it was subtracted from the comet image, resulting in what should be only flux from the coma and background. A best-fit PSF was taken to be one that minimized the standard deviation of the residual of pixels from a region centered on the comet’s centroid. For the 5.8 \(\mu\)m image there was not much coma and the diffraction spike also presented a problem so this was the best approach found to measure the nuclear flux. This scaled PSF was then taken to represent the nucleus’ contribution to the image flux and used for photometry measurements. Figure 2.4 shows radial profiles of the 5.8 \(\mu\)m comet image and scaled PSF for a selection of azimuthal angles. Figure 2.5 shows the 5.8 \(\mu\)m comet image, scaled PSF image, and residuals after PSF subtraction. Similarly, Figures 2.6 and 2.7 are for the 8.0 \(\mu\)m image.
Figure 2.4: Radial cross-section of the 5.8 µm image showing the scaled PSF. The angular descriptor indicates the position angle of the radial cross-section. The coma and artifact contributions to the images can be seen in the comet profiles. Note that there is not much coma in the core.
Figure 2.5: The (a) 5.8 µm comet image, (b) the scaled PSF, and (c) the residual after PSF subtraction.
Figure 2.6: Radial cross-section of the 8.0 µm image showing the scaled PSF. The angular descriptor indicates the position angle of the radial cross-section. Note there is not much coma present in the core.
Figure 2.7: The (a) 8.0 µm comet image, (b) the scaled PSF, and (c) the residual after PSF subtraction. Notice in (c) there is an over subtraction to the south of the centroid and under subtraction to the north of the centroid. This can be attributed to asymmetry in the star generated PSF and SW1 nucleus image.
The 24.0 $\mu$m and 70.0 $\mu$m images had sufficient coma present for a more elaborate coma modeling routine to be implemented on these images (Lamy et al. 2004; Lisse et al. 2009; Fernández 1999). The procedure for this method is to first take azimuthal pie sections of the comet image, centered on the comet’s centroid. Radial profiles of each pie section are generated. The angular width of the sections was a variable for the procedure and was selected independently for each image. The S/N of the image determined the minimum angular spread usable, with smaller angles being desired for higher fidelity in the model coma. Again, since the nucleus is unresolvable to Spitzer at this distance it will only contribute flux in the region of the PSF. In theory, the nucleus should only image as a PSF on the image plane. Thus, any flux present outside of the region of the PSF should be contributions from the coma and background. An example of these radial profiles from both the 24.0 $\mu$m and 70.0 $\mu$m image and their corresponding PSFs can be seen in Figures 2.8 and 2.10. If regions radially distant from the nucleus (regions outside the dominance of the PSF) are chosen, a coma model of the form $A(\theta)/\rho^n(\theta)$ can be fit to the profiles, generating a synthetic coma. In the equation $A$ is a scaling of the profile which is function of the position angle $\theta$ (PA), $n$ is the slope of the coma in the pie section used for the radial profile. This procedure was implemented on each of the azimuthal pie section producing the synthetic coma model shown in Figure 2.9(b) for the 24.0 $\mu$m band and Figure 2.11(b) for the 70.0 $\mu$m band. The coma model is then subtracted from the comet image yielding the PSF’s contribution to the image. A comparison of the residual PSF and an STINYTIM-generated PSF is shown in Figures 2.9(c), 2.9(d), 2.11(c), and 2.11(d). Close inspection of the two shows a high degree of similarity (the first order bright fringe as an example), giving a level of validation to our modeling technique.

Once the coma was successfully removed from the images, photometry was used to measure the spectral flux density in each of the four observational bands. Since the coma removal process...
resulted in a scaled PSF representing the contribution to the spectral flux density from the nucleus, no aperture correction was needed for the photometry. Table 2.2 shows the photometry results after the application of color corrections. Uncertainties in the spectral flux density measurements are derived from analysis of the distribution of flux measurements from the many coma models for each band. The procedure to arrive at the best-fit coma model involved varying parameter space of the model (centroid pixel location, angular size of the azimuthal pie section, size in pixels of the radial region used for fitting, center position of the radial bin of pixels) and observing how this minimized the standard deviation of the central pixels around the nucleus’ location in the residual image after coma removal for the case of the 24.0 $\mu$m and 70.0 $\mu$m images and the scaled PSF subtraction for the 5.8 $\mu$m and 8.0 $\mu$m images. Each of these coma models was stored and the resulting residuals from each model was measured for the nucleus’ contribution to the spectral flux density of the image. The distribution of the flux measurements from the many coma models that we tried for each band was used to derive uncertainties for the photometric measurements. We varied the parameter space of the model (centroid pixel location, angular size of the azimuthal pie section, and radial region used for coma slope fitting) so as to determine how a model’s fit for the nucleus photometry depended on these input parameter assumptions. The scatter in the nucleus photometry was used to derive the uncertainties we list for the nucleus in Table 2.2.

With the nuclear photometry measured, the spectral flux density measurements for a 9″.0 radius aperture of the coma’s contributions were found for each of the IRAC and MIPS bands. These values can also be seen in Table 2.2. These values were found by subtracting the nuclear flux values from each image and then performing aperture photometry on the residual coma flux. The overall comet (coma + nucleus) photometry is well constrained, and the error bar for the coma is driven almost entirely by the error bar on the nucleus measurement.
Figure 2.8: Shown are radial profiles of the 24.0 \( \mu \text{m} \) comet image, STINYTIM PSF, and synthetic coma model. The PSF effectively goes to zero at a certain radial position which can be seen to be around 30 pixels. Comet flux beyond this region was used for the fitting procedure. Extrapolation of the coma model to the center shows the excess contribution to the comet image attributed to the nucleus.
Figure 2.9: (a) 24 $\mu$m comet image, (b) the synthetic coma model, (c) the residual after model coma removal, and (d) the STINYTIM 24 $\mu$m PSF. Notice the asymmetry seen in the comet image is modeled well in the coma. Also, the residual nucleus contribution has many features similar to the optical system PSF, indicating a good coma removal.
Figure 2.10: Shown are radial profiles of the 70.0 $\mu$m comet image, STINYTIM PSF, and synthetic coma model, similar to the 24.0 $\mu$m profiles in Figure 2.8.
Figure 2.11: (a) 70 μm comet image, (b) the synthetic coma model, (c) the residual after model coma removal, and (d) the STINYTIM 70 μm PSF.
<table>
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<tr>
<th>Band (µm)</th>
<th>Coma Spectral Flux Density\textsuperscript{a} (mJy)</th>
<th>Nucleus Spectral Flux Density\textsuperscript{a} (mJy)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(9'') 0 Radius Aperture</td>
<td></td>
</tr>
<tr>
<td>5.8</td>
<td>((1.51 \pm 0.07))\textsuperscript{b}</td>
<td>(0.32 \pm 0.07)</td>
</tr>
<tr>
<td>8.0</td>
<td>(1.8 \pm 1.7)</td>
<td>(4.6 \pm 1.7)</td>
</tr>
<tr>
<td>24.0</td>
<td>(176.4 \pm 13.4)</td>
<td>(199.8 \pm 13.4)</td>
</tr>
<tr>
<td>70.0</td>
<td>(39.0 \pm 28.3)</td>
<td>(175.4 \pm 28.3)</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Color corrections for spectral flux density measurements were calculated from methods described in the IRAC and MIPS handbooks.

\textsuperscript{b} The 5.8 µm coma photometry measurement is most likely contaminated by presence of the diffraction spike, leading to the higher measurement than the 5.8 µm nucleus photometry measurement.
2.3 Thermal modeling

The Near Earth Asteroid Thermal Model (NEATM, Harris 1998) is an improvement of the Standard Thermal Model (STM) in its applicability to many small bodies since it treats phase darkening in probably a more realistic way and since it lets the beaming parameter float as a free parameter. This model has been applied to many minor bodies (Mainzer et al. 2011; Delbo et al. 2011) and was applied to the Spitzer photometry measurements, returning values for the effective radius \( R \), IR beaming parameter \( \eta \), and geometric albedo \( p_{5.8} \). The IR beaming parameter is used as a fitting parameter in the NEATM, with a value of \( \eta = 1 \) applying for a perfectly memory-less, spherical surface with modest topography. Values of \( \eta > 1.0 \) imply lower surface temperatures than what would be observed for the ideal situation possibly caused by thermal communications between the day and night sides of the object. Topography and surface roughness can be inferred from values of \( \eta < 1.0 \). This is due to the observed surface temperature being higher than what would be observed from strictly applying the STM. Excess thermal flux can be thought to arise from emission from bowl shaped craters, where emission from the sides of the crater is absorbed at the bottom of the crater. This additional flux results in an increase in the equilibrium surface temperature when compared to the STM temperature. The beaming parameter is a way to adjust the equilibrium surface temperature distribution of the object and have it match the color temperature of the object’s observations.

The 5.8 \( \mu \text{m} \) photometry value is too high to be explained by thermal emission alone. Inclusion of a reflected light component, i.e. a scaled solar spectrum, into our model however explained the 5.8 \( \mu \text{m} \) flux. This is what would have let us constrain the V-band albedo \( p_v \), in principle, although it turned out that the uncertainties were too great for a meaningful result for \( p_v \). Our best fit model (using \( \chi^2 \) minimization), making use of both thermal and reflected components, yielded \( R = 30.2_{-3.7}^{+2.9} \) km, \( \eta = 0.99_{-0.26}^{+0.19} \), and \( p_{5.8} = 0.5 \pm 0.5 \). Figure 2.12 shows the measured spectral flux density.
values, NEATM + Reflected curves, and best-fit spectral flux density values. Other parameters necessary for the thermal modeling are: bolometric bond albedo $A = 0.012$ (assuming a visible-wavelength geometrical albedo $p = 0.04$ and phase integral relation $q = 0.290 + 0.684G$, Harris & Lagerros 2002), emissivity $\epsilon = 0.95$, and slope parameter $G = 0.05$ (the same assumptions made by Fernández et al. 2013 in their Spitzer survey of cometary nuclei).

Figure 2.12: Shown are the photometry measurements from Spitzer observations. Curves shown are of the NEATM fit to the measurements and reflected solar flux. 1-$\sigma$ error bars are included on the spectral flux density measurements.
2.4 Inclusion of *Spitzer* Blue Peak-Up Images

Shortly after the publication in *Icarus* of the analysis described in the previous section (Schambeau et al. 2015) it was noticed that there existed *Spitzer* Blue Peak-Up Images of SW1 from the 2003 set of IRS observations. This gave another potential nucleus photometry value at a wavelength of 16.0$\mu$m which could be included into the NEATM analysis. In this section we briefly describe a similar analysis of the additional image and results of a new NEATM.

2.4.1 Observations

During the IRS observations, Blue Peak-up observations were taken to center the comet’s position on the detector’s “sweet spot”. A total of six independent blue peak-up observations were taken; three images with the comet located at the center of the detector and three at the detector’s sweet spot. The six images are shown in Figure 2.13 and an observational summary is given in Table 2.3.

<table>
<thead>
<tr>
<th>Observations Start (UT)</th>
<th>Observations End (UT)</th>
<th>AORKEY</th>
<th>Phase Angle (deg)</th>
<th>$[R_h, \Delta]^a$ (AU)</th>
<th>Expo. Time$^b$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>07:15:32.960</td>
<td>07:17:22.849</td>
<td>6068992</td>
<td>10.05</td>
<td>[5.73, 5.54]</td>
<td>9.44</td>
</tr>
</tbody>
</table>

$^a$ SW1’s heliocentric distance and Spitzer range during each observation (Horizons, JPL).
$^b$ Spitzer blue peak-up detector integration time for each image frame.
Figure 2.13: The six Spitzer Blue Peak-up observations used for coma modeling and removal. The corresponding times for the start of each image’s data collection on UT 2003-11-23 are as follows: (a) 07:15:32.960, (b) 07:15:48.679, (c) 07:16:04.409, (d) 07:16:41.960, (e) 07:16:57.682, and (f) 07:17:13.409. Each image had a data collection time of 9.44 seconds. Images (a)-(c) correspond to SW1’s location on the detector immediately after telescope target acquisition and (d)-(f) correspond to SW1’s position being positioned on the blue peak-up detector’s “sweet spot”. The images have been rotated such that equatorial north is up and east is to the left, indicated by the white arrows. The Sun’s projected direction is indicated by the yellow arrow and the projected direction of motion of SW1 is indicated by the red arrow. A scale bar shows a sky-plane projected distance of 100,000 km at the distance of SW1 during the observations. Significant amounts of coma are present primarily in the south-east directions. This coma morphology was also seen in the Spitzer MIPS 24.0 µm observations (see Figure 2.3).
2.4.2 Image Analysis

To obtain nucleus photometry measurements from the peak-up observations the flux from the comet’s coma must be measured and removed. This procedure was accomplished through the same methods described in Section 2.2.

2.4.2.1 PSF of the observations

The IRS Blue Peak-Up Imager has pixels that are approximately the same size as a $\sim 16.0\mu m$ PSF full width at half maximum (FWHM). Thus, the location of the PSF’s central peak on the detector has a significant impact on the intensity distribution of pixel values surrounding the peak PSF pixel location. Images of point sources which are centered on different locations of an individual pixel area can have significantly different resultant PSF shapes when the binning from the detector takes place. To generate the correct PSF for each individual Blue Peak-Up image a subsampled Point Response Function (PRF) was generated by STINYTIM. For the PRFs used in this modeling each PSF pixel was divided into 10 sub-pixels. The brightest PRF pixel value was shifted to different locations and binned to the pixel scale of the PSF. This binning of the PRF to the PSF pixel scale modeled bright sources offset from the center of the detectors pixels. Each of the six images had a different resulting PSF which was used for the coma removal process.

2.4.2.2 Coma Modeling and Removal, Nucleus Photometry, and Nucleus Thermal Modeling

The coma modeling and removal was done in a similar manner to that described in Section 2.2. Each of the six blue peak-up images was modeled, resulting in a synthetic coma model which was subtracted from the observation. Figure 2.14 an example of this process for one of the six images. The presence of the first Airy diffraction minimum in Figure 2.14(c) indicated the quality of the
coma modeling and removal.

The scaled PSF, which resulted from the coma modeling and removal, was used for nucleus photometry at 16.0 $\mu$m. We applied a color correction to each of the six individual photometry measurements. The final measurement was taken as the average of spectral flux density measurements and its standard deviation as the final measurement’s 1-$\sigma$ uncertainty: $86 \pm 7$ mJy for the 16.0 $\mu$m detection.

