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The Effects of Extinction on the Galactic Nova Rate

Adriana S. Delgado-Navarro
Clemson University

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THE EFFECTS OF EXTINCTION ON THE GALACTIC NOVA RATE

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Physics

by
Adriana S. Delgado-Navarro
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Accepted by:
Dr. Dieter H. Hartmann, Committee Chair
Dr. Mark Leising
Dr. Jeremy King
Abstract

Although many efforts have been made to correctly predict the total galactic nova rate, inconsistencies in the literature of the last two decades have shown that this issue remains largely unresolved. Since 1993, predicted global rates have varied from $20 yr^{-1}$ [Della Valle and Duerbeck, 1993], and $41 \pm 20 yr^{-1}$ [Hatano et al., 1997], to $30 \pm 10 yr^{-1}$ [Shafter, 2002]. Comparisons with observed quantities at around $5-10 yr^{-1}$ within the past 50 years show evidence that one of the largest physical inhibitors of nova observability within the Milky Way is extinction. Here, a dust extinction calculator was developed based on an axisymmetric double exponential dust distribution. The objective of this project was to develop a nova distribution model that would ultimately reproduce the observed nova rate when extinction is accounted for. The resulting product of these models showed that, with a simple double exponential distribution of novae, for which only 16 nova are ultimately observable in any given year and 10 observed, the number of novae erupting within the galaxy must be approximately $48 yr^{-1}$. This information is then compared with the CBAT list of data from all novae that have been recorded since 1612. The concluding remarks of this work are such that, although this model is rudimentary, adding the effects of a galactic bulge and spiral arms into the dust and novae distribution would improve upon it and serve as a good starting point for research regarding the relationship between galactic structure and observations of novae and other phenomena.
Dedication

For my grandma, who never ceased to be amazed by the little things in life.
Acknowledgments

I would like to thank my advisor, Dr. Dieter H. Hartmann, for guiding me through this project, as well as my committee members, Dr. Mark Leising and Dr. Jeremy King, for their sound advice.

I’d also like to thank the many graduate students in the Clemson University Physics and Astronomy Department for helping me through these past several years as both friends and colleagues. In particular, I’d like to acknowledge Amanpreet Kaur, Joshua Wood, and Jared Lalmansingh for their patience and support with all of my programming woes, as well as all of the other kindred spirits that I have had the pleasure to call my friends.

Finally, I would like to thank my family and friends back home for trusting me to choose my own course in life, and supporting me through thick and thin.
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Chapter 1

Introduction

Novae are observed when a white dwarf undergoes a rapid increase in brightness of approximately 9 magnitudes and gradually declines to a quiescent phase. This phenomenon occurs when the mass accretion from a large companion star, usually a main sequence or red giant star, ignites on the degenerate surface of the white dwarf, resulting in a thermonuclear runaway. Although novae are not as bright as supernovae, they are thought to be related, and could quite possibly be progenitors to Type Ia supernovae. Novae occur much more often, however, and can be helpful in estimating distances to closer galaxies as well as contribute to the interstellar medium. This is due to the majority of classical novae having approximately the same peak absolute magnitude of about $M_V = -7$ or $M_V = -8$ [Bode and Evans, 2008, Hernanz, 2004].

1.1 History

Due to the usefulness of novae as distance indicators, as well as their important contributions to the interstellar medium, being able to estimate where novae are likely to occur has been an important goal for astronomers wishing to observe their properties [Della Valle and Livio, 1995, Gehrz et al., 2014]. For other galaxies which encompass much smaller areas of the sky, observations are fairly straightforward. Unfortunately, since novae only reach a peak magnitude for a short while, the opportunity to observe all or part of their progression into quiescence is restricted by their high apparent magnitudes caused by extragalactic distances. While galactic novae might seemingly present the ideal nearby observing environment, they come with their own set of complications.
These include the Sun’s placement in the disk of the Milky Way as well as the difficulty in observing the vast amount of sky that the galactic plane occupies.

1.1.1 Nova Observations

The first nova observation, as recorded by western astronomers, occurred in 1612 by German Jesuit priest and astronomer Christoph Scheiner [Drake, 2014]. Prior to this date, several naked-eye observations of ”new stars” had been observed, but have since been confirmed as supernovae or other types of variable stars. It was not until the tail-end of the 1800’s that novae started being observed regularly due to the use of photographic plates in monitoring the night sky [Bode and Evans, 2008]. After this, several sky surveys were introduced in the northern hemisphere, and in 1911, the AAVSO (American Association of Variable Star Observers) was formed dedicated to the discovery of variable stars through a collaboration of international amateur and professional astronomers [AAVSO, 2015]. In the late 20th century the introduction and commercial replacement of CCD detectors, as well as the vast contributions of amateur astronomers, had more than doubled the number of observed novae from about 2-3 in the 19th century to about 4-7. Recently that number has jumped again to an average just below 10 per year in the past decade thanks to improved optics, more telescopes, and more frequent sky coverage courtesy of amateur astronomers. Figure(1.1) shows the number of nova outbursts observed from 1612 through the year 2014 [International Astronomical Union, 2010, Mukai, 2015]. From this plot, it is plain to see that, as more efficient observations of the night sky are made, more novae are likely to be observed.

1.1.2 The Galactic Nova Rate/Distribution

As stated in the previous section, the number of novae observed per year has steadily increased over the past century thanks to improved technologies and greater sky coverage. However, it is unlikely that astronomers would ever be able to directly observe all of the novae that occur throughout the galaxy thanks to foreground light, extinction, etc. Attempts to correct for these obstacles have wisely put predicted galactic nova rates well above the observed rate. However, uncertainties in the knowledge of our own galactic structure and evolution have lead to large inconsistencies. To correct for this, astronomers have taken many different steps to try and come to a conclusion.
Some of the earliest estimates of galactic nova rates were wildly contradictory, ranging from $11 \text{yr}^{-1}$ to $260 \text{yr}^{-1}$ since 1972 [Shafter, 2002]. Thankfully, within the past couple of decades, that number has gradually become a little more consistent. In 1993, Della Valle and Livio predicted a global rate of approximately $20 \text{yr}^{-1}$ based on extragalactic rates. They took known rates from galaxies such as M31 (then $\sim 30 \text{yr}^{-1}$), LMC, M33, and NGC 5182, and concluded that there must be a connection between galaxy morphology and nova rate. They predicted that novae in the Milky Way would be similar to M31 and would predominantly occur in the bulge [Della Valle and Livio, 1994, Della Valle and Duerbeck, 1993]. A few years later in their 1997 paper, Hatano et al. concluded that the galactic nova rate should be $41 \pm 20 \text{yr}^{-1}$ based on a simple Monte Carlo dust and nova distribution. Contrary to the popular notion at the time that novae were produced primarily in the bulge, they argued that based on stellar population studies, there should be more novae found within the disk as opposed to the bulge [Hatano et al., 1997]. This work has often come under critique, however, as their large error estimates come from separating observed bulge and disk populations.
according to apparent magnitude instead of known distances and then applying those assumptions to their model. In addition, they recognize that their uncertainties could be a factor of 2 greater due to an adopted rate of nova occurrences having $m_V < 11$ determined by Liller and Mayer’s $73 \pm 24yr^{-1}$ 10 years earlier [Hatano et al., 1997, Liller and Mayer, 1987]. In 2002, Allen Shafter came to the conclusion that the galactic rate of novae is actually $30 \pm 10yr^{-1}$ based on both extragalactic studies and an internal galactic structure study founded on the observed rate, resulting in $\sim 30yr^{-1}$ and $\sim 25yr^{-1}$ respectively [Shafter, 2002]. He later recognizes, however, that his results should be taken as a lower limit since he assumes that all novae brighter than $m_V < 2$ have been observed in the past. As should be noted by Shafter’s work, many of these predicted rates can be considered closer to the lower limit of the actual rate. The reason for this is that, while many astronomers take into account that dimmer novae may go unnoticed, it is possible that even the brighter novae may not be recorded simply due to limitations in regular sky coverage. Several other studies have been performed to predict the galactic nova rate, but as these are the most noteworthy, it goes to show that the number still remains elusive.

### 1.1.3 Galactic Dust and Extinction

Evidence of the effects of dust extinction on the observational properties of astronomical phenomena date back to the beginning of the 20th century when Edward Barnard first attributed the dimming of stars to a mysterious “absorbing medium” [Draine, 2011]. Later, in 1930, Robert Trumpler definitively showed the effects of this dust “extinction” through his observations of open clusters. Since then, extinction, or the absorption and scattering of light along a particular line of sight, has played a vital role in observations of intra and extragalactic objects. The Earth’s galactic position within the disk, in particular, makes it difficult to observe anything in the direction of the galactic plane due to the concentrated amounts of dust and gas obscuring objects behind it. In the past 10 years, several attempts have been made to model this material, but there still remains ambiguity, particularly with respect to the galactic center [Amôres and Lépine, 2005, Drimmel et al., 2003, Marshall et al., 2006, Misiriotis et al., 2006]. The combined effects of heavy extinction and source confusion for galactic latitudes within about 10° of the center, colloquially named the ”Zone of Avoidance”, often result in this area being omitted in such models [Marshall et al., 2006].

Due to the varying levels of opacity in the dust and gas at different wavelengths, objects
most traditionally viewed in the optical wavelengths, such as novae, are often lost to obscurity, and
direct observations of the properties of the obscuring medium become impractical. As a result,
the basis for galactic dust models have relied on such tools as color-excesses of stars using optical
surveys such as the Sloan Digital Sky Survey (SDSS) [Berry et al., 2012], more accessible infrared
observations of the dust with the Two-Micron All Sky Survey (2MASS) [Marshall et al., 2006], and
the near and far infrared instruments aboard the Cosmic Background Explorer (COBE) satellite
[Schlegel et al., 1998, Drimmel and Spergel, 2001, Misiriotis et al., 2006]. Moreover, in order to get
a more complete view of the galactic center, the high resolution radio maps at the Very Large Array
(VLA) were used in conjunction with infrared observations to better understand extinction there
[Fritz et al., 2011].

1.2 Research Goals

Even though galactic nova rate models have been gradually becoming more cohesive, there
have not been many published studies that take into account recently collected data. The study
described in this paper includes the additional data from confirmed galactic novae gained within
the past 15 years as well as all galactic novae observed since the 1612 outburst. Similar to models
that have come before, this study bases its predictions on galactic structure models of dust with an
assumed distribution of novae. The ultimate goal of this project was to develop a galactic extinction
integrator and novae distribution model that, when observability was accounted for, the observed
rate of galactic novae was reproduced. Since achieving this number requires an input of a certain
number of novae produced in the galaxy as a whole, this would, in turn, result in finding what the
global galactic nova rate must have been.

1.2.1 Outline

In order to understand the true nature of this project, as well as the importance for having
an extinction model for the Milky Way, this paper will first discuss plenty of relevant information
prior to the explanation of how these models were constructed. As can be seen by Chapter 1, the
Introduction served to present the necessary information needed to understand the difficulties in the
field that spurred the need for this work to be conducted. Chapter 2 will serve as a more in-depth
discussion on novae, their properties, and importance to astronomy. Chapter 3 will primarily discuss
the properties and effects of interstellar dust as it relates to observations. Chapter 4 will discuss the
distribution and characters of all the observed novae presented in section (1.1.1). Development of
the line-of-sight extinction model will be presented in Chapter 5, and that of the nova distribution
model in Chapter 6. Chapter 7 will serve as a walk-through of the implementation of combining both
models with observational bias as well as a discussion of results. Finally, Chapter 8 will conclude
this report with a summary of results as well as further implications.
Chapter 2

Novae

Due to the nature of their explosions, novae have been studied for a variety of reasons. One of the primary reasons for their analysis in the past has been that they can be used as extragalactic distance indicators. Another is that they are thought to be hubs for much of the synthesis of heavier elements in the galaxy as well as known producers of interstellar dust. This chapter outlines all of these important qualities as well as the underlying properties of novae, which will be discussed first.

2.1 Observed Properties

There are many different subtypes of novae, but it is generally agreed upon that they all originate from binary interactions between a white dwarf and a companion star that accretes matter onto its surface at a rate in excess of $\sim 10^{-11} M_\odot yr^{-1}$ [Bode and Evans, 2008]. The conditions necessary for development of this binary system are that, in its main sequence stage, the primary ($2 - 10 M_\odot$) does not fill its Roche Lobe until the electron-degenerate core (white dwarf $\sim 0.5 - 1.3 M_\odot$) has been established [Bode and Evans, 2008]. The orbital separation of the two stars is then decreased to where they share a common envelope resulting from the overlap in their gravitational potentials. When the stars are close enough for the evolving companion star (usually a main sequence or red giant) to exceed or nearly exceed its Roche Lobe, mass transfer can occur. The main driving force behind this mass transfer, besides gravitational attraction of the secondary’s outer material from the primary, stems from the effect of magnetic stellar winds originating from the companion star [Soberman et al., 1997, Bode and Evans, 2008]. At this point, the material is no longer gravitation-
ally bound to the companion and is free to flow onto the white dwarf. Since the white dwarf is composed of degenerate matter, accreted material is unstable as accumulating mass begins burning via the CNO cycle. The degenerate nature of the primary prevents the white dwarf from expanding significantly with increasing temperature. Therefore, even though the accreted material may burn for quite some time, unstable Hydrogen burning will eventually result in a thermonuclear runaway and produce what is known as a nova outburst on the dwarf’s surface. Unlike in a supernova, the white dwarf and companion are not destroyed, and the system can resume accretion. For this reason, novae fall under the class of stars known as cataclysmic variables. Once they explode, they ease back into quiescence over the course of a month or so. For most classical novae, their initial ascent to maximum luminosity usually takes only a few days, a time rarely captured during observation. This rise in brightness will typically present itself as a decrease in apparent magnitude of more than 9 magnitudes, and absolute magnitudes will reach average lows of about $< M_V > = -7$ or $-8$, due to a bimodality in novae types. [Bode and Evans, 2008, Hernanz, 2004]. Some novae, however, have reached absolute magnitudes between $M_V \approx -6$ and $M_V \approx -10$ [Shafter, 2002].

Novae are generally categorized based on their speed class, or how long it takes for their luminosities to drop by 2 or 3 magnitudes of their peak brightness. These times are often represented by the variables $t_2$ and $t_3$ respectively. These range from very fast and fast ($t_2 < 10$ days and $t_2 \sim 11 - 25$ days) to very slow ($t_2 \sim 151 - 250$ days) [Hernanz, 2004]. Typically it is observed that there is a relationship between absolute magnitude and the speed class of the nova. Faster novae tend to be brighter, and often experience a super-Eddington phase due to more massive white dwarf cores, and slower novae tend to be lower in luminosity [Livio, 1992]. Furthermore, there is also a tendency in spatial distribution. Faster novae appear more often in the disk and slower novae in the bulge [Livio, 1992, Della Valle and Livio, 1995, Hernanz, 2004].

Besides speed classes, novae also exhibit two main spectral types based on which emission lines appear strongest in their early post-outburst phase: He/N and FeII. It has been theorized that He/N lines are associated with fast and bright novae which show high expansion velocities and possibly originate from ONe white dwarves. FeII novae are considered to belong to the slower, fainter thick-disk and bulge population [Della Valle and Livio, 1998]. In truth, it is suspected that virtually all novae pass through some level of FeII in their evolutionary stage, and so another way of distinguishing subclasses of novae is by the composition of the underlying white dwarf. Most literature will refer to these as CO or ONe (also called ONeMg) novae and are characterized by the
strong absorption features of these elements in their infrared spectra [Bode and Evans, 2008].

Finally, although novae present a variety of different decay rates in their lightcurves, it is believed that over time all novae are eventually recurrent. Nonetheless, there are novae that are specifically categorized as recurrent novae which include all those which have been observed to erupt more than once in the span of 100 years. Currently, there are only about 10 of these known in the galaxy [Della Valle and Livio, 1996, Kato and Hachisu, 2012].

2.2 Distance Indicators and Relation to Supernovae

As stated in the previous section, novae can be used as distance indicators similar to their supernovae counterparts. However, as their absolute magnitudes only reach around $< M_V > = -7$ or $-8$, they cannot be relied upon for large distances upwards of several Megaparsecs. Therefore, they are much more effective at estimating distances to nearby galaxies, particularly within the Local Group. In order to accurately get a distance measurement, however, the absolute magnitude must be known for each eruption. Unfortunately, not all novae display the same types of light curves nor the same exact peak magnitudes despite the average. In order to get the true number, astronomers must consider the observed maximum magnitude versus rate of decline (MMRD). This relation takes into account the speed class of the nova obtained from its lightcurve. As touched on in the previous section, these speed classes correlate with where and how bright novae are able to get. In a study conducted by Della Valle and Livio in 1995, it was found that novae originating from ONe white dwarves (those related to faster,brighter novae) follow the MMRD relation more closely than white dwarves of CO [Della Valle and Livio, 1995]. Likewise, faster ”disk” novae tend to have absolute magnitudes closer to $M_V \approx -8$ and slower ”bulge” novae $M_V \approx -7$, though these fainter novae tend to be more common [Hernanz, 2004]. Comparisons of these values with galaxy morphology result in fairly reasonable distance measurements [Della Valle and Livio, 1995].

In addition to estimated distances, it is theorized that novae could also serve as progenitors to Type Ia supernovae. The leading theory on Type Ia’s is that they also occur in binary systems similar to that of a nova, except that the core is a white dwarf that nears the Chandrasekhar Mass limit of $1.4M_\odot$. The theoretical nova that could lead to a supernova explosion is most often thought to be recurrent nova, as their frequent outbursts require the presence of a massive white dwarf. For these novae in particular, the later phases of the outbursts often become supersoft X-ray sources that
overlap with a plateau and the ejecta have no heavy element enhancement [Kato and Hachisu, 2012]. These ingredients paired with the right companion star could be ideal for creating a supernova.

2.3 Contribution to the Interstellar Medium

Every time a nova explodes it expels synthesized material into the interstellar medium. If it is true that all novae are in fact recurrent, and are not completely destructive, then this poses a strong claim that novae are important contributors to galactic chemical evolution and dust production. Before reviewing the abundances and percentages described below, it is important to note that all of these values are based on underlying nova rates, many of which assume \( \sim 30 \text{yr}^{-1} \). If the rate were to change, then it would impact how much novae are considered to be relevant contributors in each case.

2.3.1 Nucleosynthesis

Despite having powerful outbursts with ejecta velocities between 1000 and 3500km/s and temperatures reaching as high as \((2 - 3) \times 10^8 \text{K}\), novae only contribute about 0.3\% of galactic interstellar matter [Bode and Evans, 2008, Gehrz et al., 2014, José and Hernanz, 2007]. Some of the most notable nuclides that are synthesized in nova explosions are \(^{13}\text{C}\), \(^{15}\text{N}\), and \(^{17}\text{O}\) and \(^7\text{Be}\) to \(^7\text{Li}\), the latter of which has both galactic and cosmological implications [José and Hernanz, 2007].