We next proceeded to incorporate this new, fifth infrared spectral flux density measurement into our previous analysis which included only four photometry measurements at different wavelengths. Figure 2.15 (top panel) shows the new 16.0 $\mu$m measurement plotted onto of the previous NEATM model. The value is in agreement with the previous NEATM. We also proceeded to apply a new NEATM model using five spectral flux density measurements and the results of this model are shown in 2.15 (bottom panel). The new model resulted in slightly larger values for both SW1’s radius and also its beaming parameter. The new values are in agreement with the previous modeled values within their 1-$\sigma$ uncertainties.
Figure 2.14: Shown are a series of images demonstrating the coma modeling and removal for the observations corresponding to Figure 2.13. The four images are cropped to a 36x36 pixel size and are as follows: (a) the blue peak-up comet observation, (b) a best-fit coma model, (c) a difference image representing the subtraction of the coma model from the comet image, and (d) a scaled STINYTIM generated PSF. Similarity between the difference image and the scaled PSF are pronounced. Each of the six scaled PSFs was used for a nucleus photometry measurement. Note the orientation of the four panels is not the same as Figure 2.13, but is the orientation of the output from the Spitzer data processing pipeline for the Blue Peak-up observations shown by the axes in the center of the figure.
Figure 2.15: Top panel: The Spitzer Blue Peak-up nucleus photometry value is plotted along with the spectral flux density values from our earlier analysis (Schambeau et al. 2015) and a NEATM from the earlier four spectral flux density measurements. Bottom Panel: Shown are the five spectral flux density measurements acquired from the 2003 November Spitzer observations along with a new NEATM incorporating the five values. New measurements for the nucleus’ effective radius and beaming were found from the modeling and are consistent with an earlier analysis (Figure 2.12), see Section 2.3.
2.5 Conclusions and Discussion

The reanalysis of archival *Spitzer* thermal observations of SW1 has led to new measurements of physical properties of the nucleus. The effective radius measurement of $R = 32.3 \pm 3.1$ km is within the 1-$\sigma$ uncertainties of several recent measurements (Stansberry et al. 2004; Stansberry et al. 2008), signifying a possible honing of the nuclear size measurement. It is emphasized that the choice of a geometric albedo $p_V = 0.04$ does not have much of an effect on the radius derived from thermal photometry. Using any realistic $p_V$ value only alters the resulting radius at the 0.1-km level or less, which is in the noise of the overall error bar. The size of SW1 places it on the larger end of the Centaur size distribution. Considering the activity levels of SW1 at such a large heliocentric distance (e.g. Paganini et al. 2013) signifies a large supply of volatile material. If the orbit ever gets perturbed sending SW1 into the inner solar system it most likely will be an impressive sight.

An infrared beaming parameter of $\eta = 1.14 \pm 0.22$ is near the middle of the $\eta$ distribution for other Centaurs. A collection of IR beaming parameter measurements for a database of 57 Jupiter family comets (JFC), 58 Centaurs, and 75 trans-Neptunian objects (TNO) (Bauer et al. 2013; Duffard et al. 2014; Fernández et al. 2013; Fornasier et al. 2013; Lellouch et al. 2013; Mommert et al. 2012; Pál et al. 2012; Santos-Sanz et al. 2012; Stansberry et al. 2008; Vilenius et al. 2012) is shown in Figure 2.16. The SW1 measurement is highlighted by a vertical bar on the histograms. The measured value of $\eta = 1.14$ for SW1 is towards the middle of each of the three small-body populations, as shown an in Figure 2.16. A value of $\eta = 1.14$ for SW1 could signify a surface with no radical topography (i.e. no high temperature regions causing infrared beaming). Alternatively, SW1 could have a low thermal inertia, resulting in little or no night side emission.

While our size measurement is within uncertainties of several previous measurements, the infrared beaming parameter of each analysis is considerably different. Stansberry et al. (2004) used a value of $\eta = 0.62$. If we use their measured spectral flux density values, a fixed $\eta = 0.99$ value, and our
model we arrive at a best fit radius value of 28.6 km. Unfortunately, a reduced $\chi^2 = 17.53$ signifies a poor modeling fit. This fit can be seen in Figure 2.17(a). A similar analysis was performed on the Stansberry et al. (2008) spectral flux density measurements. A best-fit radius value of $R = 26.8$ km was found with a smaller reduced $\chi^2 = 4.75$ value. This fit can be seen in Figure 2.17(b).

Figure 2.16: Histograms of measured beaming parameters from current journal articles (see conclusion for list of beaming parameter sources). The vertical bar in each plot signifies our measured value of $\eta = 1.14$ for SW1. The left plot shows the distribution of 57 JFC and SW1’s measured value is towards the mean of the distribution. All JFC $\eta$ values were acquired from Spitzer observations in SEPPCoN (Survey of the Ensemble Physical Properties of Cometary Nuclei) Fernandez et al. (2013). The middle plot shows SW1’s placement in the ensemble of $\eta$ values for 58 Centaurs. Again SW1’s measured value places it towards the middle of the distribution. Histogram colors represent the telescope used for observations (blue:Spitzer (Fernández et al. 2013; Stansberry et al. 2008); green:WISE (Bauer et al. 2013); red:Herschel (Duffard et al. 2014; Fornasier et al. 2013; Lellouch et al. 2013; Mommert et al. 2012; Pál et al. 2012; Santos-Sanz et al. 2012; Vilenius et al. 2012)). Plot to the right is similar, but with SW1’s placement in the distribution of measured TNO $\eta$ values. Again SW1’s measured value is towards the center of the distribution.
These values are shown to not undervalue previous measurements, but to emphasize the robustness in the measurements found in this analysis. Using archival Spitzer data products and newer more robust coma removal techniques, we have a size measurement that is in agreement with previous measurements, solidifying SW1’s place as a large Centaur. More importantly, our modeling has resulted in a beaming parameter value close to the average of a sampling of JFCs, Centaurs and TNOs.

We were unable to find constraints for the 5.8 µm geometric albedo of SW1 with the thermal observations alone (no coinciding observations of SW1 in the visible were available). Thermal modeling resulted in a value of 0.5 ± 0.5 which shows a high degree of uncertainty. While we do not claim an infrared geometric albedo measurement of 0.5, we would like to point out albedo measurements in this wavelength region are lacking in the literature. Infrared albedos may be higher than the usually low (∼0.04) values found for JFCs geometric albedos in the visible. Although the uncertainty in our measurement is high as well, we would like to show that this magnitude of infrared albedo is not physically out of the question. A normalized reflectivity gradient \( S' = 14.94 \pm 1.09 \% (1000 \, \text{Å})^{-1} \) (Duffard et al. 2014) and a V-band albedo of 0.04 would yield an albedo of 0.31 ± 0.10 in the near-infrared. Note that the normalized reflectivity gradient is a simplification and assumes a linear relation between albedo change and wavelength, which is truly not the case for mid-infrared albedos. It is mentioned here to just show the reader that the albedos of Centaurs tend to increase towards the infrared and that a value of 0.04 is not valid at these longer wavelengths. The high uncertainty in the derived IR albedo also means that SW1 may have a much lower IR albedo than 0.5.
Figure 2.17: NEATM Modeling fits to the Stansberry et al. (2004) and (2008) spectral flux density measurements. (a) 2004 nucleus photometry measurements fit with a NEATM model, but with the beaming parameter fixed to our current value. (b) Plot similar to (a) but using the 2008 values and our beaming parameter value.
To summarize:

- The measured value of $R = 32.3 \pm 3.1$ km places SW1 on the larger end of the Centaur size distribution. This value has been shown to be consistent (within 1-$\sigma$) of several previous measurements.

- An infrared beaming parameter value, $\eta = 1.14 \pm 0.22$, measured for SW1 is towards the middle of distributions of measured $\eta$ values for JFCs, Centaurs, and TNOs.

- The 5.8 $\mu$m infrared albedo was measured to be $0.5 \pm 0.5$, but with such a large uncertainty in this value it is still unclear how the reflectivity truly behaves in this wavelength regime. It was shown, however, that using a normalized reflectivity gradient for SW1 and a standard visible albedo for comets that a high ($> 0.30$) albedo can be achieved.
CHAPTER 3: SW1 OUTBURST-COMA MORPHOLOGY ANALYSIS

Determining the spin state of an active comet nucleus is often a daunting task. With observations of the bare nucleus obstructed by the coma, direct links between the comet’s photometric light curve and nucleus spin state become challenging. Variability in dust- and gas- coma activity can affect magnitude fluctuations caused by the geometric cross-section modulation during the rotation of an aspherical nucleus. Another method useful for placing constraints on the spin state of an active comet nucleus is to track changes in the coma’s morphology during a series of observations (Sekanina & Larson 1984; Samarasinha 2000; Schleicher and Woodney 2003; Farnham 2009; Mueller et al. 2013). Features in the coma (i.e. jets and shells of material) and their evolution can indicate the spin-pole orientation and/or rotation period. By tracking such features and their evolution during a time series of observations, inferences on the spin state can be made and used as initial estimates for input parameters in 3-D coma modeling routines.

In this chapter we discuss analysis of two sets of SW1 outburst observations to place constraints on the nucleus’ spin state. These constraints are later incorporated into the nucleus thermophysical model described in Chapter 4. The first set of observations is from the Kitt Peak National Observatory’s 2.1-m telescope and were acquired in 2008. Details of analysis are included in Section 3.1. The second set of observations is from the Hubble Space Telescope (HST) and were acquired in 1996 during the program GO-5829. That analysis is described in Section 3.2.
3.1 September 2008 Kitt Peak 2.1-m Outburst-Coma Analysis

The work presented in this section was previously published as “Analysis of R-band observations of an outburst of Comet 29P/Schwassmann-Wachmann 1 to place constraints on the nucleus’ rotation state” by Schambeau et al. in *Icarus*, **284**, pp. 359-371.

By observing the evolution of SW1’s coma during an outburst in a set of R-band observations from 2008 we place constraints on the time of the outburst, the 3-D shape of the outflowing outburst material, the nuclear spin state, the location of surface areas of activity involved in the outburst, and the duration of the outburst. Section 3.1.1 gives an overview of the observations, Section 3.1.2 describes the image enhancement techniques applied to the images and results from the coma morphology analysis, Section 3.1.3 is a description of the Monte Carlo 3-D coma simulation code along with its application to SW1, Section 3.1.4 discusses estimates of the amount of dust emitted during the outburst, and finally Section 3.1.5 discusses the results of the analysis.

3.1.1 Observations

R-band observations were acquired on 2008 September 25-29 UT from the Kitt Peak 2.1-m telescope while SW1 was undergoing an outburst. The $2048 \times 2048$ T2KB CCD was used for the observations. Table 3.1 gives details about each night of observations and Figure 3.1 shows a sample image from each night. Standard image processing including bias subtraction, flat fielding, and background subtraction were applied to each, generating science quality images for the analysis. Absolute flux density calibration was performed on the observations using data products from the Sloan Digital Sky Survey (SDDS). Except for deriving dust production rates, the morphological analysis doesn’t require absolute flux calibration. The orientation of the images is equatorial north up and east to the left with a pixel scale of 0.3 arcsec/pixel ($\sim$1400 km/pixel projected sky-plane...
distance at the geocentric distance of SW1). The individual 240 s image frames were used for analysis and no co-addition of frames from each night was applied.

As can be seen in the enhanced images (Figures 3.2, 3.3, and 3.4), a projected shell of material is radially outflowing due to the outburst. In addition to the shell of material, there are four linear features on the northern side of the coma at position angles (PA) 37°, 78°, 300°, and 353° measured from north through east. Morphological features such as these, which allow characterization of the outburst and measurement of properties of the underlying nucleus, are the focus of this section.
Table 3.1

<table>
<thead>
<tr>
<th>UT day</th>
<th>From (UT)</th>
<th>To (UT)</th>
<th>[R$_h$, ∆]$_a$ (AU)</th>
<th>Expo. Time$_b$ (s)</th>
<th># of Expo.$_c$</th>
</tr>
</thead>
</table>

$_a$ Average heliocentric and geocentric distance during each night of observations (Horizons, JPL).
$_b$ Exposure time for each image frame.
$_c$ Number of SW1 images for the given night of observations.

Figure 3.1: Sample of images from each night of the UT 2008 Sept. observations. Each figure is oriented with equatorial north up and east to the left. A yellow arrow represents the projected direction of the Sun, while a red arrow shows the skmplane projected direction of motion for SW1 during the observations. A scale bar shows the projected distance of 100,000 km at SW1. In each panel, a subsection of 500 x 500 pixels of the CCD chip with SW1 at the center are shown. Annotations in (a) are also applicable to images (b)-(e). In each image, a projected shell of material forms a nearly symmetric circular coma, which is observed to expand radially during the five nights. Additionally, four linear features are detectable on the northern side of the coma. The enhancement routines bring out the contrast of these features and are shown in Figures 3.2, 3.3, and 3.4.
3.1.2 Image Analysis

Coma features in comet observations can be subtle and hard to track. Brightness variations due to regions of higher gas and/or dust abundances can be possibly masked for example by the canonical $1/\rho$ brightness profile due to the quiescent coma. Image enhancement routines have been developed to bring brightness variations to a level more easily trackable. In this section the enhancement techniques are described, along with examples of enhanced features observed in the 2008 images. It needs to be emphasized that artifacts can easily creep into the products of image enhancements. A skeptical eye must be used while analyzing products of such enhancements. For this reason, features found through enhancements must to be verified in the high-contrast stretching of un-enhanced observations and application of widely different enhancement techniques.

3.1.2.1 Enhancement Routines

The image enhancement routines used for the 2008 observations are: division by a $1/\rho$ profile (where $\rho$ is the skyplane projected cometocentric distance from the nucleus), application of a radially-varying spatial filter (RVSF), and rotational shift differencing of each image. Each technique has a detailed description in Samarasinha and Larson (2014), which was used to write image enhancement routines in the programming language Python. The original non-Python routines are also available online at CometCIEF (Cometary Coma Image Enhancement Facility) site of the Planetary Science Institute. Other enhancement routines, which are described in the aforementioned paper, were applied to the 2008 observations, but did not show evidence of structures not seen in the three routines described above.

Figure 3.2 shows the images after removal of the $1/\rho$ profile, indicating deviations from a steady mass-loss rate. The shell of material is clearly visible during each night and the projected radial
distance of the shell from the nucleus is increasing with time. The shell’s projected width is also observed to increase indicating a velocity dispersion of the outflowing dust grains. A more detailed analysis of the shell’s width and its evolution with the inclusion of dust grain fragmentation, dust grain fading, and accounting for the variations of scattering properties for grains of different sizes could further constrain the outburst dust-grain size and velocity distributions, but is beyond the scope of this dissertation. Figure 3.3 shows the observations after application of a radially-varying spatial filter. This enhancement brings out brightness variations oriented in both radial and azimuthal directions. Again the expanding shell is seen, but now the four linear features are more pronounced. Lastly, the images were enhanced by rotating them around an axis centered on the nucleus’ pixel location by angles of ±θ. Then, each rotated image was subtracted from the original with these images added together resulting in the images seen in Figure 3.4 (rotational shift differencing technique). A rotation angle of ±18° was found to give the most contrast in the enhanced images. This rotation angle resulting in the best enhancement gives a rough scale for the widths of the linear features present. Each linear feature is seen to maintain its PA during the five nights of observation. The lack of curvature observed is unfortunate and restricts the amount of information which can be obtained about the rotational state of the nucleus. However, we were able to place certain constraints on possible rotational states which are discussed in Section 3.1.3.1.
Figure 3.2: (a)-(e) show enhanced images after the $1/\rho$ removal. Figures 3.2(a)-(e) correspond to (a)-(e) in Figure 3.1, with the earlier panel’s orientation and scale applicable here too. The shell of material is readily seen expanding from night to night. This is indicated by a brighter ring structure centered on the nucleus (nucleus is at the center of each panel). The darker area inside of the bright ring indicates the shell-like nature of the outflowing material and that the outburst had ended before the observations (in contrast, a cone of continuous ejected material would result in no decrease in brightness towards the center of the enhanced image).