In the case of \(^{13}\text{C}\), \(^{15}\text{N}\), and \(^{17}\text{O}\), these are the nuclides that are both created and destroyed at the time of the triggered explosion and expansion via the CNO cycle. At peak temperature, \(^{13}\text{N}\), and \(^{15}\text{O}\) are a couple of the most over-abundant and short-lived nuclei that also happen to be unstable. A following of beta-decays and proton captures rapidly ensues to produce ejecta that are rich in C, N, and O isotopes [José and Hernanz, 2007]. For novae, when production of some isotopes reach factors around \(10^3\) with respect to solar, they are considered to contribute to galactic abundances. In a nova nucleosynthesis model of CO and ONe white dwarves of mass \(1.15M_\odot\), where there is 50\% mixing with the core and an accretion rate of \(2 \times 10^{-10}M_\odot \text{yr}^{-1}\), O isotopes have overproduction factors around \(10^4\) solar [Hernanz, 2004]. Galactic \(^{17}\text{O}\), in particular, is suspected to be almost entirely of nova origin [Hernanz, 2004].

The mysteries behind \(^7\text{Li}\) and \(^7\text{Be}\) are more intriguing on a larger scale, especially since the topic of \(^7\text{Li}\) production through the thermonuclear runaway model of a nova is not widely agreed
upon [Bode and Evans, 2008]. As one of the primordial constituents of the Big Bang, knowledge of 
\(^7\)Li can lend some insight into cosmological chemical evolution. As far as the nova contribution to the 
galactic content goes, \(^7\)Li production is a small, but not irrelevant (\(\sim 15\%\))[Bode and Evans, 2008, 
Hernanz, 2004]. While direct \(^7\)Li overproduction alone is just at \(10^3\) and \(10^2\) solar for CO or ONe 
novae respectively, it can be produced by other means as well [Hernanz, 2004]. Currently, galactic 
chemical evolution models show that abundance levels could not be as high as they are without the 
presence of novae [Bode and Evans, 2008, José and Hernanz, 2007, Hernanz, 2004]. Additionally, 
\(^7\)Be plays an important role in \(^7\)Li production, as Lithium can be created through \(^3\)He(\(\alpha,\gamma\))\(^7\)Be with 
the capture of an electron. Fortunately, \(^3\)He and \(^7\)Be are abundant in CO novae and can lead to 
more production of \(^7\)Li [José and Hernanz, 2007, Gehrz et al., 2014]. 

Although novae are powerful outbursts, temperatures and pressures are usually still not 
sufficient enough that synthesis of much heavier elements is significant. Therefore, the theoretical 
limit of nova nucleosynthesis is considered to stop at Calcium (\(A<40\)) [José and Hernanz, 2007].

### 2.3.2 Dust Production

In addition to the synthesis of heavier nuclei, novae are also known to be prolific dust 
producers. It is suspected that the formation of dust depends upon the speed class of the nova as 
well as its environment upon eruption [Bode and Evans, 2008, Williams et al., 2013]. This is better 
analyzed through the MMRD(Maximum-Magnitude to Rate of Decline) which was explained in 
section(2.2). As speed class can also be related to whether a nova is a CO or ONe nova, the dust 
production process also manifests itself differently in each. As soon as the ejecta becomes optically 
thin, free-free Bremsstrahlung emission follows and infrared development diverges between CO and 
ONe novae [Bode and Evans, 2008]. Faster, hotter ONe novae offer little to no dust production 
as this free-free emission is extended into a coronal emission phase. On the other hand, many CO 
novae appear to experience a sudden extinction event in their visible light curve which are attributed 
to a condensation time-scale at about 30-80 days post-maximum. Condensation temperatures are 
estimated to be about 1000-1200K here and significant amounts of dust production can be deduced 
by analysing the novae in the infrared [Bode and Evans, 2008, Williams et al., 2013].
2.4 Summary

In this chapter, the properties of novae were explained more in detail. Additionally, several important uses and observations were presented in order to emphasise the importance of studying novae to the scientific community. Of these included their use in extragalactic distance measurements, possible progenitors to Type Ia supernovae, and contribution to the interstellar medium through heavier nuclei and dust. This last section serves as a nice segue into the next chapter which will be about dust and the observational effects of extinction.
Chapter 3

Dust and Extinction

As light travels through the interstellar medium it is often either absorbed, scattered or altered some other way before it reaches the instruments that observers use to analyze its properties. The difference in the amount of light that was emitted from the source and the amount that observers see due to absorption and scattering off of this medium is called extinction. Although extinction is attributed to both interstellar dust and gas, for the sake of this project only dust will be considered as it relates to observations from Earth.

3.1 Properties of Dust

Dust plays many different roles in galaxies. It is not only critical to galactic structure and evolution, but can be used in describing the physical conditions and dynamics of astrophysical phenomena [Draine, 2011]. Although interstellar dust cannot be analyzed in a laboratory, with the exception of scarce meteoritic data, much of what has been discovered about dust has been a result of its interactions with electromagnetic radiation (light) [Draine, 2011]. So far we know that attenuation of light due to absorption and scattering through dust is wavelength dependent. In general, the smaller the wavelength, the more likely it is that light will be extincted, but this will be covered more in section (3.2.2). Thermal emission from dust can also be uncovered at very large wavelengths from 2μm to sub-mm radiation, and can be studied more directly with large surveys such as the 2 Micron All Sky Survey (2MASS), as well as with near and far infrared observations to map physical locations of galactic dust [Drimmel et al., 2003, Marshall et al., 2006]. This includes
dust in the direction of the galactic center [Fritz et al., 2011].

In order to determine the properties of dust specific to the galaxy, extinction curves are observed over a large range of wavelengths. These are generally represented by graphs of the ratio of extinction in two bands to inverse wavelength. What is worth taking note of here is that there is a steady increase as the inverse wavelength increases, but there is usually a large bump around 2175 Å [Draine, 2011]. This is attributed to polycyclic aromatic hydrocarbons, and two smaller ones at 10μm (Silicate), and 3.4μm (C-H) implying that these are largely present in the dust. The intensity of these features is a bit different for each galaxy, but the increasing extinction ratio is generally apparent in most [Draine, 2011]. With the aid of these extinction curves, paired with scattered light from reflection nebulae in which the albedo of dust can be measured, properties such as abundance and grain characteristics can also be analyzed [Draine, 2011]. As the physical processes of absorption and scattering can be quite complex, particularly in the case of aspherical grains, many studies assume a spherical shape. In their 2001 paper on grain size distributions, Weingartner and Draine assumed spherical grain shapes that scattered light according to Mie Scattering theory. While the grain-size distribution for diffuse clouds is expected to range mostly between 50Å and 0.25μm, they determined that the grain-size distribution for the LMC and SMC gradually increased until a sharp cutoff just above 0.1μm [Weingartner and Draine, 2001]. Rayleigh scattering models show that for wavelengths around 6μm, the radii for interstellar dust particles are typically ≈ 0.1μm and are composed of mostly silicates and carbonaceous material [Draine, 2011].

3.2 Physics of Extinction

3.2.1 Radiative Transfer and Optical Depth

Before any processes can be discussed with relation to dust, we must first look at them through the eyes of radiative transfer. As light propagates through a medium, the total intensity of light over any given surface area changes depending on whether light is being absorbed, emitted or scattered. The total effect of what happens can be characterized by the transfer equation, where $I_\nu(\tau_\nu)$ represents the resulting intensity of light at a given frequency $\nu$, and $I_\nu(0)$ is the initial
intensity at that frequency before it interacts with whatever medium it is passing through:

\[ I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)}S_\nu(\tau'_\nu)d\tau'_\nu \]  

(3.1)

Here, the source function \( S_\nu \) is defined to be the ratio of the amount of emission over absorption. In the event that both absorption and scattering are happening at the same time, this value becomes a combination of the absorption coefficient \( \alpha_\nu \), scattering coefficient \( \beta_\nu \) and the thermal radiative nature of the environment it passes through. For the purposes of this project, the source function is taken to be 1 for simplicity. In equation (3.1), \( \tau_\nu \) represents the optical depth, or how much light is absorbed or scattered away from a particular line of sight. It can be calculated by integrating the combined values of \( \alpha_\nu \) and \( \beta_\nu \) over a given path length \( ds \) [Rybicki and Lightman, 2004]:

\[ d\tau_\nu = (\alpha_\nu + \beta_\nu)ds \]  

(3.2)

The value \((\alpha_\nu + \beta_\nu)\) is also called the extinction coefficient and will be discussed in the next section. As can be deduced from equations (3.1 and 3.2), the greater the value of optical depth, the less light is able to get through the medium [Rybicki and Lightman, 2004].

### 3.2.2 Absorption and Scattering Coefficients

How light is absorbed or scattered by a particle depends on several aspects including, but not limited to; grain size and shape, wavelength/frequency of light, grain composition, external fields, etc. This section will only cover the wavelength of light as it relates to grain size and composition and assume a spherical shape. In section (3.2.1), the concept of absorption and scattering coefficients were introduced to make up the total extinction coefficient. As these are related to optical depth in equation (3.2), and as they will be reviewed in section (3.2.3), these correspond to the effective cross-sections of the grains. Hence forth, they will be referred to as \( \sigma_{abs} \) and \( \sigma_{scat} \), where \( \sigma_\lambda \) is the total effective cross-section and \( \sigma_\lambda = \sigma_{abs} + \sigma_{scat} \) [Draine, 2011].