Figure 3.3: (a)-(e) show a sample of images after application of a radially-varying spatial filter. The orientation and scale of the panels are the same as in Figure 3.1. The shell of material is seen clearly in the southern region expanding radially during the observations. The dark regions of discontinuity on the northern side of the coma corresponding to the shell are due to the presence of the four linear features. The shell of material is still present in this region, but the linear features dominate due to the characteristics of spatial filtering (Samarasinha and Larson 2014). The dark regions around field stars present in the images are artifacts of this spatial filtering too.
Figure 3.4: (a)-(e) show a sample of images after application of the rotational shift differencing technique. The orientation and scale of the panels are the same as in Figure 3.1. The four northern radial features are present in each night’s observation, indicating that these features are long lived in the coma. Their position angles $37^\circ$, $78^\circ$, $300^\circ$, and $353^\circ$ are seen not to deviate radially or temporally. Low contrast linear enhancements on the southern side of the coma are also present, but are not as prominent as those in the north. Most likely these are due to more gradual brightness variations in the shell of material similar to that seen in the north. Corresponding southern linear features in the high-contrast stretched un-enhanced images could not be identified (i.e., they are likely to be of extremely low contrast), so their incorporation into further analysis is limited. Artifacts from the rotation-subtraction enhancement result in two dark negative images for each field star. Disappearing of the shell (an azimuthal feature) is also an artifact of this image enhancement technique.
3.1.2.2 Shell of Material

A projected shell of material was observed expanding away from the nucleus. This is best observed from the RVSF-enhanced images shown in Figure 3.3. Radial profiles from each night of observation reveal the expanding shell of material. An example is shown for position angles PA = 140° and PA = 230° in Figure 3.5(a). The peak positions in the RVSF profiles correspond to a higher intensity or peak surface brightness variation in the un-enhanced images (not shown). It is possible that radial positions of the peak brightness variation for each night do not correspond to the same dust grains in each night of observation. Effects such as grain fragmentations and/or grain-brightness fading could mean that the Gaussian peak positions measured from radial profiles correspond to different dust grains during each night of observation. However, it is clear that a shell of expanding material is seen through the five nights of observation. What is unclear is whether the velocity measurements made are actual dust grain velocities or a “group velocity” measurement made of the dust grain size distribution.

To generate the radial profiles, the RVSF images were first “unwrapped” using a $(\rho, \theta)$ polar coordinate conversion. Since each image has been centered on the nucleus’ position, $\rho = 0$ corresponds to the nucleus. Next, an azimuthal binning of the radial profile was done for a $\Delta \theta = 10°$. A Gaussian profile was fit to the peak region of each night’s profile, with the center taken as the shell’s position. Figure 3.5(b) shows an example of the unwrapped RVSF images along with vertical lines indicating the corresponding PAs of the radial profiles in Figure 3.5(a). The possibility of an asymmetric projected shell expansion velocity was investigated by measuring the shell positions for a range of PAs between 120°-250°. Using the Gaussian peak positions, the image pixel scale, and their corresponding observation times, projected velocity measurements were calculated for the expanding shell at each PA. For each PA, a total of ten unique velocity measurements were made using different combinations of peak feature position and their associated time of observation:
\[ v_{ij} = \frac{(\text{Peak Position}_i - \text{Peak Position}_j)}{\Delta t_{ij}}, \] where \( i \) and \( j \) identify the specific night of observations and \( \Delta t_{ij} \) is the time between the observations. No significant asymmetry in velocity measurements are observed for different PA positions. The velocity differences from measurements of different PAs were comparable to the scatter in measurements from a single PA. The PA range from 120°-250° allowed 140 independent velocity measurements for the expanding shell. The 140 independent velocity measurements are from 10 measurements for a given PA for different images pairs from different nights plus 14 different PAs (at a 10 deg cadence starting from PA=120 deg and ending at 250 deg). The distribution of velocities was found to follow a Gaussian distribution and is shown in Figure 3.6. An overall projected velocity value of \(0.11 \pm 0.02 \text{ km/s} \), using the 1-\( \sigma \) deviation as the uncertainty for the velocity measurement.

Using the velocity measurement and its distribution, a Monte Carlo approach was used to extrapolate and measure the initial time of outburst. The Gaussian peak positions for the five nights of observations were taken to be the distances traveled by the outflowing material since the outburst occurred. The observation time from the FITS headers gave an accurate time stamp for each peak position. The time associated with the middle of the exposure was used for calculations and all images had a 240 s integration time. For each of the 140 peak-position and time-stamp pairs, 1000 velocity values were chosen randomly from the velocity distribution to calculate an outburst start time \((\text{UT}_{\text{start}})^{i,j} = ((\text{UT}_{\text{observation}})_i - \text{Peak Position}_j)/v_j\), where \( i \) refers to the 140 pairs and \( j \) refers to the 1000 velocity values. The value of 1000 was chosen to sample the velocity distribution well, producing a distribution of outburst start times following a Gaussian distribution. Using this method, a date of 2008-09-21.03 \( \pm 0.95 \) days was found for the beginning of the outburst.
Figure 3.5: (a) Radial profiles of RVSF-enhanced images in blue from each night of observations for the position angles $140^\circ \pm 5^\circ$ and $230^\circ \pm 5^\circ$. (b) Corresponding unwrapped RVSF images in polar coordinates with a red vertical line indicating the position of the $PA = 140^\circ$ profile and orange line indicating the $230^\circ$ profile. The radial profiles clearly show the expanding shell of material. The peak position of the shell was found by fitting the profile with a Gaussian function. The best-fit Gaussian profile in red is also included in each plot. The decrease in relative amplitude of the shell’s peak compared to the relative width of the shell over the course of the five nights is attributed to both dust grain size sorting and velocity dispersion of the grains. It should be noted that the RVSF enhancement does not preserve the amplitude of intensity variation of the image, but if the same set of RVSF parameters are used to enhance each image, the positions of intensity variation are preserved. In the unwrapped RVSF images (Figure 3.3), the shell can be identified as the horizontal white feature seen to move to larger radial positions throughout the five nights of observation. Field stars present in the unwrapped RVSF images are identified by a white spot surrounded by eight dark blue spots.
Figure 3.6: Histogram of the 140 velocity measurements along with a Gaussian model to the velocity measurement distribution. The velocity-measurement histogram values were fit with a Gaussian. The returned Gaussian mean and standard deviation were used as the outflowing material’s velocity measurement: \((0.11 \pm 0.02 \text{ km/s})\).

3.1.2.3 Northern Linear Features

The linear features seen in the northern half of the coma are best observed in the rotational shift differencing enhanced images (Figure 3.4). Four very pronounced features are seen to expand radially throughout the five nights of observations. The position angles of the features are \(37^\circ\), \(78^\circ\), \(300^\circ\), and \(353^\circ\). No major curvature is seen in the features indicating a possibly slow rotation period and/or short outburst duration. By analyzing the linear extent of the radial features it was determined that the four linear features are contained within the shell of expanding material,
implying their origin is from the same event as the expanding shell. Figure 3.7 shows azimuthal profiles for an array of radial positions for a rotational shift differenced image from the third night of observations. The radial positions for the profiles were chosen so one profile would be interior to the shell’s inner boundary, three contained within the shell’s radial boundaries, and one exterior to the shell’s outer radial boundary. As shown in Figure 3.7, these positions confirmed the inner and outer boundaries of the four linear features and that they are contained within the expanding shell of material.

The azimuthal profiles for the rotationally-shift differenced image in Figure 3.7 show that the linear extent is within the shell. It is important to note again the tendency of the enhancement routines to generate artifacts in the resulting images. One must analyze any feature produced through enhancements and verify its corresponding feature in the un-enhanced image. Figure 3.8 shows the same azimuthal profiles as in Figure 3.7, but for the un-enhanced image. While subtle, the four peaks can be seen for the three inner azimuthal profiles.
Figure 3.7: (a) Azimuthal profiles from the rotational shift differenced image from the third night of observations. The PA = 0° has been shifted so that it is in the middle of the plots and is indicated by the black vertical line. For the plots $\Delta \rho = 1$ pixel. The radii of the profiles, indicated by the projected radial distance value on the right of each panel in terms of image pixels (pixel scale is $\sim 1400$ km/pixel), are such that at least one profile is interior to and one exterior to the expanding shell of material. The four linear features appear as bright bands in the enhanced images and their corresponding peaks are observed in the profiles indicated by the red vertical lines in the $\rho = 35$ panel. The red vertical lines identifying the linear features were omitted in the remaining panels to improve the visibility of the plots. The rotationally enhanced image from the third night of observations is shown in (b) along with a mask overlaying the positions of the profiles. It can be clearly seen that the outer profile does not contain any signatures of the linear features. The inner profile is a little trickier, where close visual inspection of the image suggests that the features are possibly connected with the nucleus and influenced by the specific $\pm 18^\circ$ rotational shift. Figure 3.7(b) has the same orientation and scale as Figure 3.1.
Figure 3.8: Similar to Figure 3.7, but for the corresponding un-enhanced image from the third night of observations. For the plots $\Delta \rho = 1$ pixel. (a) Azimuthal profiles and (b) corresponding masked image. Investigation of (a) shows the same four regions in the un-enhanced images as having an increase in surface brightness. What is more pronounced in the images is the containment of the linear features in the shell of material, consistent with our assessment of the features being part of the outburst and not from separate active areas or events.
3.1.2.4 Inferred Outburst Coma Structure

The coma morphology and its evolution over the five nights suggest its 3-D structure resembles a cone of outflowing material probably projected towards the general direction of the observer. The semi-circular shape of the coma seen in observations is due to the projection of the 3-D cone onto the sky plane. With a source region on the nucleus’ surface slightly south of the sub-Earth point and an initial material ejection direction slightly south of the comet-Earth vector direction, the projected cone of material generated by this geometry explains the asymmetric circular shape seen in the observations. With the expanding material producing a projected nearly circular ring around the nucleus, the location of the outburst on the surface can be placed close to the sub-Earth point on the nucleus. It should be mentioned that the solar phase angle during observations is small, $\approx 10^\circ$ (i.e. source region for the outburst is close to the peak insolation which is also close to the sub-Earth point on the surface of SW1). In the next section we build on this by using a 3-D Monte Carlo coma simulation.

3.1.3 Monte Carlo Coma Modeling

Morphological features in a comet’s coma have proven useful for placing constraints on properties of cometary nuclei which may be obscured from direct observation by the coma itself (Sekanina & Larson 1984; Samarasinha 2000; Schleicher and Woodney 2003; Farnham 2009; Mueller et al. 2013). By tracking features in the coma, it is possible to discern the rotation state and nucleus surface area(s) of activity. The dynamic features measurable from observations are highly dependent on their timescales and on the cadence of observations. 3-D Monte Carlo coma modeling is used to measure or constrain properties of the nucleus’ spin state by generating synthetic comet images and comparing them with observations. In this section we describe the 3-D Monte Carlo coma model (Samarasinha 2000) used for modeling the SW1 2008 outburst and show constraints
derived for the nucleus of SW1.

The coma model assumes a nucleus with active areas represented by circular regions on the surface. No shape information for SW1’s nucleus is known so nucleus shape is ignored during modeling. A principal-axis rotation state (Samarasinha et al. 2004) was initially used for modeling. This is reasonable as recent measurements suggest SW1’s nucleus size being larger when compared to other JFCs ($R \sim 27$ km, Stansberry et al. 2004; $R \sim 19$ km, Stansberry et al. 2008; $R \sim 23$ km, Fernández et al. 2012; $R \sim 30$ km, Schambeau et al. 2015 and previous sections of this dissertation). Although other measurements have indicated non-principal-axis rotation for SW1’s nucleus (Meech et al. 1993), SW1’s larger size gives confidence in the principal-axis rotation assumption. Damping forces for a larger nucleus in an excited state of non-principal-axis rotation would quickly result in a principal-axis state (e.g. Samarasinha et al. 2004). Also, torques driven by outgassing, outbursts, and micrometeorite impacts are relatively ineffective at exciting the rotation state because of the relatively larger nuclear size.

Table 3.2 shows input parameters for the coma modeling and their associated modeling values. Free parameters are identified by their associated symbols. The generation of an outburst coma model proceeds as follows (note: the term “coma” or “coma model” used here refers to the portion of SW1’s coma generated by the outburst event and excludes the quiescent background coma unless explicitly stated). The orbital geometry of the observations is set up for the specific night of observation. A set of input values for the free parameters are chosen and the Monte Carlo modeling code is run for the appropriate time of the given night under investigation. Once the 3-D coma model has been generated, it is projected onto the sky plane of the observations, thus generating the synthetic coma observation. It should be noted that the coma modeling routine only generates the portion of the coma produced by the outburst. To fully generate a synthetic comet image, flux contributions from the nucleus and background (quiescent) coma must be added to the outburst coma model. The background coma was modeled using a canonical $\frac{A}{\rho}$ profile, where $A$ is a scaling
factor to match the background coma’s flux. To generate the final synthetic comet image the point
spread function (PSF, simulated with an Airy function), outburst coma, and quiescent coma are
added together, then convolved with an appropriate kernel to mimic the seeing conditions of the
observations.

Table 3.2
3-D Monte Carlo Coma Model Input Parameters

<table>
<thead>
<tr>
<th>Known Parameters</th>
<th>Free Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heliocentric distance (6.06 AU).</td>
<td>Cometographic longitude and latitude of source center (ϕs, λs).</td>
</tr>
<tr>
<td>Geocentric distance (6.4 AU).</td>
<td>Size of the active region on the nucleus (ra).</td>
</tr>
<tr>
<td>Right ascension and declination of the Suna</td>
<td>Angular dispersion of emitted dust velocity (θd)c.</td>
</tr>
<tr>
<td>(RA = 19:28:54, DEC = -25° 30' 34'').</td>
<td>Right ascension and declination of the angular momentum vector (αc, δc).</td>
</tr>
<tr>
<td>Right ascen. and declination of the Eartha</td>
<td>Rotation period of nucleus (P).</td>
</tr>
<tr>
<td>(RA = 20:08:02, DEC = -23° 39' 49'').</td>
<td>Initial velocity of dust grains (vd).</td>
</tr>
<tr>
<td>Time of coma modelingb.</td>
<td>Outburst duration (Δt).</td>
</tr>
<tr>
<td>(Night 1, t = 408672.0 s)</td>
<td>(Night 2, t = 495072.0 s)</td>
</tr>
<tr>
<td>(Night 3, t = 581472.0 s)</td>
<td>(Night 4, t = 667872.0 s)</td>
</tr>
<tr>
<td>(Night 5, t = 754272.0 s)</td>
<td></td>
</tr>
</tbody>
</table>

a RA and DEC as viewed from SW1 at the time of the observations.
b t = 0 refers to the beginning of the outburst.
c Angular dispersion of the initial dust grain velocity direction, with 0° being normal to the local surface.
3.1.3.1 Nucleus Spin State Results

Initial analysis of the five nights of observation resulted in the realization that the determination of a spin-pole orientation is not possible with this data set. The morphological features present in the observations do not suggest any sense of rotation (e.g. curved features characteristic of a rotating nucleus). The similarity present throughout the five nights signifies an outburst duration that is significantly shorter than the rotation period. If the outburst duration was a significant fraction of the rotation period, then signatures of dust ejection over an angular arc would be present. The coupling between the spin period and outburst duration impacts the analysis of the coma morphology because features present in observations can be attributed to either property. Therefore, this analysis can only result in constraints on the spin period to outburst duration ratio (P/Δt). While we can’t say definitively what the spin period and pole orientation are, we can still constrain the spin period for assumed spin-pole orientations.