The three regimes of scattering theory discussed here are as follows: that where the wavelength of light is far greater than the grain size (i.e. the electric dipole limit); that where the

---

1These equations were all adapted from Ch.1 of Rybicki and Lightman’s ”Radiative Processes in Astrophysics”. For the sake of clarity here, the scattering coefficient is designated as \( \beta_\nu \), although it is important to note that Rybicki and Lightman refer to it as \( \sigma_\nu \) [Rybicki and Lightman, 2004]. This is not to be confused with the effective cross-sections of grains that is discussed in the rest of this chapter.
frequency of light is far below the resonant frequencies of the grains; and that where the sizes are comparable. In the first case, where the wavelength far exceeds the size of the grain, the effective cross-sections are:

\[ \sigma_{\text{abs}} = \frac{4\pi \omega}{c} \quad \text{and} \quad \sigma_{\text{scat}} = \frac{8\pi}{3} \left( \frac{\omega}{c} \right)^4 |\epsilon|^2 \] (3.3)

where \( \epsilon \) represents the electric polarizability of the grain material, defining its dipole moment as proportional to the external electric field, and \( \omega \) is the angular frequency of the affected light wave. As \( c \) is the usual speed of light, it can be seen that, particularly for material that is susceptible to being polarized, high frequency (smaller wavelengths) are far more likely to be scattered than lower frequencies (larger wavelengths).

For the regime in which the frequency of light is far below any resonant frequencies of the grain, absorption and scattering can be based on whether or not the grain is a predominantly good insulator or conductor. For insulators:

\[ \sigma_{\text{abs}} \to 36\pi^2 \frac{Ac}{(\epsilon_0 + 2)^2 \lambda^2} \quad \text{and} \quad \sigma_{\text{scat}} \to 24\pi \frac{\left(\epsilon_0 - 1\right)^2 V^2}{(\epsilon_0 + 2)^2 \lambda^4} \] (3.4)

here, \( V \) is volume of the grain and \( A \) is a constant with dimensions of time, so that absorption will dominate in the case where \( \lambda \to \infty \). The arrows represent the tendency to take on these approximate values for this wavelength-to-size regime and \( \epsilon_0 \) signifies the external electric field. For conductors:

\[ \sigma_{\text{abs}} \to \frac{4\pi c}{\sigma_0 \lambda^2} V \quad \text{and} \quad \sigma_{\text{scat}} \to 24\pi \frac{V^2}{\lambda^4} \] (3.5)

In this case, \( \sigma_0 \) represents a constant conductivity at zero frequency of the grain.\footnote{All of these equations have been adapted from ch22 of Bruce Draine’s book: The Physics of the Interstellar and Intergalactic Medium [Draine, 2011]}

This finally brings us to Mie theory, which is the widely accepted scattering theory for interactions where the wavelength of the incoming photon is on the order of the size of a spherical particle. In this instance, the electric and magnetic fields are broken up into spherical harmonics and depend on the relative sizes as well as the refractive index of the grain. For the most part, however \( \sigma_\lambda \) is considered equivalent to twice the geometrical cross-section [Draine, 2011]. For the sake of simplicity, the cross-sections of the dust grains in this project are considered as purely geometrical so that \( \sigma_\lambda = \sigma = \pi a^2 \), with no wavelength dependence since the extinction model to be presented

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only accounts for visual extinction.

In all of these different cases it is quite apparent that scattering dominates over absorption as wavelength decreases. However, it must be noted that for extremely high energy photons, such as gamma rays or hard x-rays, the interstellar medium is effectively transparent. At such high energies, the interaction of high energy particles with matter must be taken into account. In the range of 1 MeV and above, the coherent scattering discussed above becomes negligible compared to pair-production at the atomic level, and rather than being scattered or absorbed, they are simply transmitted since electron-binding energies of the grain are not enough to stop them. In fact, detection of gamma rays becomes quite difficult, because an effective detector requires an interaction between the surface and a photon to occur [Nelson and Reilly, 1991].

### 3.2.3 Calculating Extinction

The total amount of extinction $A_\lambda$ along any line of sight is measured via the apparent magnitude $m_\lambda$, absolute magnitude $M_\lambda$, and the distance to the object in parsecs $d$:

$$m_\lambda - M_\lambda = 5 \log_{10} d - 5 + A_\lambda$$  \hspace{1cm} (3.6)

Since distance is related to the intensity of light at a certain optical depth, as seen in equation (3.1) if we set $I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu}$, it can be combined with equation (3.6) to reflect the change in apparent magnitude, or $m_\lambda - m_{\lambda,0} = -2.5\log_{10}(e^{-\tau_\lambda}) = 1.086\tau_\lambda$. Hence:

$$A_\lambda = 1.086\tau_\lambda$$  \hspace{1cm} (3.7)

In other words, extinction is directly proportional to the optical depth, which can be compared to equation (3.2), which if written in terms of the number density of particles in the obscuring medium and their effective cross-sections, can be written as:

$$d\tau_\lambda = \int_0^s n\sigma_\lambda ds$$  \hspace{1cm} (3.8)

Equations (3.7) and (3.8) are important, as they will be used in the integrated extinction model developed for this project.\(^3\)

\(^3\)The equations in this section are all adapted from Rybicki and Lightman’s "Radiative Processes in Astrophysics" [Rybicki and Lightman, 2004] and Carrol and Ostlie’s "Introduction to Modern
3.3 Reddening

Unlike scattering and absorption, reddening is not so much a physical process as it is the observed effects that result from them. Despite what its name might suggest, it is unrelated to the effects of redshift caused by the Doppler Effect of objects travelling away from our line of sight. In that instance, the entire spectrum of the object is shifted along with the peak intensity. A high energy object may display all of the same characteristics, just shifted towards the red end of the spectrum. For reddening due to extinction, there is no change in the placement of spectral lines. It is only the intensity of the lines that is affected. In the optical regime, if smaller (bluer) wavelengths are scattered more, as discussed previously, the amount of intensity received from that part of the spectrum will be much lower than expected if there were no extinction, because higher energy photons are simply not reaching the detector. Likewise, longer (redder) wavelengths are not deflected as much, so more of the originally emitted light is able to be observed. The observed effects of reddening can be measured by calculating the color excesses of a given object. This is done by taking the difference between the theoretical intrinsic color of the source and the observed colors at two different wavelengths [Draine, 2011].

3.4 Summary

In this chapter, the properties of dust and its role in extinction were discussed in detail as they relate to this project. The physical processes of the interaction of light with dust particles were explored as an introduction to radiative transfer by means of absorption and scattering. The observational effects of extinction were then introduced in terms of reddening.

Extinction affects light of all wavelengths. If it is strong enough, that is to say, if it should reduce the intensity of all light below observing capabilities, the object is totally obscured from sight. The Earth’s galactic placement in the disk of the Milky Way makes it so that this effect becomes a significant problem when trying to observe anything along or through the galactic plane or galactic center. In the next chapters, the extinction model and nova distribution model developed for this project will be discussed. First, however, some observational data of galactic novae must be reviewed.
Chapter 4

Observed Data and Observational Parameters

4.1 Observational Data

Before any distribution models can be developed, a review of observational data and parameters must be studied for comparison. This project includes observational data taken from all 407 galactic novae recognized by the Central Bureau for Astronomical Telegrams (CBAT) from 1612 to 2010 [International Astronomical Union, 2010]. In addition, it also includes the 35 recent galactic nova observations recorded by the American Association for Variable Star Observers (AAVSO) member Koji Mukai from 2010-2014 that were not included in the original list [Mukai, 2015]. A histogram for the number of novae observed throughout each of these years was presented in the introduction as figure (1.1), as well as an explanation for the rapid increases within the past century or so in section (1.1.1). In order to get a spatial sense of where these novae occurred throughout the galaxy, as well as how bright they were at the time of observation, an equal-area Aitoff projection map was developed for all novae observed from 1612 to 2014. This is presented in figure (4.1).

As can be seen by the distribution of actual nova observations, it appears that there is a strong bulge concentration with no observations recorded in the very central plane of the disk and

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1 Traditional galactic Aitoff projections start with 0 degrees longitude in the center and increase to the left with 360 degrees terminating in the middle. All Aitoff projections in this paper increase to the right and assign negative values for longitudes above 180 degrees.
Figure 4.1: A galactic coordinates equal-area Aitoff map of all novae recorded from 1612 through 2014. The color of each circle designates the observed apparent magnitude of the novae upon eruption. Blue represents novae observed at $m_V \leq 5$; green represents $5 < m_V \leq 10$; yellow $10 < m_V \leq 15$; and red with magnitudes fainter than 15th magnitude. Large circles represent all novae that were discovered prior to 1911, when the AAVSO was established. Observational bias is displayed with equatorial contours as + signs. Cyan +’s are at a declination of -30° and magenta +’s are at a declination of +30°. The northern equatorial pole is also marked with a magenta +.

Towards the galactic center. Of course, this absence is expected to be a result of the infamous "Zone of Avoidance" described in section (1.1.3), where objects appear to "avoid" the galactic plane and center. This is not because objects are physically repelled by this region, but is rather the effect of large amounts of dust, gas, and light obscuring objects in that direction. Aside from the central concentration, there seems to be a preference towards the disk of the plane at very small latitudes, with fewer outbursts at farther distances from the center.