Certain properties of the outburst inferred from the observations are valid for any spin-pole orientation (e.g. the active area’s size and center location with respect to the sub-Earth point on the nucleus’ surface). To place a constraint on these parameters, the rotation period was fixed to 10,000 days, so that any morphological features in the coma due to nucleus rotation are negligible and the outburst duration was set to 10.5 hours. Using the cone-of-ejected-material hypothesis (Section 3.1.2.4), the location of the source center was found. A grid of source region locations was setup to sample the parameter space well. Each set of parameters was used to generate a set of synthetic comet images representing one image for each of the five nights of observation. Comparing radial surface brightness profiles similar to those shown in Figure 3.12(b) from the synthetic comet images with profiles from the observations resulted in a best-fit set of parameters. A source region having a 28° ± 5° angular radius (∼ 6 % of the surface) and location ∼ 4° below the sub-Earth point most suitably reproduced the expanding shell of material. It was found that a 0.3 km/s initial
dust grain velocity, including a $10^\circ$ angular dispersion of velocities with respect to the local surface normal direction, generated the 0.11 km/s projected shell of expanding material. It should be noted that other initial dust grain velocities combined with other shapes for the 3D outburst coma structure (e.g. hemispherical as opposed to conical) can also result in the measured 0.11 km/s skyplane projected shell expansion velocity. The above stated 0.3 km/s scenario fit the observations more closely when comparing radial surface brightness profiles and thus was chosen as the “best-fit” solution. Figure 3.9 shows the synthetic comet images resulting from the best-fit parameters for each of the five nights of observation. The linear features in the northern region of the coma have been ignored during this stage of modeling since they are simply a product of higher dust grain density regions. No independent or additional information would be gained from their inclusion in this stage of modeling.

![Figure 3.9](image)

Figure 3.9: Top row: (a)-(b) Synthetic comet images for the five nights of observations. Using an active area covering $\sim 6\%$ of the surface and a large $P/\Delta t$, the synthetic comet images are able to reproduce morphology seen in the observations. The expanding shell is accurately reproduced, with a slight offset of the nucleus to the north of the shell. The images have the same pixel scale, image scale, and orientation as Figure 3.1. Bottom row: Same synthetic comet images from the top row, but with a $1/\rho$ removal similar to Figure 3.2. The removal of the $1/\rho$ profile brings out the outburst coma shell in the synthetic models.
Effects due to solar radiation pressure have been ignored during Monte Carlo coma modeling. The region of the outburst coma observed and modeled is in the inner coma region where solar radiation pressure has not significantly altered the emitted dust grain’s sky-plane velocity. This was determined by calculating the distance \( d \) traveled by a dust grain in the projected sky-plane of the observations before being turned back due to solar radiation pressure (Mueller et al. 2013).

\[
d = \frac{v^2 \cos^2 \gamma^2}{2\beta g \sin \alpha}
\]

where \( v \) is the initial ejection velocity of the dust grains, \( \gamma \) is the angle between the initial direction of the dust grains and the sky-plane, \( \beta \) is the ratio of radiation pressure acceleration to solar gravity, \( \alpha \) is the solar phase angle of the observations (for the 2008 observations \( \alpha = 8.5^\circ \)), and \( g = GM_\odot/R_h^2 \) is the gravitational acceleration on the dust grains. Using a range of values typical for \( \beta \) (0.1, 0.6, and 1.0) we calculated values for the projected turn-around distance to be \( d \approx (3,500,000 \text{ km}, 590,000 \text{ km}, \text{ and } 350,000 \text{ km}) \) for dust grains leaving the edge of the modeled source region (i.e. a value of \( \gamma = (90^\circ - 28^\circ) = 62^\circ \)). The projected sky-plane radius of the coma’s shell for the fifth night of observations is less than 350,000 km, as seen in Figure 3.1, signifying radiation pressure effects have not significantly altered the coma’s morphology. Additionally, there is no appreciable “deformation” of the shell structure seen to evolve during the later nights of observations, indicating visually that solar radiation effects are minimal for our analysis.

With constraints found for the active area’s location and size, dust grain velocity, and dust grain velocity angular dispersion it is now possible to place constraints on the spin period for a set of assumed spin-pole orientations. As was stated earlier, the morphology of the observations did not have sufficient structure with differentiating characteristics to determine the spin-pole orientation, so making assumptions on the orientation allows constraints to be placed on the spin period for these specific orientations. This information will be useful in future analysis of SW1 outburst ob-
servations and to provide possible starting points for analysis of different outburst observations. Four spin-pole orientations were chosen: perpendicular to the Sun-Earth vector during observations (RA = 300°, DEC = 66°), in the same plane as the Sun-Earth vector, but perpendicular to the Earth direction during observations (RA = 32°, DEC = 0°), 45° above the Sun-Earth plane and 45° between the spin-pole direction and the comet-Earth direction (RA = 347°, DEC = 21°), and along the comet-Earth direction (RA = 302°, DEC = -23°). The procedure for placing a constraint on the spin period is similar for each pole orientation. First, the modeling code input parameters were changed to reflect the relevant spin-pole orientation. Next, the spin period was set to 10,000 days and outburst duration set to 10.5 hours, with the modeling code run for each of the five nights of observation. This gave a baseline for comparing the images when decreasing the spin period. The spin period was then decreased until the synthetic comet images deviated significantly in morphological structure when compared with the observations. Figure 3.10 summarize the results of the spin period analysis for the four assumed spin-pole orientations with constraints on the spin period to outburst duration ratio. Overall, it is seen that modeling the outburst requires a spin period that is ≥10 times the outburst duration and/or a spin-pole direction nearly parallel to the comet-Earth direction.
Figure 3.10: Left: Diagram of spin-pole orientation: blue arrow indicates spin-pole direction, black line represents comet equator, blue circular area indicates the active area on nucleus, red circle indicates sub-Earth point, and yellow circle indicates sub-solar point. Right: Synthetic comet images for the fifth night of observation for the assumed spin-pole orientation shown to the left. The orientation of the synthetic comet images is the same as in Figure 3.1. The results are expressed in terms of the ratio of spin period (P) to outburst duration ($\Delta t$): (left to right and top to bottom: 22857, 11, 9, 7, 5, 2).
3.1.3.2 Dust Velocity Distribution and Upper Limit to the Outburst Duration

With constraints found for \( P/\Delta t \), a method of constraining the outburst duration was undertaken. Radial surface-brightness (SB) profiles of the comet observations provided this independent method of analysis. Longer duration outbursts result in more dust grains closer to the nucleus and thus steeper slopes for the radial SB profiles in the synthetic comet images. Plots of radial SB profiles for a selection of four PAs from the comet observations and the synthetic comet images were compared to place constraints on the outburst duration. The synthetic comet images are similar to those from Section 3.1.3.1 and have been convolved with a Gaussian kernel to mimic the seeing conditions during the observations.

The velocity distribution of the Monte Carlo coma model was varied to see its effect on the modeling output. First, a boxcar distribution for velocity was used to mimic a delta function where only the initial velocity \( (v_o) \) was chosen. A random initial angular deviation from the local surface normal was used to impart dispersion in the velocities. A dispersion of \( \theta_d = 10.0^\circ \) was used for all modeling. Secondly, a Gaussian distribution with a standard deviation \( \sigma \) of \( \pm 0.2v_o \) in velocities centered on \( v_o \) was used in the Monte Carlo model. A spin period of 10,000 days, outburst duration of 10.5 hours, and the spin-pole orientation equivalent to the top of Figure 3.10 was assumed for the nucleus for both distributions. Figure 3.11 shows a sample of radial SB profiles from both distributions. It was found that a Gaussian velocity distribution more accurately modeled the observations. It should be noted that the modeling shown in Section 3.1.3.1 assumed a Gaussian velocity distribution identical to that used in the models generating the radial SB profiles in Figure 3.11(b).

Using the Gaussian velocity distribution, the outburst duration was varied to find constraints on its length. Figure 3.12 shows examples of two outburst durations and how they affect the radial SB profiles of the synthetic comet images. A 5-day outburst (Figure 3.12(a)) results in too much dust
close to the nucleus and thus radial SB profile slopes too steep to model observations. The overall shapes of these profiles also do not match the observations. By decreasing the outburst duration by 0.5-day steps, an upper limit of 1.5 days was concluded for the length of the outburst. Figure 3.12(b) shows radial SB profiles for a 1.5-day outburst. While the model profiles do not align exactly with the observation profiles, the overall shape matches the observations well. A rescaling of the outburst coma flux, when compared to the nucleus and background coma, is able to shift the profile to match the observations. The offset in between profiles was retained in the figures to remain consistent by applying the same linear scaling of the synthetic comet images throughout this work. Therefore, a 1.5-day outburst duration was chosen as the upper limit.

Decreasing the outburst duration below 1.5 days unfortunately did not result in a lower limit for the outburst duration. All modeled outburst durations below the upper limit generated synthetic comet images that were consistent with observations. The dispersion in the dust grain velocities becomes the dominant parameter controlling the projected material’s radial SB profiles at this limit and not dictated by the spread of material due to an extended period of dust emission and therefore we consider this upper limit to the outburst duration as a robust determination.
Figure 3.11: Radial SB profiles from the fifth night of observations for a boxcar vs. Gaussian velocity distribution for dust grains. (a) The boxcar velocity distribution radial SB profiles do not model the observations well. The outflowing shell of material is too concentrated in radial direction thus creating the overly curved radial SB profiles when compared to observations. (b) The Gaussian distribution modeled the observations much better in the radial direction, ($\rho \sim 40$ to 140 pixels). The deviation of model and observations in the radial region from $\rho = 15$ to 35 pixels is due to the canonical $1/\rho$ background coma not modeling the observations well and was ignored because of its irrelevance to the focus of this work.
Figure 3.12: Radial SB profiles from the fifth night of observations comparing the modeling length of the outburst duration. (a) A 5-day outburst shows deviations between the observation and modeling images. For this situation too much dust is still in the close vicinity of the nucleus during observations. The increased dust number density close to the nucleus leads to the radial SB profiles having a slope too steep. (b) A 1.5-day duration is shown and found to be an upper limit for the outburst duration. Longer outbursts show deviations from the observed radial SB profiles similar to those seen in (a). The red profile in the top-left panel of (a) and (b) represents the comet nucleus with only a canonical $1/\rho$ profile.
3.1.4 Dust Production During the Outburst

3.1.4.1 Outburst Dust Mass Measurement

Until this point no mention of apparent flux calibration has been made for the 2008 SW1 observations. For the analysis of coma morphology only changes in relative brightness were necessary. Therefore making additional relative flux measurements are appropriate to estimate lower limits for the mass of dust emitted during the outburst. For this, each image was calibrated with respect to a set of standard stars. For apparent flux calibration we used the outburst observations of SW1 and Sloan Digital Sky Survey (SDSS) r-band magnitudes of stars in each observation frame. Each of the seventeen observations of SW1 from the five nights of observations were calibrated. Aperture photometry of the calibrated images resulted in apparent R-band magnitudes, \( A_f \rho (10''') \) values, and dust production rates derived from the \( A_f \rho \) values (\( \dot{M}_{\text{dust}} (10''') \)) for the five nights of observations are shown in Table 3.3. The value for each single night is the average of the individual exposures from that night.

The \( A_f \rho \) parameter is a proxy for dust-production rate first derived in A’Hearn et al. 1984.

\[
A_f \rho (\text{cm}) = \frac{(2\Delta R_H)^2}{\rho} \left( \frac{F_{\text{com}}}{F_\odot} \right) \tag{3.2}
\]

where, \( \Delta \) (AU) is the geocentric distance of the comet, \( R_H \) (cm) is the heliocentric distance of the comet, \( F_{\text{com}} \) is the observed flux of the comet within a circular aperture of projected radius \( \rho \) (cm), and \( F_\odot \) is the solar flux at 1 AU. \( A_f \rho \) is derived assuming a spherically-symmetric dust emission and provides an estimate for the dust production rate, \( \dot{M}_{\text{dust}} \).
\[
\dot{M}_{\text{dust}} = \frac{8a\rho_d v_d (Af\rho)}{3p} \tag{3.3}
\]

where, \(a\) is the dust grain radius (assumed spherical dust grains of a single size), \(\rho_d\) is the dust grain density, \(v_d\) is the dust grain expansion velocity, and \(p\) is the geometric albedo of the dust grains. The following standard values were chosen to be consistent with other comets: \(a = 1.0\mu m\), \(\rho_d = 1000.0\ \text{kg/m}^3\), and \(p = 0.04\) (Hosek et al. 2013; Ivanova et al. 2011). While there is clearly a dust grain size distribution associated with cometary outburst, the assumed 1 \(\mu m\) grain is chosen due to its efficiency at scattering light at R-band wavelengths. It should also be noted that the albedo value used for the dust production rate measurement was adjusted for phase effects of the nonzero phase angle observations of SW1. From this equation the dust production rate measurements were calculated for the 10" aperture for each of the five nights and are given in Table 3.3.