Figure (4.2) shows a better representation of the apparent magnitude distribution of the novae displayed in figure (4.1). From here it is clear to see that the vast majority of observed novae lie between 5 and 15 magnitudes, with a peak just below 10 magnitudes.
4.2 Observational Bias

4.2.1 Sky Coverage

One initially perplexing feature about figure (4.1) is that there is a strong preference for galactic longitudes between 0° and 180° with what appears to be a diagonal band reaching from about 60° latitude at the longitudinal center, to about −45° latitude just below 180° longitude. While this may seem puzzling at first, it is most likely that this can be attributed to equatorial hemispheres and the amount of sky coverage available to amateur and professional astronomers. The northern hemisphere not only has many more ground-based observatories than the southern hemisphere, but also a larger base of amateur astronomers. This can be seen visually in figure (4.1) by the equatorial contours.

Since there should be no reason why the Earth’s orientation in the galaxy should have an affect on the distribution of celestial phenomena, this bias has been accounted for in this study. As distributions in both galactic extinction and modelled novae in this project were assumed to be axisymmetric, the total effective “observable rate” was calculated by doubling the average number of novae observed between 0° and 180° galactic longitude within the past decade. This number then corrects for the lack of southern hemisphere data and distinguishes a difference between “observed”
novae, and "observable" novae. In this case, the number of novae observed between 0° and 180° within the past 10 years was 75 out of 99. This averages to approximately 8 novae per year for half of the galaxy, which, if novae were distributed axisymmetrically, the total "observable" novae per year throughout the galaxy would be 16. This is different from the actual observed average, which is 10 yr$^{-1}$ for the past decade.

4.2.2 Telescope Limitations

In addition to sky coverage bias, the observability of celestial objects is strongly affected by the magnitude limitations of the telescopes used to detect them. Although there are now space-based observatories and enormous ground-based telescopes that can reach upwards of 25 magnitudes, they do not prioritize nova discovery. On the other hand, since the majority of recent nova discoveries come from amateur observations, the limiting magnitudes affecting observability are closer to those of sub-meter class telescopes. For the sake of this project, this limiting magnitude is taken to be 18, even though the limiting magnitude of most amateur telescopes is around 16 or 17 for 12-18 inch telescopes. The reason for this is that there also exist meter-class telescopes capable of reaching 20th magnitude and tools such as the Sloan Digital Sky Survey with a limiting optical magnitude of about 22 that are more accessible to amateur researchers [Stoughton et al., 2002]. It is also worth mentioning that the dimmest galactic novae observed through 2014 only reached an apparent visual magnitude of 18.2, which stands as proof that it is possible to catch faint objects with the tools at hand, though admittedly unlikely, as it was almost an entire magnitude off from the next faintest.

4.2.3 Other Observational Limitations

Sections (4.2.1) and (4.2.2) both considered observational biases that were accounted for in this study. Unfortunately, there exist many other limitations that were not considered. These include, but are not limited to: seasonal observing conditions, sky conditions, light pollution, funding, observing time, etc.

4.3 Summary

This chapter reviewed the observational constraints to be used in the extinction and novae distribution model according to actual observed data. The overall structure of the observed galactic
nova distribution was discussed as well as a distinction made between observed data and observable data. The observed nova rate of $10\text{yr}^{-1}$ is the raw data without any bias accounted for, and the observable rate of $16\text{yr}^{-1}$ is the number expected to be observed if both equatorial hemispheres contributed the appropriate amount for the galactic distribution to be axisymmetric. Also, the limiting visual magnitude for detecting galactic novae was set to 18 to account for the types of telescopes used. The next chapters introduce the models developed to ultimately determine the global nova rate of the galaxy.
Chapter 5

Extinction Model

5.1 Dust Distribution and Parameters

As was explained in section (3.2.3), in order to describe extinction, the optical depth of the material must be known. The two are directly proportional by the relation: $A_\lambda = 1.086 \tau_\lambda$. From equation (3.8) it is plain to see that several variables need to be established first. For simplicity’s sake, since the majority of novae are first observed in the optical band, the wavelength dependence can be ignored if we consider all cross-sections to be purely geometrical. Hence, all magnitudes from this point on will be in terms of the visible band. With this new modification, equations (3.7) and (3.8) become:

$$A = 1.086\tau \quad \text{and} \quad d\tau = \int_0^n n\sigma ds \quad (5.1)$$

In these equations $\sigma$ denotes the geometric cross section. As was discussed at the end of section (3.1), the radius of the average dust particle is about 0.1$\mu$m, and so sigma can easily be calculated as $\sigma = \pi a^2$, where $a$ is the radius [Draine, 2011]. Since $s$ signifies the path length of the material, all that is needed is the particle density distribution $n$ that it passes through. The integrated value $\int n ds$ is the column density along a given line of sight.

For this project a double exponential extinction model was developed for the Milky Way. This distribution, in particular, was chosen for its similarity to the one that Hatano et al used in 1997 to define the galactic nova rate based on galactic properties [Hatano et al., 1997]. The in-
tent of this portion of the project was to produce a model in which the extinction along any line of sight originating from the Sun’s galactic position could be calculated. This was done using a simple double exponential distribution similar to the one developed by Drimmel and Spergel in which a 3-dimensional structure of the Milky Way was developed for galactic radii beyond $0.35R_{\odot}$ [Drimmel and Spergel, 2001]. Their model attempted to accurately depict the distribution of dust and stars in the galaxy without consideration of the galactic center. Equation (5.2) below shows the distribution where $n$ refers to the particle density of dust particles at a polar radius $r$ from the galactic center, and $z$ is the distance from the central plane of the disk. $r_0$ and $z_0$ represent the scale length and scale height of the galaxy. These are both constant parameters where $z_0$ was chosen to be 0.134kpc based on the work of Drimmel and Spergel [Drimmel and Spergel, 2001]. $r_0$ was a free parameter chosen as 3.0kpc so that the extinction value to the galactic center was equal to an approximate value of $\sim 45$. This was in accordance with infrared research specifically conducted to measure extinction at the galactic center [Fritz et al., 2011]. It was, however, comparable to previous estimations of past astronomers of 2.26kpc [Drimmel and Spergel, 2001], 2.510kpc [Marshall et al., 2006], and $1.35 \pm 0.25kpc$ [Jones et al., 2011].

$$n(r, z) = n_0 e^{-r/r_0} e^{-|z|/z_0}$$  \hspace{1cm} (5.2)

### 5.2 Establishing the Particle Density at the Galactic Center

$n_0$ in equation (5.2) refers to the particle density of dust particles at the galactic center. This equation is necessary to line of sight calculation since extinction is dependent upon the column density used to determine optical depth. However, in order to calculate an actual number for the particle density at any point $r$ and $z$, a constant value for $n_0$ needed to be established. Although $n_0$ is not known directly, it can be estimated using different solar vicinity values.

Since the sun lies approximately 8.5kpc from the galactic center, and essentially in the galactic plane, we can rearrange equation (5.2) to reflect $n_0$ at this point, or:

$$n_0 = n(r_\odot, z_\odot) e^{r_\odot/r_0} e^{z_\odot/z_0}$$ \hspace{1cm} (5.3)

Here, $n(r_\odot, z_\odot)$ represents the galactic particle density at the sun’s location. In order to find this value, due solely to dust, it must be broken up into the relatively known values of the local dust-to-
gas mass ratio ($DTG$), as well as grain characteristics described in section (3.1). Since mass ratios can also be written in terms of number densities and masses, or mass densities and volumes, the relation $DTG = \frac{m_d n_d}{m_g n_g} = \frac{\rho_d V_d}{\rho_g V_g}$ can be reformulated as:

$$n(r_\odot, z_\odot) = DTG \times \frac{m_p n_H}{\rho_d V_d}$$

For the solar-vicinity dust particle density, the gas particle mass $m_g$ and gas particle density $n_g$ have been changed to the known mass of a proton $m_p$ and the particle number density of Hydrogen $n_H$. Since most gas particles in the Universe are Hydrogen atoms, and the Hydrogen particle mass consists of a proton and an electron of comparatively negligible mass, this was a logical assumption that simplified matters.

For most spiral galaxies, the dust-to-gas mass ratio is estimated to be around 1/600. However, the value for the Milky Way is typically taken to be $\sim 1/150$ [Young and Scoville, 1991]. Furthermore, while the number densities of particles can vary greatly depending on location, the ISM is generally considered to be a well-mixed combination of dust and gas that generally contributes about 1.8 magnitudes kpc$^{-1}$ for nearby objects. From these ratios, an average number density of hydrogen atoms in the solar vicinity is estimated to be $n_H \approx 1.1$ cm$^{-3}$ [Li, 2005].

By combining equations (5.3) and (5.4) together, we can easily calculate the dust particle number density at the sun’s distance from the galactic center. Using the expected decline in particle distribution at $r_\odot=8.5$kpc in the galactic plane where $z_\odot=0$kpc, the particle density for dust at the galactic center can be calculated as:

$$n_0 = DTG \times \frac{m_p n_H}{\rho_d V_d} e^{r_\odot/r_0} e^{z_\odot/z_0}$$ or $$n_0 = 1.66 \times 10^{-11} cm^{-3}$$

From here, all it takes to calculate the line-of-sight extinction is to define a distance $s$ from an observational point of origin. The newly formed integral is as follows:

$$A = 1.086 \times \sigma \times n_0 \int_0^s e^{-r/r_0} e^{-|z/z_0|} ds$$
5.3 Line of Sight Integration

5.3.1 Establishing a Relative Coordinate System

Although all of the parameters discussed in the previous section account for a dust distribution which is galactocentric, the integration must be performed through a one-dimensional spherically radial space which is not. In truth, since extinction is measured as an observed quantity from Earth, \( ds \) in equation (5.6) must be measured from the solar position in the galaxy which is 8.5 kpc removed from the galactic center. In order to do this, several coordinate transformations needed to be made. The easiest way was to convert \( r \) and \( z \) into a galactic coordinate system centered on the Sun’s location so that a scalar distance \( s \) could be easily integrated over. Hence, the only necessary pieces of information that would be needed for extinction calculation would be two constants \((l, b)\) and the singular variable \( s \).

The coordinate transformation of \( r \) and \( z \) was performed in three steps. First, a transformation from heliocentric galactic coordinates \((l, b, s)\) to a heliocentric Cartesian coordinate system \((x_s, y_s, z_s)\).

\[
x_s = s \cos b \sin l \quad , \quad y_s = -s \cos b \cos l \quad , \quad z_s = \sin b
\]  

(5.7)

Next, these heliocentric Cartesian coordinates were shifted along the \( y_s \) axis by the solar distance to the galactic center \( r_\odot \). This formed the new galactocentric Cartesian coordinate system \( x_g, y_g, z_g \):

\[
x_g = x_s \quad , \quad y_g = y_s + r_\odot \quad , \quad z = z_g
\]  

(5.8)

At the end, the galactocentric cylindrical coordinates could be written in terms of these new galactocentric Cartesian coordinates:

\[
r = x_g^2 + y_g^2 \quad , \quad \phi = \tan^{-1} \frac{y_g}{x_g} \quad , \quad z = z_g
\]  

(5.9)

Ultimately, this allows a simple transformation from galactocentric cylindrical coordinates to be written in terms of heliocentric galactic coordinates:

\[
r = \sqrt{s^2 \cos^2 b - 2s r_\odot \cos b \cos l + r_\odot^2} \quad and \quad z = s \sin b
\]  

(5.10)
Equation (5.6) can finally be written in terms of one variable $s$ for a given line of sight:

$$A = 1.086 \times \sigma \times n_0 \int_0^s e^{-\sqrt{\frac{s^2}{c^2} - 2s_0 \cos b \cos l + r_0^2}} e^{-|s \sin b|/z_0} ds$$  \hspace{1cm} (5.11)$$

The benefit of being able to write the total extinction integral in terms of galactic coordinates is two-fold. Firstly, it allows for easily understood galactic maps so that readers can see the symmetry present in distribution models without being confused by where the observer is supposed to be. It has no affect on the physical distribution of the dust, and allows for $l$ and $b$ to remain as constants along any line of sight. Since there exist many astronomical coordinate transformation tools between equatorial and galactic coordinates this also makes comparison with observed data easy. Secondly, the intermediate steps of transformation allow for galactocentric Cartesian coordinates to be recorded for everything. This allows for quick spatial confirmation and easily understood 3-dimensional models of the galaxy.

5.3.2 Programming

The programming tools used to ultimately calculate and display data for this extinction model alternated between Fortran90 and Python. Plotting tools shifted between Gnuplot, Python, and IDL. The integrator itself was developed with Fortran90 and incorporated the trapzoidal rule to approximate the definite integral for each individual line of sight, given in $(l, b)$ coordinates, between 0 and its corresponding distance $s$. The program was able to take in coordinate files of arbitrary length, as long as they contained all three galactic coordinates $(l, b, s)$. The input file must also have contained the corresponding apparent magnitude for each object as observed on Earth due solely to the inverse square law of light dissipation over distance.

The integration process looped through each line of text by first taking in the distance to the object and splitting it up into step sizes equal to 1/1000 of that distance. It then used the trapezoidal rule to calculate the average of the function evaluated at both ends of each subsequent step to get the area under the total curve. Since the equation for integrated extinction included the absolute value of distance from the galactic plane, the function chosen depended on whether the galactic latitude input $b$ was positive or negative.

In order to make sure that calculated extinction values were appropriate, the integration process was restricted to one line of sight at a time with varying distances. For galactic
coordinates away from the center, values were cross-checked with the V band numbers obtained from existing extinction calculators provided by the NED (NASA/IPAC Extragalactic Database) [NASA/IPAC, 2012, NASA/IPAC, 2013]. Since these extinction calculators generally blew up at the galactic center, the values for \((l,b) = (0,0)\) were compared to extinction-specific infrared studies of the galactic center. As the galactic scale-length appeared to be one of the least agreed upon parameters in literature, this number was slightly adjusted until a value of \(~45\) was achieved for extinction at the galactic center [Fritz et al., 2011]. An all-sky heat-map of extinction values at a distance of 8.5kpc is shown in figure(5.1).

5.3.3 Observability Testing

In order to test that this extinction map worked appropriately, a uniform cylindrical distribution was developed for 5000 equal magnitude points along the galactic plane. To simulate the effect that the inverse square law alone has on apparent magnitude, distances from the solar location were accounted for before being sent through the extinction integrator. This diagram is shown in figure (5.2a). Since the goal of the project was to be able to predict observable novae, a limiting
magnitude of 30 was applied at the tail-end of the extinction calculations. As will be seen in the next chapters, this limit was reduced to 18 for reasons discussed in section (4.2.2). The resulting distribution is shown in figure(5.2b).

Figure 5.2: These two figures show the color-coded heat map for the apparent magnitudes of 5000 randomly distributed points over the central disk of a simulated galaxy. Each point has an absolute magnitude of -9. (a) is before extinction is accounted for and (b) is after, with a limiting magnitude of 20 applied.

These test models show the expected results of the extinction model. The location of the solar neighborhood is easily seen at 8.5kpc in both figures. If extinction were not responsible for obstructing light, all points would be visible, but that is not the case. Applying a limiting magnitude eliminates everything past the galactic center, and only objects at the edges of the galactic disk and near the solar system are visible.

5.4 Limitations

Since this extinction model considers an overly simplistic version of the generally accepted galactic dust structure, there are several missing features that this author must acknowledge. The most obvious differences in structure are the lack of a galactic bulge and spiral arms. Should a bulge have been included, the values for extinction would be very different as there is a large difference in the amount of dust and gas in the bulge. Spiral arms would have also proven a difficulty since they not only defer from the axial symmetry of the model, but could also have different orientations that would greatly affect the line-of-sight integration with even slight modification. Some other
components that were not accounted for in this model, but were included in similar models were the presence of a galactic bar and a warp in the disk [Drimmel and Spergel, 2001, Drimmel et al., 2003]

5.5 Summary

This chapter overviewed the development process of the underlying galactic extinction model and integrator. In order to get the appropriate distribution, several parameters from literature were used and are summarized in table (5.1). After that, the line-of-sight integration was set up by first establishing a proper coordinate system in galactic coordinates. Once this was corrected for, Fortran90 was used to calculate extinction values for individually integrated lines of sight in accordance with known extinction calculators. The effect of the extinction model on observability was then added and tested at the end by accounting for a limiting magnitude for observers. The next chapter introduces the nova distribution model developed for this project.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust Scale Length</td>
<td>$r_0$</td>
<td>3.0 kpc</td>
<td>[Drimmel and Spergel, 2001]</td>
</tr>
<tr>
<td>Dust Scale Height</td>
<td>$z_0$</td>
<td>0.134 kpc</td>
<td>[Drimmel and Spergel, 2001]</td>
</tr>
<tr>
<td>Extinction to Galactic Center</td>
<td>$A_{GC}$</td>
<td>$\sim$ 45</td>
<td>[Fritz et al., 2011]</td>
</tr>
<tr>
<td>Solar Distance to Galactic Center</td>
<td>$r_\odot$</td>
<td>8.5 kpc</td>
<td>[Draine, 2011]</td>
</tr>
<tr>
<td>Solar Distance from Galactic Plane</td>
<td>$z_\odot$</td>
<td>0 kpc</td>
<td>Assumed value</td>
</tr>
<tr>
<td>Dust to Gas Mass Ratio</td>
<td>$DTG$</td>
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<td>[Young and Scoville, 1991]</td>
</tr>
<tr>
<td>Proton Mass</td>
<td>$m_p$</td>
<td>$1.67 \times 10^{-24}$ g</td>
<td>[NIST, 2015]</td>
</tr>
<tr>
<td>Hydrogen Number Density</td>
<td>$n_H$</td>
<td>1.0 cm$^{-3}$</td>
<td>[Li, 2005]</td>
</tr>
<tr>
<td>Dust Grain Mass Density</td>
<td>$\rho_d$</td>
<td>3.0 g cm$^{-3}$</td>
<td>[Draine, 2011]</td>
</tr>
<tr>
<td>Average Radius of Dust Grain</td>
<td>$a$</td>
<td>0.1$\mu$m</td>
<td>[Draine, 2011]</td>
</tr>
<tr>
<td>Average Cross-Section of Grains</td>
<td>$\sigma$</td>
<td>$\pi a^2$</td>
<td></td>
</tr>
<tr>
<td>Volume of Individual Dust Grains</td>
<td>$V_d$</td>
<td>$\frac{4}{3}\pi a^3$</td>
<td></td>
</tr>
<tr>
<td>Limiting Magnitude for Observability</td>
<td>$m_T$</td>
<td>18</td>
<td>Section(4.2.2)</td>
</tr>
</tbody>
</table>

Table 5.1: A summary of the parameters discussed in this chapter that were essential to modelling the extinction integrator.
Chapter 6

Nova Distribution Model

6.1 Determination of Parameters

6.1.1 Distribution

The nova distribution chosen for this project followed the same galactocentric axisymmetric distribution used for the extinction model. The number of particles decreased exponentially in both the radial and vertical directions. As the goal of this research project was to determine the appropriate nova rate based on an observed rate before extinction was brought into the picture, it was important that this step be saved until after the ideal extinction model was developed. Steps in determining the exact parameters for the distributions in each direction were similar to those for extinction. Since stars tend to follow the dust distribution in the galaxy, the scale height and scale length were kept the same as described in Chapter 5. This means that the scale height $z_0 = 0.134\text{kpc}$ and the scale length $r_0 = 3.0\text{kpc}$ were kept in accordance with Drimmel & Spergel’s Milky Way structure and Fritz et al.’s measurements of extinction at the galactic center [Drimmel and Spergel, 2001, Fritz et al., 2011].