Figure 3.13(a) shows the spectral flux-density measurements for increasing photometric aperture size. An \(\sim 30''\) aperture contains almost all of the comet’s detectible flux from the outburst and is used for calculating the total amount of dust mass \(M_{\text{dust}}\) ejected during the outburst. Using the same assumptions for the 1.0 \(\mu m\) dust grain’s size and density as above, a lower-limit on the amount of dust emitted during the outburst was calculated with the following equations (Jewitt 1991):

\[
M_{\text{dust}} = \frac{4\rho_d a C_{\text{dust}}}{3} \tag{3.4}
\]

where \(C_{\text{dust}}\) is the total scattering cross section of the collection of 1.0 \(\mu m\) dust grains which is measured from the flux contained in the 30'' aperture. The 30'' aperture is used to fully enclose the dust emitted during the outburst, which is indicated by the profiles in Figure 3.13(a). \(C_{\text{dust}}\) was
found with (Lamy et al. 2004):

$$A\Phi(\alpha)C_{\text{dust}} = 2.238 \times 10^{22} R_H^2 \Delta 10^{0.4(m_\odot - m)}$$ (3.5)

where, $\Phi(\alpha) = 10^{-0.4\alpha\beta}$ is the phase function used for the dust grains, $\alpha$ is the phase angle of the observations, and a value of $\beta = 0.04$ mag/deg was used for the linear phase coefficient. Additionally, $m_\odot$ is the solar magnitude in the R-band and $m$ is the R-band magnitude measured for the outburst dust flux. The number of 1.0 $\mu$m dust grains is found by dividing the total scattering cross section $C_{\text{dust}}$ by the scattering cross section of an assumed spherical individual grain ($C_{1.0\mu m}$). The lower-limit measurement for the amount of material ejected during the outburst is shown in the last column of Table 3.3 for each of the five nights. The amount of material measured for each night is consistent within uncertainties. An average value of $(1.8 \pm 0.07) \times 10^9$ kg was measured as the lower limit to the amount of dust emitted during the outburst.
Table 3.3

Summary of Photometry: \( R \) Mag, \( A_f \rho \), \( \dot{M}_{\text{dust}} \), \( M_{\text{dust}} \)

<table>
<thead>
<tr>
<th>Epoch (^a)</th>
<th>( R ) Mag (^b) (10''')</th>
<th>( A_f \rho ) (10'') (cm)</th>
<th>( \dot{M}_{\text{dust}} ) (10'') (kg s(^{-1}))</th>
<th>( M_{\text{dust}} ) (30'') (^c) (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td>11.9 ± 0.1</td>
<td>77000 ± 7000</td>
<td>4700 ± 500</td>
<td>(1.8 ± 0.2) ( \times ) 10(^9)</td>
</tr>
<tr>
<td>26.5</td>
<td>12.0 ± 0.05</td>
<td>67000 ± 3000</td>
<td>4100 ± 300</td>
<td>(2.0 ± 0.1) ( \times ) 10(^9)</td>
</tr>
<tr>
<td>27.5</td>
<td>12.2 ± 0.1</td>
<td>54000 ± 5000</td>
<td>3300 ± 400</td>
<td>(1.8 ± 0.2) ( \times ) 10(^9)</td>
</tr>
<tr>
<td>28.5</td>
<td>12.5 ± 0.1</td>
<td>44000 ± 6000</td>
<td>2700 ± 400</td>
<td>(1.7 ± 0.2) ( \times ) 10(^9)</td>
</tr>
<tr>
<td>29.5</td>
<td>12.6 ± 0.1</td>
<td>40000 ± 3000</td>
<td>2400 ± 200</td>
<td>(1.7 ± 0.1) ( \times ) 10(^9)</td>
</tr>
</tbody>
</table>

\(^a\) Day of 2008 September, UT at beginning of observations.

\(^b\) Magnitude measurements are in agreement with analysis of independent observations of the same UT Sept. 2008 outburst (Trigo-Rodriguez et al. 2010).

\(^c\) Lower limit for total mass of dust emitted during the outburst using a photometric aperture of 30'' (using Equation 3.3).
Figure 3.13: Flux density and $A_f \rho$ profiles from photometry of the five nights of observations. The average photometry values from each night’s individual observations were chosen to represent the activity level for that particular night. (a) Spectral flux density measurements from the five nights for an increasing aperture size, where the spectral flux density is a measure of the electromagnetic radiation reflected by the dust grains received by the CCD for a specified wavelength. The slopes of the profiles decrease during the five nights representing the movement of dust grains and possibly grain fading and/or fragmentation. For each of the profiles an aperture of $\approx 30''$ signifies enclosing all of the flux associated with the comet. For this reason the 30” aperture flux value was chosen for measurements of the total dust emitted during the outburst. (b) $A_f \rho$ measurements for the five nights of observations for the same set of apertures.
3.1.4.2 Lower Limit for the Outburst Duration

To estimate a lower limit for the outburst duration, we present a simple thermal model which includes the sublimation of either pure CO or CO$_2$ ice. Equations for the thermal modeling are taken from Prialnik et al. 2004, Meech & Svoren 2004, Sarid et al. 2005, and Sarid 2009. The lower limit is the time required to eject the amount of dust from the surface of SW1 assuming a value for the dust to gas ratio. Our modeling assumptions include: a dust to gas ratio of 4.0 from recent Rosetta spacecraft measurements of Comet 67P (Rotundi et al. 2015), thermal properties of nucleus materials from Huebner et al. 2006, a porosity of $\Psi = 0.7$ (Rosetta measurements, Taylor et al. 2015), and an active region comprising 6% of surface area which is based on our best-fit coma model described in Section 3.1.3.1. It is noted that there are several other plausible arguments for what drives cometary outbursts, but this idealized calculation of one possibility is shown to help constrain the spin-period outburst-duration relation found during coma morphology modeling.

First, energy balance was used at the nucleus’s surface to solve for the temperature, $T$, of the surface area undergoing outburst.

\[
\frac{(1 - A)L_\odot}{4\pi R_H^2} \cos z = \epsilon \sigma T^4 + \sum_i F_i P_i(T) \sqrt{\frac{m_i}{2\pi kT}} H_i(T)
\]  \hspace{1cm} (3.6)

In the equation, $L_\odot$ is the solar constant, $R_H$ is the heliocentric distance in units of AU, $A$ is the bolometric albedo of SW1’s surface (assuming a geometric albedo of 0.04 and the same phase function as in Section 5.1), $z$ is the local solar zenith angle of the active surface area, $\epsilon$ is the emissivity of the cometary surface (assuming a value of 0.95 found to be standard for most cometary thermal models), $\sigma$ is the Stefan-Boltzmann constant, $P_i$ is the saturation vapor pressure of species $i$, $m_i$ is the mass of species $i$, $k$ is the Boltzmann constant, and finally $H_i$ is the latent heat of
sublimation. Both the saturation vapor pressure and latent heat of sublimation are temperature dependent. Equations from Heubner et al. (2006) were used for both material properties. The factor $F_i$ is the fractional area of the unit surface element covered by the $i$-th sublimating ice species. If pure CO and/or CO$_2$ ice is present and producing the outburst, it will most likely not be at the nucleus’ surface as the above calculation is assuming. A thermal wave from the surface traveling to subsurface supervolatile ice pockets is probably a better description of the process, but for the simple calculation done here we ignore this fact and proceed as if the supervolatile ices are at the surface.

Once the temperature is found, by solving Equation 3.6, the sublimation rate per unit surface area ($q_i$) for the species is calculated.

$$q_i = (P_{\text{vap},i}(T) - P_i)\sqrt{\frac{m_i}{2\pi kT}}$$

where, $P_{\text{vap},i}(T)$ is the saturation vapor pressure, $P_i$ is the vapor pressure of the sublimating gas and assumed to be negligible at the nucleus’ surface when compared to the saturation vapor pressure.

Finally, the 6% active area of SW1’s nucleus found from modeling amounts to $7 \times 10^8$ m$^2$, but only a fraction of this surface area may consists of CO and/or CO$_2$ ices. Table 3.4 shows the total CO and CO$_2$ production rates for a sampling of possible compositional ratios along with their associated lower-limit outburst duration values. All values of the outburst duration lower limit are on the order of hours, which is plausible given the morphological evolution seen in the observations and the rapid brightening observed during the onset of the outburst. Also, this lower limit is consistent with what one should expect based on tensile strength considerations corresponding to a weakly held nucleus (e.g. Weissman et al. 2004).
Table 3.4

Summary of gas-production rates for different assumed material compositions

<table>
<thead>
<tr>
<th>CO</th>
<th>CO₂</th>
<th>H₂O</th>
<th>Dust</th>
<th>(\dot{q}_i^a)</th>
<th>(\Delta t^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{F}_{CO})</td>
<td>(\mathcal{F}_{CO_2})</td>
<td>(\mathcal{F}_{H_2O})</td>
<td>(\mathcal{F}_{\text{Dust}})</td>
<td>(molecules/s)</td>
<td>(hours)</td>
</tr>
<tr>
<td>0.01</td>
<td>0.0</td>
<td>0.49</td>
<td>0.5</td>
<td>1.718\times10^{30}</td>
<td>1.56</td>
</tr>
<tr>
<td>0.1</td>
<td>0.0</td>
<td>0.4</td>
<td>0.5</td>
<td>1.645\times10^{30}</td>
<td>1.63</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.5</td>
<td>1.603\times10^{30}</td>
<td>1.68</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.587\times10^{30}</td>
<td>1.69</td>
</tr>
<tr>
<td>0.0</td>
<td>0.01</td>
<td>0.49</td>
<td>0.5</td>
<td>4.143\times10^{29}</td>
<td>4.13</td>
</tr>
<tr>
<td>0.0</td>
<td>0.1</td>
<td>0.4</td>
<td>0.5</td>
<td>4.457\times10^{29}</td>
<td>3.84</td>
</tr>
<tr>
<td>0.0</td>
<td>0.5</td>
<td>0.0</td>
<td>0.5</td>
<td>4.598\times10^{29}</td>
<td>3.72</td>
</tr>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>4.645\times10^{29}</td>
<td>3.68</td>
</tr>
</tbody>
</table>

\(a\) Gas production rate assuming the fraction of active area is composed of the supervolatile species.

\(b\) Minimum time required to eject the measured dust produced during the outburst assuming a dust to volatile ratio of four from recent Rosetta mission results (Taylor et al. 2015).

\(c\) Fraction of surface area element composed of the specified ice used in Equation 5.

3.1.5 Results of 2008 Outburst Coma Analysis

The morphological evolution of the outburst coma did not allow constraints to be placed on the spin-pole direction, but constraints were found for the spin period for a set of assumed spin-pole orientations. By sampling a coarse grid in spin-pole orientation space, applying a 3-D Monte Carlo coma model, and thermal modeling we find that a lower limit for the spin period is on the order of days and/or the spin-pole direction during the observations was closely aligned with the sub-Earth direction. The possibly slow rotation rate has an interesting implication, one that is supported by earlier works favoring a spin period on the order of 57-60 days (Trigo-Rodriguez et al. 2010, Miles...
et al. 2016a). Such a long rotation period would only further emphasize SW1 as a unique comet. While we have no evidence for such a slow rotation, it cannot be ruled out by our analysis. We find no suggestions of non-principal axis rotation, although a complex spin state with slow rotational components cannot be ruled out by our analysis. Previous measurements of SW1 being in a non-principal axis rotation state (Meech et al. 1993) are intriguing when considering the results of this analysis. The observations used for their analysis were obtained in August 1987, over twenty years prior to our 2008 observations. A complex spin state suggested by their observations could have damped down during the interim between observations due to the large size of SW1’s nucleus.

This unique rotation period when compared with known cometary periods (Samarasinha et al. 2004; Kokotanekova et al. 2017) could help explain its enigmatic outburst behavior. Recently, the theory of subsurface gas cavities reaching pressures exceeding overlaying material’s strengths and ejecting large amounts of interjected material have been proposed to explain SW1’s outbursts (Gronkowski & Wesolowski 2015; Miles et al. 2016a). Such a slow rotation could allow time for such cavities to reach these pressures, thus producing outbursts. Alternatively, the slow rotation rate could be periodically allowing insolation to reach areas on the surface that have a higher concentration of supervolatile ices. During these times of increased activity, would there be enough ice sublimation to emit the amount of dust typically measured for SW1 outburst? To test this mechanism we applied a simple thermal model to the ∼6 % active surface region found from 3-D Monte Carlo coma modeling which incorporated either CO or CO$_2$ ice sublimation. The measured lower limit (1.8 ×10$^9$ kg) of dust ejected during the outburst could be released through sublimation of either CO or CO$_2$ with a timescale on the order of 1-4 hours. This minimum outburst duration is in agreement with timescale requirements found from the Monte Carlo coma modeling and tensile strength considerations.
To summarize:

- Five consecutive nights of observations of SW1 ~4 days after a major outburst were analyzed.
- An expanding shell of material was measured to have a skyplane projected velocity of 0.11±0.02 km/s due to the outburst.
- Linear features on the northern side of the outburst coma were found to be contained in the expanding shell of material and originate from the same event producing the shell.
- 3-D Monte Carlo coma modeling of the morphological evolution of the outburst coma suggest either a slow (on the order of days) rotation period or a spin-pole directions directed towards Earth during observations.
- Comparing radial surface-brightness profiles of the observations to synthetic comet images generated using the coma models provide an upper limit for the outburst duration of ~1.5 days.
- Using a simple thermal model to describe the outburst event and the total amount of dust emitted during the outburst, a lower limit for the outburst duration was calculated to be on the order of hours.
- Photometry of the outburst resulted in an estimate of \((1.8±0.07) \times 10^9\) kg as a lower limit to the total amount of dust ejected during the outburst.

3.2 1996 Hubble SW1 Outburst-Coma Analysis

In this section we present analysis of Hubble Space Telescope (HST) observations of SW1 shortly after an outburst and apply the 3-D Monte Carlo coma modeling similar to Section 3.1 to place
further constraints on SW1’s spin state. The layout of this section is as follows: Section 3.2.1 provides details of the 1996 HST observations, Section 3.2.2 we describe our image analysis, which predominantly included the application of a suite of image enhancement routines developed for application on cometary coma images (Samarasinha and Larson 2014), Section 3.2.3 includes application of a 3-D Monte Carlo Coma model to place constraints on the nucleus’ spin state, and finally we describe results of modeling in Section 3.2.4.

3.2.1 Observations

The HST observations were acquired during the Cycle 5 as part of the program GO-5829: “The Activity of Periodic Comet Schwassmann-Wachmann 1” (Feldman et al. 1996). Their investigation centered around spectroscopic observations of SW1 using the Faint Object Spectrograph with the goal of determining the volatile species driving the comet’s continuous activity. Wide Field and Planetary Camera 2 (WFPC2) observations were acquired before acquisition of each spectrum. While the proposal did not request target-of-opportunity (ToO) observations during a phase of outburst activity, the observations serendipitously captured the comet shortly after a major outburst. The serendipitous nature of the outburst observations unfortunately resulted in the first four of the eight total WFPC2 exposures being significantly saturated near the nucleus. While the saturated images have reduced science return when compared to an image with proper exposure time, the serendipitous timing of capturing images shortly after an outburst resulted in the highest resolution images of SW1’s outburst coma to date. These high resolution images are ideal for coma morphology analysis and Monte Carlo coma modeling for nucleus spin state constraints (Schambeau at al. 2017).