6.1.2 Nova Parameters

In order for extinction to have any meaning, the inherent brightness of the source must be considered. Most novae eruptions peak at an absolute magnitude of about $M_V = -7.0$ or $M_V = -8.0$ [Bode and Evans, 2008, Hernanz, 2004]. Although most novae fall between these magnitudes, a
much broader range lies between \( M_V \approx -6 \) and \( M_V \approx -10 \) [Shafter, 2002]. For the sake of simplicity, all the novae in this model were considered to be at a peak magnitude of \( M_V = -8.0 \). This is one of the largest assumptions made throughout this project, as not all novae are caught at peak magnitude, or even erupt in the same manner, as discussed in section (2). In truth, while taking into account the variability of each individual nova observation would have been ideal, it would have added a level of difficulty unnecessary to the scope of this project.

6.2 Programming

6.2.1 Monte Carlo Method

All of the programming for the nova distribution model was performed using Python. Since the desired overall distribution of points was known, but not the exact number of points to generate, the best solution was to use a familiar Monte Carlo method of generating random points that followed the previously mentioned double exponential distribution such that:

\[
N \propto \int_{z_1}^{z_2} \int_{\phi_1}^{\phi_2} \int_{r_1}^{r_2} e^{-r/r_0} e^{-|z|/z_0} r dr d\phi dz
\]

where \( N \) is the number of points within a designated region

This was done using one of Python’s many random number generators (RNG). Since RNGs can only generate one number at a time, one large for-loop was developed to generate each single three-dimensional coordinate at a time, according to a galactocentric cylindrical model \((r, \phi, z)\). The azimuthal coordinate \( \phi \) was simple to develop. There was no preferred distribution for it and so any number between 0 and \( 2\pi \) was acceptable.

6.2.2 Inversion and Newton Raphson Method

Unlike the azimuthal coordinate \( \phi \), \( r \) and \( z \) each needed to have a distribution that followed an exponential decay such that:

\[
\Sigma_z = \frac{1}{2z_0} \int_{-\infty}^{z} e^{-|z|/z_0} dz \quad \text{and} \quad \Sigma_r = \frac{1}{r_0} \int_{0}^{r} e^{-r/r_0} r dr = 1 - \frac{r}{r_0} e^{-r/r_0} - e^{-r/r_0}
\]

33
where $\Sigma_z$ and $\Sigma_r$ represent the cumulative distribution functions. It is important to note that, although $r$ is technically one dimension, it expands over a surface and therefore must be integrated over $\pi r dr$ to account for all angles. For most cases, this is a simple matter of inverting the distribution function such that the random number generated is equal to the cdf [Casella, 2008]. For $z$, since it has the same distribution underneath the central plane, the random number $RN$ was found such that:

$$\frac{1}{2} RN = \frac{1}{2z_0} \int_0^{+z} e^{-z/z_0} dz \quad \text{or} \quad z = -z_0 \ln(1 - RN) \quad (6.3)$$

To account for negative values, points were again randomly selected to be negative or positive. The resulting distribution for 1000 generated points is shown in figure (6.1).

Figure 6.1: A comparison between the expected point distribution of $z$ values from the galactic center (line) and that of the generated points of the model (histogram).

In the case of the radial distribution, this method does not work, as the function is not easily invertible. Instead, the Newton Raphson Method was invoked as a way to find the roots of a function. In order to do this, both the function and its derivative were needed. In this case, the function was the cdf function minus the $RN$, or:

$$f(r) = 1 - \frac{r}{r_0} e^{-r/r_0} - e^{-r/r_0} - RN \quad \text{and} \quad f'(r) = \frac{r}{r_0^2} e^{-r/r_0} \quad (6.4)$$
From here, the Newton Raphson Method is carried out by starting out with a guess, \( x_n \). It then goes through each consecutive iteration until converging. This is exhibited in equation (6.5) [Casella, 2008].

\[
x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}
\]  

(6.5)

As stated previously, since the exponential radial function occurs over a surface, it had to have been integrated over a surface. As a result, figure (6.2) shows the expected and modelled surface density for the same 1000 points developed in figure (6.1)

![Surface Density Distribution of r](image)

Figure 6.2: A comparison between the expected surface density distribution of \( r \) values from the galactic center (line) and that of the generated points of the model (histogram).

Since all of these generated points were developed in a cylindrical galactocentric frame, they were all individually converted into a galactocentric cartesian frame and then to heliocentric galactic coordinates in the same manner as section (5.3.1). This was especially important, as the distance \( s \) from Earth was needed in order to calculate apparent magnitude.

### 6.2.3 Coordinates and Apparent Magnitude

Since all of these generated points were developed in a cylindrical galactocentric frame, they were all individually converted into a galactocentric cartesian frame and then to heliocentric galactic
coordinates in the same manner as section (5.3.1). This was especially important, as the distance $s$ from Earth was needed in order to calculate apparent magnitude.

Without the effects of extinction, the apparent magnitude of every source would still be affected by the distance from the observer. In order to account for the amount of light lost due to the inverse square law, a short line of code was added within the for-loop of number generation to also compute and record the apparent magnitude due to its distance $s$.

![Generated distribution of nova points](image)

**Figure 6.3** These figures show the distribution characteristics of 1000 generated nova points according to a double-exponential distribution. Figure (6.3b) shows a top-down view of figure (6.3a) with apparent magnitudes of novae with absolute magnitude $M_V = -8$ before extinction is accounted for.
6.3 Summary

This chapter reviewed the steps taken in establishing the modelled nova distribution. The parameters that were discussed in making the model are summarized in table (6.1). In order to get the appropriate distribution, a Monte Carlo method of random number generation with two different techniques was used for each exponentially decaying coordinate. At the end, the apparent magnitude due to distance was also calculated for each point.

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
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<td>Dust Scale Length</td>
<td>( r_0 )</td>
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</tr>
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<td>[Drimmel and Spergel, 2001]</td>
</tr>
<tr>
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<td>( r_\odot )</td>
<td>8.5 kpc</td>
<td>[Draine, 2011]</td>
</tr>
<tr>
<td>Solar Distance from Galactic Plane</td>
<td>( z_\odot )</td>
<td>0 kpc</td>
<td>Assumed value</td>
</tr>
<tr>
<td>Absolute Magnitude of Nova Peak</td>
<td>( M_V )</td>
<td>-8.0</td>
<td>[Bode and Evans, 2008, Hernanz, 2004]</td>
</tr>
</tbody>
</table>

Table 6.1: A summary of the parameters discussed in this chapter that were essential to modelling the nova distribution.

Now that both the extinction integrator and nova distribution modelling processes have been discussed, they can be combined to find the total nova rate of the galaxy. The results and discussion of this are presented in the next chapter.
Chapter 7

Results and Discussion

7.1 Implementation

7.1.1 Extinction Effect

In order to determine the ratio of how many novae are observable vs how many are extincted (i.e. unobservable due to excessive extinction), a global distribution of 1000 novae were generated with the nova distribution model explained in Chapter (6). When extinction was added, an average of about 330 novae were ultimately observable up to a limiting magnitude of $m = 18$. This corresponds to a 67% loss in the global rate due to extinction. Figure (7.1b) below shows the difference in observability before and after extinction are taken into account for the same 1000pt distribution described above as well as in figures (6.1) through (6.3).

7.1.2 Magnitude Distribution

In comparing the observable properties of the modelled distribution to that of the observed data, it can be seen that there are similarities in the apparent magnitude distribution. From figure (7.2), of the 330 out of 1000 novae that are observable, there seems to be very few novae with magnitudes below 5, but also a familiar peak around $m = 10$ with a small decline afterward. This decline is understandable as our solar system lies in the outer disk of the Milky way, meaning the density of dust and stellar material is not that great. Naturally, the lack of extinction and reduced number of surrounding novae at the edge of the galaxy mean that apparent magnitudes
Figure 7.1: These figures show two-dimensional top-down views of a modelled galactic distribution of the 1000 novae shown in figure (6.3) with absolute magnitudes $M_V = -8.0$. Colors represent the apparent magnitudes as seen from Earth. Figure (7.1a) shows a map of the novae with apparent magnitudes due only to the inverse square law. Figure (7.1b) shows the observable magnitudes of the same points after extinction up to an observable magnitude of $m = 18$.

can hardly surpass 12 or 13 magnitudes for longitudes $|l| > 90^\circ$. In figure (7.1b), these longitudes are represented as $Y \geq 8.5\,\text{kpc}$. Although there are many more stars near the center of the galaxy, their light also experiences much more extinction, and so the number of sources at larger apparent magnitudes slowly starts to decrease.

In contrast with figure (4.2), the greatest number of magnitudes peak just below $m = 10$, whereas the modelled data peaks just above 10. There is also a sharp decline after the peak. This is most likely due to the observational bias caused by the limiting magnitudes of the eye as well as most amateur telescopes described in section (4.2.2). It is only the larger, less accessible telescopes that can see the higher magnitudes. Another reason for this sharp decline at a much earlier point in the magnitude distribution is that, even though telescopes are able to detect a nova just below its limiting magnitude, whether or not it is recorded depends on the observers ability to recognize it. Faint novae are not as noticeable since they do not provide the high level of contrast to the background as brighter ones.