Specifics for the WFPC2 observations are given in Table 3.5 and the 120 second exposure image from each of the two epochs of observations is shown in Figures 3.14 and 3.15. Hereafter images
from either of the two epochs observations will be referred to as exposure 1 (Exp-1) or exposure 2 (Exp-2). The WFPC2 was composed of four separate detector chips: three wide field (WF1-3) chips and one planetary camera (PC) chip. Details of the WFPC2 instrument and analysis of its data products can be found in the Instrument Handbook (McMaster et al. 2008) and Data Analysis Cookbook (Gonzaga et al. 2010). The three wide field (WF) chips had an effective pixel scale of 0'.5/pixel and the PC chip had a 0''.046/pixel scale. Figures 3.14 and 3.15 show the results of combining the four detector chips from each exposure into a single image. The resolution of the resultant, combined image is at the WF pixel scale. During the observations the comet nucleus was positioned to be near the center of the PC on the highest resolution part of the image. The outburst coma was fully contained in the field of view (FOV) of the PC during all of the exposures.

Analysis of the individual PC images from each observation allows the full resolution of the PC to be appreciated. Figure 3.16 shows cropped examples of the PC resolution observations for the two epochs from Figures 3.14 and 3.15. The observations are shown on a logarithmic scale to emphasize the outburst coma.
<table>
<thead>
<tr>
<th>UT day</th>
<th>Observation Start (UT)</th>
<th>Phase Angle (deg)</th>
<th>[R(_h), (\Delta)](^a) (AU)</th>
<th>Expo. Time(^b) (s)</th>
<th>Filter(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>07:38:15</td>
<td>2.34</td>
<td>[6.262, 5.296]</td>
<td>120</td>
<td>F702W</td>
</tr>
<tr>
<td>11</td>
<td>07:42:16</td>
<td>2.34</td>
<td>[6.262, 5.296]</td>
<td>400</td>
<td>F702W</td>
</tr>
<tr>
<td>11</td>
<td>07:51:16</td>
<td>2.34</td>
<td>[6.262, 5.296]</td>
<td>600</td>
<td>F702W</td>
</tr>
<tr>
<td>12</td>
<td>02:56:15</td>
<td>2.47</td>
<td>[6.262, 5.300]</td>
<td>120</td>
<td>F702W</td>
</tr>
<tr>
<td>12</td>
<td>03:00:16</td>
<td>2.47</td>
<td>[6.262, 5.300]</td>
<td>400</td>
<td>F702W</td>
</tr>
<tr>
<td>12</td>
<td>03:09:16</td>
<td>2.47</td>
<td>[6.262, 5.300]</td>
<td>600</td>
<td>F702W</td>
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<td>03:26:16</td>
<td>2.47</td>
<td>[6.262, 5.300]</td>
<td>600</td>
<td>F702W</td>
</tr>
</tbody>
</table>

\(^a\) Heliocentric distance and HST range during each observation (Horizons, JPL).

\(^b\) Exposure time for each image frame.

\(^c\) WFPC2 filter selected for the observation.
Figure 3.14: WFPC2 observation of SW1 from 1996. The image includes the exposures from the three Wide Field Cameras and additionally the Planetary Camera. The first exposure (Exp-1) is shown here. The image was acquired for use as an exposure calibration for the Faint Object Spectrograph. Exp-1 is saturated in the region of the image containing the nucleus. This saturation is evident by the diffraction spikes present Exp-1. The arrows indicates the directions of equatorial coordinates. The projected solar direction and negative of the comet’s velocity direction are indicated by the yellow and red arrows. A scale bar on the bottom right of each image shows a projected distance of 100,000 km at the location of SW1. Close inspection of both PC observations shows the outburst dust flow from the nucleus.
Figure 3.15: Similar to Figure 3.14, but for the second epoch of observations (Exp-2) taken 19.3 hours after Exp-1.
Figure 3.16: Planetary Camera (PC) cropped observations of SW1 from 1996 observations. In both observations the compass indicates the directions of equatorial coordinates. The projected solar direction and negative of the comet velocity direction are indicated by the yellow and red arrows. A scale bar shows a projected distance of 14,000 km at the location of SW1.
3.2.2 Image Analysis

The HST WFPC2 observations give us another opportunity to place constraints on SW1’s nucleus’ spin state. The high-resolution nature of the HST observations gives an advantage to those analyzed previously. In this section we briefly describe the analysis and enhancements to the images. The reader is referred to Section 3.1.2 for a more detailed description of the image enhancement techniques.

3.2.2.1 Enhancement Routines

The same suite of image enhancements described in Section 3.1.2.1 were applied to both Exp-1 and Exp-2. Figure 3.17 shows examples of the enhanced images for both epochs of observations. The asymmetry of the outburst coma is clearly visible in the enhanced images. The western side of the coma has a nearly circular appearance, suggestive of the coma morphology seen in the Kitt Peak 2008 images, and the eastern side seems to be completely lacking in noticeable scattered light between position angles ±45° centered on PA = 90°, implying a lack of coma material present. Enhanced images seem to suggest two curved features on the north and south of the coma at position angles of approximately 20°, 160°, and 250°, but these features also could be artifacts from the enhancement methods used.

Noticeable in the un-enhanced images and also in each set of enhanced images is the lack of change in overall morphology between Exp-1 and Exp-2. The images and enhanced images look like scaled versions of each other, implying no convincing features containing signatures of the nucleus’ rotation. Their lack of azimuthal evolution of features and only radial scaling hints at the similar morphology present in the Kitt Peak 2008 observations (Section 3.1).
Figure 3.17: The figure’s panels show different enhanced versions of the \textit{HST}'s Exp-1 and Exp-2. (a) shows the images after the removal of a $1/\rho$ profile, (b) shows the images after application of a radially-varying spatial filter, (c) shows the images after rotational shift differencing, and (d) shows the images after division by the azimuthal mean. Each of the enhanced observations shows clearly the noticeable east-west asymmetry.

### 3.2.3 Monte Carlo Coma Modeling

The Monte Carlo coma modeling applied to the \textit{HST} observations is similar to that used for the Kitt Peak 2008 observations. The reader is referred to Section 3.1.3 for more details. A search was made in Monte Carlo model parameter space to find combinations of parameters which would also produce the asymmetric morphology seen in the observations. No such similarity could be found when searching parameter space using a grid which included models with spin-pole orientations covering the $4\pi$ solid angle of the celestial sphere and spin periods less than a few days. This further strengthened the case for modeling the outburst observations to have a similar morphology to the 2008 Kitt Peak observations.
It is additionally mentioned that the features in the inner coma which we are investigating are well within the region which can ignore influence from solar radiation pressure. The coma expansion velocities found from modeling are on the order of 0.3 km/s. With this velocity range, the projected cometocentric distances of morphological features present in the observations, and application of Equation 3.1 we concluded that the coma features are not significantly affect by solar radiation pressure, similar to the results of Section 3.1.3.1.

3.2.3.1 Spherical-shell outburst model

Similarities between the western side of the \textit{HST} outburst coma and the overall structure detected in the Kitt Peak 2008 observations (Figure 3.1) influenced the starting parameters of modeling the \textit{HST} observations. A shell of material was assumed to be the 3-D shape of the outburst coma. Figure 3.18(a) shows the comet Exp-2 observation on the top panel and a synthetic comet image using an outburst coma model having the shape of a shell of material originating near the sub-solar point on the nucleus having the same PA as the skyplane projected Sun direction. Additionally, Figure 3.18(b) shows radial surface brightness profiles comparing the comet observations and synthetic comet image. The surface brightness profile fits between the observations and shell of material are compelling. It appears that the asymmetry present in the outburst coma are not a result of the nucleus’ rotation. The exact cause of this asymmetric dust emission is unknown, but could result from a nucleus surface feature, such as a cliff of consolidated material, near the outburst source region blocking dust emission into position angles on the eastern side of the coma. Also, dust emission from cometographic surface regions greater than 10° away from the sub-solar point produced coma models with radial surface brightness profiles which did not fit the observations well. This analysis reinforced that the source region for dust emission during the outburst was close to the sub-solar point.
3.2.3.2 Asymmetric outburst model

As described in the previous section, coma models including a spherical-shell shaped outflow of material replicates the outburst observations well, but what is producing the lack of ejected material on the eastern side of the outburst coma? The exact cause of this outburst obstruction is unknown and a detailed investigation of this phenomena is beyond the scope of this dissertation. It is hypothesized that local surface topography around the surface region of the outburst is obstructing the flow of material from expanding towards the east. Using this modeling approach, the “best-fit” modeling parameters used in the previous section are used in the modeling in the remainder of this section, but with material emission from the eastern side of the coma suppressed during modeling.

Figure 3.18: The panel shows the Monte Carlo coma modeling with an assumed shell of material similar to the Kitt Peak 2008 observations, shown in Figure 3.1. (a) The top panel is Exp-2 with four white lines indicating the position angles of the radial profiles used for comparison in (b). The lower panel shows the “best-fit” coma model for Exp-2 using a cone of outflowing material. (b) Shown are four radial profiles comparing the surface brightness characteristics of the observation and model.
This suppression of material was accomplished by excluding dust grains from being emitted onto initial trajectories toward the eastern side of the coma, but allowing emitted dust grains to evolve into the eastern side via the natural material evolution inherent in the Monte Carlo Model. Figure 3.19 shows an example of the “best-fit” Exp-2 asymmetric outburst coma model and a comparison with observations.

Figure 3.19: (a) The panel shown is similar to Figure 3.18, but now the comparison is for the “best-fit” synthetic comet image using an asymmetric outburst coma. The western side of the outburst coma is identical to that shown in Figure 3.18. Material was suppressed on the eastern side manually through modeling to replicate the asymmetric nature of the coma. (b) Plotted are the image and model’s pixel values vs. projected cometocentric distance for the four quadrants of the images providing a comparison of model fit.

3.2.4 Nucleus spin state results

Similar to the Kitt Peak 2008 observations we could not find constraints on the spin-pole direction. We proceed with modeling to find constraints on the spin period for assumed spin-pole directions.
Figure 3.20 shows an example of this modeling for one spin-pole direction. The results of the modeling are in terms of the ratio of spin period to outburst duration. Assumed values for the outburst duration covering plausible durations, we constrain the lower limits on the nucleus’ spin period: a 10 minute outburst duration results in a spin period lower limit of \( \sim 1 \) day, a one hour outburst duration gives a spin period lower limit of \( \sim 6 \) days, and finally a 10 hour outburst duration gives a spin period lower limit of \( \sim 60 \) days. The results of this second coma morphology analysis and modeling reinforce the conclusions found earlier with analysis of the 2008 Kitt Peak observations, that SW1’s nucleus seems to be in a slow rotation state. With a spin-period lower limit on the order of days. The results of this analysis are summarized below.

<table>
<thead>
<tr>
<th>Spin-Pole Orientation</th>
<th>Synthetic Comet</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image-url" alt="Diagram" /></td>
<td>![Images]</td>
</tr>
</tbody>
</table>

Figure 3.20: Panel showing examples of Monte Carlo coma models for Exp-2 for the spin pole orientation identified by the diagram to the left. The nucleus diagram is orientated with the same geometry as the images in Figure 3.16. The synthetic comet models are shown on a panel with decreasing ratio of spin period to outburst duration.

To summarize:

- The source region was found to be near the sub-solar point on SW1’s surface and to the west of the comet-Earth direction.
• The asymmetric nature of the coma morphology could be the result of non-isotropic outflow of coma material and does not originate from the rotation of the nucleus.

• 3-D Monte Carlo Coma modeling implies a lower limit to the outburst duration being on the order of days.

• The geometry of the 1996 HST observations and the Kitt Peak 2008 observations indicate that even if the spin-pole direction was pointing at the Earth during one set of observations, the lower limit the the nucleus’ spin-period still needs to be on the order of days to replicate both sets of observations.
CHAPTER 4: THERMOPHYSICAL MODELING

Thermophysical modeling of a comet’s nucleus has the goal of understanding the compositions and structures of materials contained within the interior layers of a nucleus’ interior. As was introduced in Chapter 1, this material is thought to be some of the most pristine from the beginnings of the Solar System’s formation ∼4.5 Gyr ago because of the cold interior conditions believed to be present in the deep interiors of a cometary nuclei. The material we are currently limited to observe through remote sensing techniques is either in the upper few cm of the surface, on the surface, or material recently emitted from the surface due to the comet’s activity. The interiors of comet nuclei remain a mystery. To date there has been a limited number of experiments which have successfully probed into the sub-surface interior layers of a nucleus’ interior, most notably the Deep Impact investigation of the Comet Tempel 1 (A’Hearn & Combi 2007; Schultz et al. 2007) and the Rosetta Mission’s surface lander Philae’s brief period of performance on the surface of Comet 67P/Churyumov-Gerasimenko (Kofman et al. 2015). With limited access to direct measurements of nucleus interior material, we must probe these deeper layers through the material we are able to detect, e.g. material on the surface of cometary nuclei (detected by spacecraft missions), in the gas and dust comae, and in the dust and ion tails, all of which has all undergone material processing alterations from its more pristine state. Signatures from the material's original state during formation are blurred. A link must be made between the materials we are able to directly detect today and the materials believed to have been in existence during the early stages of our protosolar nebula. Thermophysical modeling is one approach to understanding this link.

This chapter is a discussion of the developments and advances in our understanding of thermal modeling prior to many of the spacecraft visited nuclei over the last few decades. Section 4.1 gives an introduction to the methods of comet nucleus thermophysical modeling and gives details of the thermophysical model developed during the dissertation research using Python. Section 4.2 shows
examples of thermophysical modeling results for SW1 performed during this dissertation.

4.1 Cometary Thermophysical Modeling

Comet thermophysical modeling has experienced an increase in developments with the incorporation of complex physical processes thought to be occurring on cometary nuclei (Prialnik et al. 2004; Huebner et al. 2006; Capria et al. 2009; De Sanctis, Lasue & Capria 2010). The thermophysical model developed for this dissertation is based on the governing equations explained in Prialnik et al. (2004), Sarid et al. (2005), Huebner et al. 2006), and Sarid (2009) and is implemented using the Python programming language.