### 7.1.3 Spatial Distribution

To see the galactic distribution of the 1000 generated novae in the sky, they were all plotted onto an equal-area Aitoff projection map shown in figure (7.3). In order to get a sense for the effects
Figure 7.2: This histogram shows the distribution in apparent magnitude of the observable novae generated in figure (6.3). This figure is comparable to the magnitude distribution of all observed novae in figure (4.2). Explanation of the slight decline in is discussed in section (7.1.2).

of extinction, the observable novae are plotted in green and those that have been extincted past an observable magnitude of $m = 18$ are plotted in red underneath. As expected, the concentration of novae increases towards the galactic center both in the longitude and latitude. The effects of extinction are greatest towards the galactic center as well. The majority of extincted novae lie within $60^\circ$ longitude of the galactic center. Although there are observable novae in the direction of the galactic plane, the majority are either only a few kiloparsecs away. In figure (7.1b), there are novae located directly past the galactic center, but these are only observable as they are also at greater distances above or below the plane, hence they have less extinction.

7.2 Results

7.2.1 The Galactic Nova Rate

The purpose of this project was to develop a galactic extinction integrator and nova distribution model that, when observability was accounted for, the observed rate of galactic novae was reproduced. However, as was described in section (4.2.1), the observed rate does not necessarily reflect all of the observable novae that are capable of being seen if sky coverage were evenly distributed
Figure 7.3: This is a galactic coordinates equal-area Aitoff map showing all 1000 nova sources generated in figure (6.3) shown in red and green. Red points represent novae that fall below the observability threshold and are considered lost to extinction. Green points represent all novae that are still observable after extinction.

across the celestial sphere. Therefore, the global rate hoped to be achieved by adding extinction to the nova distribution model was $16 \text{yr}^{-1}$. With the imbalance of observations in the southern hemisphere, the real observed global rate can be estimated to be around $10 \text{yr}^{-1}$ for a model that produces $16 \text{yr}^{-1}$.

From the analysis described above, it can be determined that for any given number of observable novae, approximately 3 times that many had erupted within the galaxy within the same time frame, with $2/3$rds being lost to extinction. With this taken into consideration, it can be deduced that for an observable rate of $16 \text{yr}^{-1}$ where 10 are ultimately observed, the global rate of nova outbursts must be about $48 \text{yr}^{-1}$.
7.2.2 10yr Comparison

In order to get a clear comparison between observed and modelled nova rates, a time frame of 10 years was selected. As can be seen by the historical nova rate record in figure (1.1) from Chapter (1), the last 10 years provides the most accurate and consistent rate at an average of roughly $10^{\text{yr}^{-1}}$. In truth, there have been a total of 99 novae observed from 2005 through the end of 2014. As previously discussed, due to the lack of contribution from southern hemisphere novae, the observable number of novae within that time frame was probably around 160. This corresponds to about 480 novae that possibly erupted from 2005 through 2014. In order to simulate this rate, 480 novae were input into the extinction model so that $\sim 160$ could be reproduced. The data for this distribution is shown in figures (7.4) and as a map in figure (7.5).

In comparing the 10 year model with the past 10 years of observations, we can see that there is lacking a large bulge population in the model. As expected, the model overestimates how many novae should appear towards the southern hemisphere, but is much closer to observations in the northern hemisphere. Despite this consideration, the model appears to overestimate how many novae should appear in the outer disk behind the sun’s galactic position relative to the center.

7.3 Sources of Error

The stark differences in distributions for the modelled and observed novae described in section (7.2.2) could be due to a number of complications that this work did not consider. In reality, both the dust and novae distributions that were assumed here have much more complicated structures that are not necessarily the same. Most galactic models include a separate bulge component to the disk in which the stellar light does not necessarily follow the dust structure. This is quite apparent in figure (7.5) as there is a clear bulge like characteristic near the galactic center consisting of a concentration of novae. In addition, it is taken for granted in this work that extinction is only due to dust when it is actually caused by gas as well. Even though gas is generally very diffuse, there is far more of it in the galaxy than dust and should not be ignored completely.

One of the other major sources of error in this project was also discussed in section (5.4). The structure of the galaxy is generally agreed upon to have other features such as spiral arms. While the bulge, discussed previously, and spiral arms are considered in many galactic structure models [Drimmel and Spergel, 2001], they were not considered here. Spiral features could account
Figure 7.4: These four figures show the distribution characteristics of 480 generated nova points expected to occur within a 10yr period. Figures (7.4a) and (7.4b) are comparative distributions of what is expected and what is produced by random-point generation. Figure (7.4c) shows a top-down projection onto the galactic plane of the nova distribution with colors designating the apparent magnitude without extinction. Figure (7.4d) shows a similar projection of apparent magnitudes of observable novae with extinction included. All absolute magnitudes are $M_V = -8.0$. 

for different concentrations of observed objects along the disk. In addition, there is also theorized to be a central barlike structure as well as a galactic warp [Drimmel and Spergel, 2001] that could affect nova observations.

Other limitations in the extinction model must also be considered. The primary concern for determining the extinction values at any point within the galaxy was to calibrate it to the Galactic Center [Fritz et al., 2011] and then again at infinite distances according to the NASA/IPAC Extragalactic Database (NED) [NASA/IPAC, 2013, NASA/IPAC, 2012]. This involved adjusting parameters such as the scale length and others in table (5.1). One parameter to take note of in
Figure 7.5: A galactic coordinates equal-area Aitoff map showing 480 nova sources, shown in red and green, as the number expected to be produced in a 10-year span. As in figure (7.3), red dots are extincted novae and green are observable. All known galactic novae that have erupted within the 10-year span from 2005 through 2014 are overlayed in cyan for comparison. Note that the modelled novae (green and red) are not corrected to account for southern hemisphere observations and therefore the overabundance in model is expected.

In particular, is the average grain size used in calculating dust characteristics. For instance, in this model the average radius squared $< a^2 >$ of a dust particle was used in the cross section calculation where the average square radius $< a^2 >$ would have been the proper choice. The distribution of grain sizes in the ISM goes as a power law, and therefore these numbers can be very different [Draine, 2011]. While these parameters may not have had drastic changes to the extinction calculator due to being absorbed into the calibration process, using more appropriate parameters would have been ideal.

Assumptions made in the nova model could also have adverse effects on the expectations of this model. As touched upon in section (6.1.2) and (2.1), novae observations are not identical as assumed here. They are often caught at different stages in their development, and have different peak magnitudes depending on their speed classes which could range from a few weeks to several
months [Livio, 1992, Bode and Evans, 2008]. Novae of different types, such as ONe or CO may also have different spatial distributions from one another, as described in section (2.1) [Livio, 1992, Della Valle and Livio, 1995, Hernanz, 2004].

Finally, one last source of error must be taken in regards to the observed nova rate. Although this model does account for the discrepancy in number of novae accounted for in each hemisphere due to sky coverage, it might be that there are many more observable novae that occur which simply go unnoticed. If this were the case, then this would greatly affect the observed, and therefore the observability, rate of novae in the galaxy. As a result, the predicted global nova rate as calculated here would be much higher.

7.4 Summary

In this chapter, the results of adding extinction to the nova distribution were discussed. It was concluded that, for the current observed nova rate of about $10yr^{-1}$, $16yr^{-1}$ should be observable from Earth and $48yr^{-1}$ should be occurring throughout the galaxy. In order to get a better understanding of the comparison between the modelled data and actual observed data, 10 years worth of generated nova points were compared to the past 10yrs of actual data. As there were many discrepancies between the two distributions, many possible sources of error were reflected upon.
Chapter 8

Conclusion

The main goal of this thesis work was to ultimately determine the total global rate of nova occurrences in the Milky Way based on the observed rate due to the effects of galactic extinction. In order to do this, a double exponential extinction model was developed that was able to measure the line-of-sight extinction to any coordinate on the celestial sphere where the distance was known. This extinction model was then added to a similar double exponential nova distribution which, in the end, not only accounted for the observability of each source’s apparent magnitude, but also for observational bias of sky coverage.

In the end it was found that, with the recently acquired observed rate of $10\,yr^{-1}$, there should be approximately 48 nova outbursts happening throughout the galaxy per year. This was determined by taking into account the lack of southern hemisphere contributions which, if novae were presumed to occur axisymmetrically about the galactic center, might have put the actual observed rate to $16\,yr^{-1}$.

Implications

The implications of this work could prove potentially useful. If this nova rate were believed to be true, it would mean that observers are losing about $2/3$ of all galactic nova outbursts, not to mention missing a little less than half of what is observable. This is much more than previous studies have predicted at $20\,yr^{-1}$ or $30\,yr^{-1}$ [Della Valle and Duerbeck, 1993, Shafter, 2002]. As discussed in the Introduction and in chapters (2) and (3), novae present a valuable resource to the astronomical
community. Galactic novae, in particular, can prove to be ideal targets to study simply due to their proximity. If observers can improve upon a more systematic way of finding novae, much could be discovered. Furthermore, having a properly defined galactic structure could prove useful to any number of studies, galactic or extragalactic.

Future Studies

Although this project is completed, there is much room for improvement and expansion of all topics discussed in this work. Future studies on galactic structure, whether they are focused on dust, gas, stars, or some combination there of, can account for the different components of the galaxy. These include such things as the galactic bulge, spiral arms, a central bar, galactic warp, and even the galactic halo. Studies focused towards nova properties and distribution could attempt to model the different populations of nova by type. Whatever the course of action, the work presented in this thesis provides a great starting point for future work regarding the relationship between galactic structure and observations of celestial phenomena.
Bibliography