The model developed and used in this dissertation is as follows: The 1-D heat diffusion equation is used to solve for a radial temperature profile of the nucleus’s interior beneath a specified cometographic location assuming a rotating spherical nucleus. A Crank-Nicolson method was used for numerically solving the 1-D Heat Equation in Python. The heat equation, solving for the temperature profile ($z$ is the depth below the surface), is given by

\[
\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} - \frac{1}{c_p \rho} \sum_i q_i \mathcal{H}_i
\]  

(4.1)

where $\alpha = k/(c_p \rho)$ is the thermal diffusivity, $k$ the thermal conductivity, $c_p$ is the heat capacity, $\rho$ is the density of each layer, $\mathcal{H}_i$ is the latent heat of sublimation (or enthalpy) of the $i$-th volatile species, and $q_i$ is the volume sublimation rate of the $i$-th volatile species. In the equations $i$ represents different volatile species used in the modeling. The thermal conductivity and heat capacity are functions of the composition ($n_i$), temperature ($T$), and porosity ($\Psi$) of each layer such that $k(n_i, T, \Psi)$ and $c_p(n_i, T, \Psi)$. Their relations are derived from empirical formulae found
in Huebner et al. (2006). The heat capacity, heat conductivity, and density of the material together can be combined to form a property of the material called thermal inertia, which describes the amount of resistance to temperature changes of the material resulting from an input of energy. Thermal inertia is defined as

\[
I = \sqrt{k\rho c_p}
\]  

(4.2)

The thermal properties of the bulk material change during the evolution of the model and are calculated for each interior layer during the beginning of each time step. The values depend on the layer’s current mass fractions, porosity, temperature, and material phases (i.e. material in ice form or sublimated gas). The second term on the right-hand side of Equation 4.1 describes the heat loss due to sublimation from each layer. The volume sublimation rate of each species is given by

\[
q_i = S(\Psi, r_p) \left[ (P_i - P_i) \sqrt{\frac{m_i}{2\pi kT}} \right]
\]  

(4.3)

where \( S \) is the surface-to-volume ratio of the porous medium, \( P_i(T) \) is the saturation vapor pressure of the species, and \( P_i(T) \) is the partial pressure of the gas in the pore space of the layer. \( S \) was modeled similarly to the treatment of a distribution of cylindrical capillaries found in Prialnik et al. (2004) and Sarid et al. (2005). Gas pressures and the change in enthalpy due to sublimation, \( \mathcal{H}_i \), were calculated using empirical formulae from Huebner et al. (2006). The surface boundary condition is given by equating energy balance at the surface of the nucleus,

\[
(1 - A) \frac{L_\odot \cos z}{R_H^2} = \epsilon \sigma T^4 + \sum_i F_i P_i \sqrt{\frac{m_i}{2\pi kT}} \mathcal{H}_i + k \frac{dT}{dz}
\]  

(4.4)
where solar energy input, blackbody emission of the nucleus, heat loss due to sublimation at the surface, and heat conduction into the subsurface are included. Variables in the equation are as follows: the bond albedo \( A = 0.012 \), derived from an assumed geometric albedo of 0.04, solar constant \( L_\odot \), heliocentric distance \( R_H \), emissivity \( \epsilon = 0.95 \), fraction of surface area containing the i-th ice species \( F_i \). The \( \cos z \) term incorporates the local solar zenith angle of the cometographic surface region.

Mass loss due to volatile sublimation was included in the model by calculating the sublimation rate of three volatile species (H\(_2\)O, CO, and CO\(_2\)) for each interior layer at the end of every time step. The sublimation rate was assumed to be constant during each time step which allowed a total amount of sublimated material to be calculated. Importantly, this amount of material was then subtracted from the compositional mass fractions of the layers. Gas flow through the porous comet material and also the possibility of condensation of volatiles onto pore walls was ignored for this simple model. Any material released through sublimation was assumed to be emitted from the nucleus. This assumption implies production rates from modeling are upper limits.

Thermal evolution of the nucleus is controlled by the following equations which are used to simulate the orbit of the comet:

\[
\begin{align*}
t &= \sqrt{\frac{a^3}{GM_\odot}} (E - e \sin E) \\
R_H &= a(1 - e \cos E)
\end{align*}
\]

The equations incorporate the semi-major axis \( a \) and eccentricity \( e \) of the comet’s orbit and are functions of the eccentric anomaly \( E \). In the equations \( G \) is the gravitational constant and \( M_\odot \) is
the mass of the Sun. The first equation calculates the time since aphelion passage that has passed for a given orbital position. The second equations calculates the heliocentric distance associated with this orbital position and time.

4.2 Thermal Modeling of SW1

The thermophysical model described in 4.1 has been applied to SW1’s nucleus incorporating the nucleus size and slow spin period from measurements described in Chapters 2 and 3. Preliminary modeling results are shown for three initial progenitor nucleus configurations to highlight the capabilities of the model and also mention possible future applications for the Python-based thermophysical model.

Certain initial modeling parameters were chosen to be the same for each of the three progenitor nuclei and are summarized in Table 4.1. The initial temperature of the nucleus material was chosen to be 5 K, equivalent to a heliocentric distance of $\sim$3000 AU in the current Solar System, so sublimation rates of the volatile species could be ignored until the nucleus material was heated sufficiently by Sun. The Internal heating from the decay of radioactive nuclei is ignored in this modeling. The average capillary tube pore size of the bulk material was chosen to be 1.0 $\mu$m to represent the average grain size emitted from the nucleus as measured during the Spitzer IRS analysis (Schambeau et al. 2015) and an initial porosity of the bulk material was chosen to be 70% (from recent Rosetta mission results from comet 67P (Taylor et al. 2015)). Values for the bond albedo (0.012) and emissivity (0.95) were retained from the earlier thermal modeling efforts of this dissertation (e.g. Sections 2.3 and 3.1.4).

With little information known about SW1’s nucleus spin state, the modeling efforts of this dissertation include a spin-pole direction perpendicular to the orbital plane of SW1, a cometographic
source region at latitude = longitude = 0.0°, and the nucleus spin was ignored. Implications of this assumed nucleus spin state are that the surface region modeled on the nucleus is receiving an upper limit on solar heating. Thus, all modeling gas-production rates represent upper limits for modeling results. Future thermal modeling efforts will incorporate spin-state constraints when they become known.

The orbital evolution of each model included an inbound segment from a cold storage heliocentric distance of 30 AU to SW1’s current aphelion distance. Once at SW1’s current aphelion distance the model’s orbital evolution was set to replicate SW1’s current orbit using Equations 4.5 and 4.6 and parameters from Table 1.1. Models were evolved for 20 of SW1’s current orbital periods representing a total time of ∼ 300 years. CO-production rates from each model are compared to measurements of SW1’s CO-production rate.

Table 4.1

<table>
<thead>
<tr>
<th>Varying Parameters:</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Model #</td>
<td>Water Ice</td>
</tr>
<tr>
<td>1</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
</tr>
</tbody>
</table>

Parameters Common to All Models:

- Initial Temperature: 5 K
- Bond Albedo: 0.012
- Emissivity: 0.95
- Latitude of Source Region: 0.0°
- Initial Porosity: 70%
- Average Pore Radius: 1.0 μm

*a Percentage of the layer volume composed of material.
4.2.1 Thermal Model 1

The initial composition of Model 1 is 33% crystalline water ice, 2% CO ice, 5% CO$_2$ ice, and 60% dust by volume for each of the interior layers. Future thermal modeling efforts, after completion of this dissertation, will explore in more detail different plausible compositions for the progenitor nucleus. Figures 4.1, 4.2, and 4.3 show the evolution of the radial profile’s temperature, surface temperature, CO layer volume fraction, CO-production rate, and thermal inertia. All plots involving the radial profile’s evolution are orientated such that the surface of the nucleus is at the bottom of the figure and the time evolution goes from left to right. The top-axis label identifies the position on the plot where the model has completed the orbit identified by the label. For example, the Orbit 1 label identifies where on the plot the model has completed the evolution through one complete revolution of SW1’s current orbit. The plots includes the inbound portion of the thermal model which starts at a heliocentric distance of 30 AU and the Start label identifies when the model starts to use an orbit similar to SW1’s current orbit.

Inspection of the temperature profile evolution (Figure 4.1, top panel) shows that layers below a certain depth retain their initial formation temperature. It is interesting to note that at even a 1 m depth, the signatures of the orbital-thermal wave are not present. For Model 1, below a depth of approximately 5 meters the temperature has never heated significantly from its initial 5 K formation temperature and could represent the presence of pristine materials. Inspection of CO-ice volume fractions in Figures 4.2 shows that these layers retain their initial formation abundances of CO ice. The temperature profile represents the thermal wave’s ability to penetrate into the interior of the nucleus, thereby altering the layer’s materials. Figure 4.1 (bottom panel) shows the evolution of the surface temperature and it’s direct link to the orbital position of the nucleus. Additionally, the evolutions of layer temperatures for depths of 0.01, 0.1, 1.0, and 10 m are shown in Figure 4.1 (bottom panel). The top layers of the nucleus show a temperature fluctuation that
is directly linked with the comet’s current orbital position and which is only able to penetrate the top few centimeters of material. This region of orbital fluctuations represents the orbital skin depth of the thermal wave. All CO and CO$_2$ ice, and most water ice, is removed from these upper layers due to sublimation, representing the generation of a volatile-depleted dust mantle on the surface. The amount of sublimated material for each volatile species is removed from the interior layer’s compositions at the end of each time step to account for the mass loss due to sublimation. The temperature profile also shows depths at which certain temperatures are maintained for the entire 20 orbit evolution. These are identified on the temperature plot by horizontal transitions between colors and represent discontinuities in the thermal properties between layers of the radial profile resulting from material composition changes. A material layering structure is established by the thermal wave’s ability to penetrate below the surface. Layering depths are dependent on the volatility of the species in question.

The model’s CO-production rate was tracked during the 20-orbit evolution of SW1 and is shown in Figure 4.2 (bottom panel). There are oscillations present in the synthetic CO-production rates returned from the Python-based thermophysical model that do not seem to follow the orbital period of SW1. The oscillation are not observed for the model generate H$_2$O- or CO$_2$-production rates and are believed to be a numerical artifact in the existing Python-based code relating to the CO-production rates. The overall trend for the CO production however does follow expected trends seen in independent thermal modeling efforts (Meech & Svoren 2004; Prialnik et al. 2004). This potentially numerical artifact will be investigated before future publications using thermal modeling from the Python-based code. The CO-production rate is seen to increase quickly during the inbound portions of SW1’s model evolution from 30 AU and then slowly decays during the evolution during the 20-orbit model. No drastic changes in CO-production rate, representing outbursts, are seen with a homogeneous nucleus model. To replicate the quiescent CO-production rate measurements on the order of 1.5-2.0 x10$^{28}$ molecules/s (see Figure 1.6), requires an active
surface area $\sim 17$ times the nucleus' total surface area (using a sample of the Model 1’s production rate, $8.0 \times 10^{16}$ molecules/s/m$^2$ for Orbit 10, and SW1’s measured radius of 32.3 km). This active area fraction is extreme. Sublimation of subsurface pure CO ice, using this model’s initial homogeneous compositional volume fractions, is not an initial configuration which replicates SW1’s current CO activity. Future thermal modeling using extremes for the initial CO volume fraction of the progenitor nucleus could establish whether sublimation of subsurface pure CO ice can be a viable activity driver and will be pursued in future thermal modeling.

Figure 4.3 shows a plot of the thermal inertia evolution of each layer. The thermal inertia value of the established dust mantle, $\sim 40$ J/m$^2$ K s$^{1/2}$ is consistent with values reported from the Deep Impact, Stardust-NExT, and Rosetta missions (Groussin et al. 2013; Gulkis et al. 2015).
Figure 4.1: Evolution of the interior layer’s temperature profile (top panel) and temperature profiles for the surface of the nucleus and subsurface layers at depths of: 0.01, 0.1, 1, and 10 m (bottom panel) for Model 1. The plots are with respect to (True Anomaly + $n \times 360^\circ$), where $n$ represents the number of orbits completed.
Figure 4.2: Evolution of the radial profile’s CO volume fraction (top panel) and CO-production rate (bottom panel) for Model 1. The radial profile’s CO volume fraction evolution is depleted to a depth of $\sim 30$ cm because the plot starts after the first time step, highlighting the volatile nature of CO even at heliocentric distances of the Kuiper Belt.
4.2.2 Thermal Model 2

Model 2 has the same initial compositional configuration as Model 1 except layers between 2 to 4 meters below the surface have an increase in the initial CO ice abundance: volume fraction of 20% CO ice, 20% water ice, and 60% dust. This layering scheme models the possibility of primordial heterogeneity of ices on the scale of meters to be present in the interior layers of the nucleus during formation. These ice pockets are a hypothesized source for cometary outbursts (Prialnik et al. 2004). When the thermal wave penetrating the nucleus’ interior reaches these pockets there is an increase in sublimation rate and corresponding increase in activity.

Examination of Model 2 results shows that the temperature and thermal inertia evolution are nearly identical to those of Model 1. Figure 4.4 shows the evolution of the CO layer volume fraction and
also the CO-production rate. The thermal wave reaches the CO-ice pocket during orbit 6 where we see a corresponding increase in the CO-production rate. An increased activity is maintained for several orbits when compared to the CO-production curve for Model 1. No outburst in CO-production is observed to arise during the thermal evolution of a primordial CO-ice pocket. Varying the depth and concentration of CO ice contained in the pocket would only modify the orbit of increased activity onset and the duration of the increase activity of the, but the outburst nature of SW1 is not replicated by this process. Incorporating the presence of amorphous water ice into the initial material layerings could allow possibilities for outbursts of CO gas production due to the energy available during the exothermic amorphous-to-crystalline water ice phase transition, which will be explored in future thermal modeling efforts.
Figure 4.4: Evolution of the radial profile’s CO volume fraction (top panel) and CO-production rate (bottom panel) for Model 2. The increase in CO-production rate corresponds to the thermal wave reaching the subsurface CO ice patch. The increase production is sustained for many orbits and does not show the characteristics of an outburst.
4.2.3 Thermal Model 3

The last model shown in this dissertation is a preliminary modeling effort for the activity drivers recently introduced by the inclusion of scarp retreat. The initial composition of the progenitor nucleus is the same as Model 1, except that during the 15th orbit a slope failure is simulated by the introduction of CO ice into the uppermost layers of the model. An introduction into the physical mechanisms of scarps retreat is first introduced, followed by a summary of the modeling results.

4.2.3.1 Scarp Retreat

Our understanding of the geologic surface processes driving cometary activity have been evolving since the first resolved nucleus images from spacecraft visited comets. For example, analysis of Comet 19P/Borrelly images from the Deep Space 1 spacecraft identified localized geologic processes occurring on its surface (Britt et al. 2004) which seemed to be the dominate source regions of activity. While a broad diffuse component of gas and dust emission from dust covered surfaces may be present, spacecraft resolved images of cometary nuclei indicate that the vast majority of emission comes from a small percentage of the surface. In these regions where more freshly exposed volatile-rich material is in view of insolation. Figure 4.5 depicts one example of localized surface activity first hypothesized by observations of Comet Borrelly (Britt et al. 2004) and later verified by observations of 9P Tempel 1 (Farnham et al. 2012) and 67P (Birch et al. 2017): thermally driven fatigue of consolidated nucleus material and sublimation driven scarp retreat. In this process, a volatile-depleted topographic “cliff” cracks under thermally induced stresses caused by the temperature differential of the low thermal inertia material eventually resulting in scarp slope failure. Once collapse occurs, more pristine, volatile-rich material is exposed on both the cliff face and also in the talus pile of debris. Figure 4.6 depicts a more zoomed-in view of this process.
Figure 4.5: Cartoon depicting possible surface activity processes on cometary nuclei, potentially leading to freshly exposed volatile materials on the surface resulting in an outburst of activity. Time increases from (a) - (d). The image is adapted from Figure 12 in Birch et al. (2017), which they describe the process as follows: “Blue materials represent volatile-rich regions, while grey/black portions represent non-volatile lag materials. Pits...represent those forming in a lower permeability substrate where negative relief is generated more violently, either through collapse or explosive outgassing. Regions of negative relief, and free of non-volatile lag materials act as instability points for scarp-induced erosion that acts to increase pit width and/or reduce wall slopes. Insets show OSIRIS WAC images of pits at different evolutionary stages.” (Note: Birch et al. (2017) is referring to the OSIRIS Wide Angle Camera onboard the Rosetta spacecraft.)
Figure 4.6: Cartoon depicting thermal fatigue of consolidated material and sublimation induced scarp retreat as a source of surface activity. Image from Figure 10(b) in Birch et al. (2017).

Figure 4.7 shows results of the preliminary thermal modeling of a slope failure event and the CO-outburst to follow. Inspection of the lower panel shows the same evolution of CO-production rate as seen in Model 1 (Figure 4.2 (bottom panel)). During Orbit 15 the slope failure is triggered and a relatively short-lived (on the order of hours) increase in CO production is observed. The exact CO-production rate depends on the size and depth of the freshly exposed CO ice, but the general properties of an outburst are replicated with this model.

Efforts for future thermophysical modeling must include such scarp retreat processes because of their likelihood to be present on all cometary surfaces. Modeling of this process eventually must incorporate a 2-D model of local surface topography. This thermal modeling approach could indicate if this process is occurring on SW1. Slight modification to assumptions could be as follows: (1) scarps on SW1 have exposures of amorphous water ice on or near their surfaces which is driving the quiescent activity through the releases of gases during the amorphous-to-crystalline water ice phase transition. (2) A periodic slope failure occurs on the scarp, described in (1), driven by the combination of: thermal fatigue and material weakening due to the crystallization of water ice. (3) The slope failure leads to the exposure of a high concentration of fresh amorphous water
ice which quickly crystallizes exothermically (releasing supervolatile gases possibly trapped in the pore space of the amorphous water ice) or other supervolatile species (e.g. CO or CO$_2$) which quickly sublimate leading to a rapid increase in both gas and dust production (i.e. an outburst). Future thermophysical modeling with the inclusion of rheology of surface materials is the next step in a better understanding of SW1’s behavior.
Figure 4.7: CO-production rates for Model 3 showing outburst like behavior. The bottom panel shows the production rate with the same ranges for the axes as Figure 4.2 (bottom panel) for comparison. The production rate due to the slope failure is $\sim 10^{12}$ times higher than the production rate in Model 1, which does not include the slope failure, for the same time in the thermal model’s evolution.
CHAPTER 5: THE FUTURE OF COMETARY SCIENCE

Cometary science is entering a new and exciting era because of the acceleration of observational campaigns surveying more statistically significant numbers of comets. The characterization of larger numbers of comets will reveal statistical trends in nuclei compositions and link this information to their the dynamical groups. Once and for all allowing links between the orbital properties of the current comet populations, including knowledge of their nuclei compositions, to their initial formation regions in the early SS.

As emphasized in Section 1.1.3.3, the Centaur-to-Jupiter family transition region contains a relatively uncharacterized populations of small icy bodies in an orbital space outside of the dominance of water-ice sublimation. Investigation of this population allows other possible nuclei volatiles, which are often masked due to the relatively high water-production rates for closer-in objects, to be detected and more fully characterized. SW1 is one of the largest and most historically observed from this population. This dissertation has explored SW1 in detail, with the goal of linking what we learn from this individual comet to the population of icy bodies in this transitional region. Observational efforts during the National Optical Astronomy Observatory (NOAO) 2016A, 2017B, and 2018A semesters by myself and several collaborators (most notably Yan Fernández and Laura Woodney) have acquired high-cadence imaging of several JFCs with perihelion larger than 4.5 AU using the Kitt Peak WIYN 0.9-m and Cerro Tololo SMARTS 0.9-m telescopes. Figure 5.1 shows examples of observations for several comets showing both active and inactive nuclei at large heliocentric distances. SW1 has shown cometary activity can be very dynamic on many time scales when water sublimation is not the driver. It is uncertain whether SW1 is unique in this activity pattern or if there are other high-perihelion JFCs also showing this activity variability. Given SW1’s erratic activity, the question arises: is this activity pattern truly unique or do other comets in similar orbits display matching behavior? Is SW1 simply the best known and brightest of a whole sub-
population of comets with continuous and highly variable activity driven by processes other than water sublimation? Future high-cadence observational campaigns of other distantly active comets will place SW1 in context with the larger populations of icy bodies in this orbital environment.

Figure 5.1: Panel showing 6 JFCs with perihelion larger than 4.5 AU observed in the R-band from either the SMARTS or WIYN 0.9-m telescopes during my dissertation research project. The comet is at the center of each panel. The comet name, heliocentric distance \( R_H \) and geocentric distance \( \Delta \) at time of observation are indicated on the image. The top row shows comets active during observations and the bottom shows comets displaying no extended emission.

The research efforts of this dissertation have focused on measuring nucleus properties of SW1 for use in thermophysical modeling applications to better understand its enigmatic activity patterns. Individual dissertation research results include: establishing confidence in measurements of SW1’s large nucleus size when compared to other JFCs, a nucleus surface characterized by a low thermal inertia, and constraints on the nucleus’ spin period (Schambeau et al. 2015; 2017). These nucleus properties were used as input parameters for preliminary nucleus thermophysical modeling of SW1 contained in this dissertation and will be included in future thermal modeling efforts. It is highlighted that thermal modeling results for SW1 will potentially be more robust when compared to other comets in this orbital space because of the higher number of observations over a long baseline which have been acquired for SW1 due to its nucleus’ larger size and activ-
ity level, leading to more constrained thermal models. Compositional and structural constraints returned from SW1’s thermal modeling can be used as the initial guesses for progenitor nuclei in modeling efforts for other less commonly observed Centaur-to-Jupiter family comets. This will aid in compositional studies of a larger group of comets in this orbital space. To improve future thermal modeling efforts of SW1, my dissertation research has indicated future projects which are possible with currently existing observational facilities to better understand this comet. Several of these projects are described here with justification as to why these future observations would hold significance. Additionally, observational facilities coming online over the next decade have potential to accelerate our understanding of SW1 through their higher resolutions, higher sensitivities, and increased wavelength range for future observations. This chapter and this dissertation are concluded by the description of a hypothetical spacecraft mission to SW1, which represents the pinnacle of observational strategies to better understand the enigmatic nature of this intriguing comet.

5.1 SW1’s Nucleus Spin State

Analysis of SW1 outburst observations described in Chapter 3 has indicated that the nucleus is rotating very slowly, with a lower limit for the spin period on the order of days. If SW1’s spin period is truly this slow it could be one of the slowest rotating comets when compared to ensemble properties for known cometary spin states (Samarasinha et al. 2004; Kokotanekova et al. 2017). Future observations and modeling approaches to more concretely measure SW1’s spin state are necessary for future thermal modeling efforts and are described in this section.

A natural step after analysis contained in this dissertation for future observations to constrain the nucleus’ spin state is to acquire high-resolution observations of SW1 while not in an outburst phase of activity. Focusing on coma morphology originating from dust emission from continuous jet fea-
tures. This would eliminate the uncertainty of coma morphology analysis and modeling inherently having the spin-period-to-outburst-duration ratio degeneracy seen in the modeling efforts of Chapter 3. Using continuous jet features eliminates the uncertainty of outburst duration from the 3-D Monte Carlo coma modeling. An example of this type of observation is highlighted by images of SW1 during a period of quiescent activity acquired by the *HST* Wide Field Camera 3 from program GO-11536, which imaged the comet during three epochs in 2010: May 17, June 21, and October 29. Figure 5.2 shows an example image along with enhancements to this image similar to those described in Chapter 3. The enhanced images show a comma-shaped feature, implying signatures of nucleus rotation. Unfortunately, the planing of the 2010 observations only included two exposures, separated by minutes, for each of the three epochs. Follow up observations on the order of hours to days would potentially have allowed detection of coma morphology evolution. Observations of continuous jet features such as these acquired using high-resolution imaging systems (e.g. *Gemini*, *HST*, and in the future *JWST*) could once and for all determine the nucleus’ spin state.
Figure 5.2: Panel showing the UT 2010-06-21 WFC3 observation of SW1. This represents one of the highest resolution images of SW1: \( \sim 200 \) km/pixel. A scale bar indicates a skyplane project distance at the location of the comet of 12,000 km. The orientation is shown by the white arrows. The anti-solar direction is indicated by the yellow arrow and the negative of the comet’s projected velocity direction is indicated by the red arrow. Orientation and scale of each panel are the same. A curved comma-shaped feature is clearly seen in the \( 1/\rho \) removal enhanced observations, potentially representing a coma feature reflective of the nucleus’ rotation. But feature could also be the result of solar radiation pressure on dust grains forming the comet’s tail. A follow up WFC3 observation or series of observations hours to days afterwards potentially could have determined if this feature was due to nucleus rotation or to solar radiation pressure effects. While it is unfortunate a second observation with an appropriate time interval was not obtained, the presence of this WFC3 observation shows the utility of future high-resolution observations of SW1 in a state of quiescent activity for determining nucleus spin-state measurements.

5.2 SW1’s Nucleus Shape

Measurements of SW1’s shape have been limited, with one published ellipsoidal minimum-to-maximum cross-section ratio reported at \( a/b = 2.6 \) through photometric light curve analysis (Meech et al. 1993). A future observational strategy to obtain shape information about SW1’s nucleus involves the acquisition of high cadence multi-broadband filter infrared imaging over the course of several days. More specifically the acquisition of several broadband near- and mid-
infrared filter images acquired in a short duration time sequence, on the order of minutes, at several epochs over the course of several days. A future system ideally suited for such an observational strategy is the JWST Mid-Infrared Instrument (MIRI), which has 9 broadband IR imaging filters from 5.6-25.5 µm. A hypothetical observing strategy and image analysis would proceed as follows: (1) image SW1 in each of the 9 broadband infrared filters with the spacing between each imaging being the minimal instrument overhead time. (2) Image SW1 using the same procedure at (1) with the spacing between each 9-filter set on the order of one hour for the course of a week. (3) Implement the coma modeling and removal procedures from Chapter 2 for nucleus photometry measurements for each of the 9-image observational epochs. (4) Apply the NEATM to each of the 9-image observational epoch nucleus photometry measurements, retrieving an effective radius measurement from each model. (5) Analyze the effective nucleus size measurements to see if any periodic nature exists. Potentially, if there is a high enough cadence between the 9-image infrared observation sets there could be a spin-period measurement too.

5.3 Future Thermophysical Modeling Methods

Thermophysical modeling techniques for cometary nuclei must experience a revolution due to the complex nature of geologic surface processes driving activity which have been identified through spacecraft visited nuclei over the last two decades. Previous use of such models has been of utility by laying the groundwork for our understanding of the interiors of commentary nuclei (e.g. Meech & Svoren 2004; Prialnik et al. 2004), but these models lack the complexity to accurately model the physical processes occurring on their surfaces and in sub-surface layers. Spacecraft missions to comet nuclei have turned them into geologic objects “with complex surface processes and a rich history of erosion and landform evolution” (Britt et al. 2004). Future modeling efforts of activity drivers must included these observed processes.
One such example of surface-process driven activity was demonstrated in Section 4.2.3.1 for the increase in activity associated with freshly exposed volatiles after the collapse of a cliff during scarp retreat. Another possible activity driver for outburst behavior involves pressurized gas-filled subsurface cavities eventually reaching pressures that exceed overlying material strengths leading to the disruption of surface dust mantle. Figure 5.3 depicts the process as described by Belton & Melosh (2009). Theories of pressurized subsurface cavities being the driver of SW1’s outburst activity have been proposed (Ipatov & A’Hearn 2011; Ipatov 2012; Gronkowski 2014), but little detailed thermophysical modeling results have been published to date. Observational evidence for this outburst process is likely to have been identified on 67P by the Rosetta spacecraft (Agarwal et al. 2017), increasing the urgency to better understand this physical mechanism through modeling efforts.

Figure 5.3: Cartoon depicting the process of cometary outburst through the release of pressure from sub-surface gas-filled cavities. Image from Figure 6 in Belton & Melosh (2009).
5.4 Spacecraft Mission to SW1

To conclude my dissertation, I explore possibilities of accomplishing a better understanding of SW1 through a hypothetical spacecraft mission to this comet. Described are science goals for studying SW1 in situ along with possible instrumentation which would allow observations to address these science goals. For this gedanken-experiment mission concept I’m ignoring normal budgetary and spacecraft payload limitations. Science goals are presented in a list format with each goal having an example instrument or suite of instruments whose observations could address the individual science goal. Implications for how each science goal informs our greater understanding of SS are also given. This is not an exhaustive list of possible science goals, but a list of possibilities highlighting my current desires for the advancement of our understanding of SW1.

- **Science Goal**: What is the composition of SW1’s nucleus? What does its composition indicate about the temperature(s) present during its formation?
  
  - **Instrument**: Infrared imaging spectrometer.
  
  **Implications**: High-spatial and high-spectral resolution infrared spectral mapping of SW1’s nucleus surface and inner coma would allow the identification of material compositions on the surface and in the inner coma. Spectral mapping of the inner coma region could reveal the parent gas species which is responsible for the comet’s distant activity. In particular the infrared CO emission lines could trace the source regions for CO emission on the surface. Additionally, the near-infrared spectral mapping of the inner coma could reveal signatures of water ice grains, most importantly their 1.5 \( \mu m \) and 2.0\( \mu m \) absorption features comparing amorphous vs. crystalline forms.

  - **Instrument**: Lander with radio wavelength transmission sounding capabilities.
  
  **Implications**: Mapping of the radio wavelength’s signal propagation through the in-
terior of the nucleus would allow determination of the material’s electric permittivity. The interior permittivity would be investigated for its uniformativity. A nucleus with a uniform permittivity could imply SW1’s formation was from one single accretion event. Alternatively, a heterogeneous permittivity could imply the formation of SW1’s nucleus is the combination of many different, smaller units of homogeneous material composition, which coalesced through low-impact collisions.

– **Instrument**: High velocity nucleus impactor. **Implications** Similar to the Deep Impact mission’s goal (A’Hearn & Combi 2007) of excavating material from the subsurface of Comet 9P/Tempel 1, the impactor would allow the analysis and collection of material’s in cold storage below the nucleus’ surface. Using the remote based instruments described above this excavated sub-surface material could be investigated for its compositional makeup.

* Science Goal: What is the shape of SW1’s nucleus?

  – **Instrument**: Optical imaging camera.

    **Implications**: If the nucleus is a single mostly spheroidal shape of ~ 60 km in diameter it could represent its formation was from the accretion of a single body in an environment less prone to collisions. If the shape is bilobed it could represent a body that formed in an environment including more collisions between bodies.

* Science Goal: What are the activity drivers for SW1’s activity?

  – **Instrument**: Optical imaging camera.

    **Implications**: High resolution images of SW1’s surface would allow the identification of regions which are emitting gas and dust. Are the regions of quiescent activity at the same cometographic locations as the outbursts? What surface topography is associated with both states of SW1’s activity?
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