ABSTRACT

Title of Dissertation: PHYSICAL PROPERTIES OF COMETARY NUCLEI

Yanga Rolando Fernández, Doctor of Philosophy, 1999

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I present results on the physical and thermal properties of six cometary nuclei. This is a significant increase in the number of nuclei for which physical information is available. I have used imaging of the thermal continuum at mid-infrared and radio wavelengths and of the scattered solar continuum at optical wavelengths to study the effective radius, reflectivity, rotation state, and temperature of these objects. Traditionally the nucleus has been difficult to observe owing to an obscuring coma or extreme faintness. I have taken advantage of new mid-infrared array detectors to observe more comets than were possible before; I have also co-developed a technique to separate the coma and nucleus from a comet image. I developed a simple model of the thermal behavior of a cometary nucleus to help interpret the thermal flux measurements; the model is an extension to the Standard Thermal Model for asteroids. We have enough nuclei now to see the first demarcations of the "cometary" region on an albedo-diameter plot; I make a comparison of the cometary nuclei with outer Solar System small bodies and near-Earth asteroids. All of the cometary nuclei studied in this thesis are dark, with geometric albedos below 8%, and have

effective diameters of around 3 to 8 km, except for comet Hale-Bopp C/1995 O1, which is in the next order of magnitude higher. I give an extensive discussion of the nuclear characteristics of comets Hale-Bopp and 2P/Encke, the two comets for which I have large datasets.

PHYSICAL PROPERTIES OF COMETARY NUCLEI

by

Yanga Rolando Fernández

Dissertation submitted to the Faculty of the Graduate School of the
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Advisory Committee:
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PREFACE

Sections of this thesis have already been published in scientific, peer-reviewed journals and conference proceedings. A discussion of comet Hyakutake appeared in *Planetary and Space Science* in 1997 (volume 45, pages 735-739). A treatment of comet Encke is currently under review by *Icarus*. An overview of comets Tempel-Tuttle, Wild2, and Utsunomiya will appear in the upcoming book *Cometary Nuclei in Space and Time* (edited by M. F. A'Hearn and published by the Astronomical Society of the Pacific), which is based on the IAU colloquium held in Nanjing, China, in May of 1998. A paper on comet Hale-Bopp appeared in *Icarus* in July 1999 (volume 140, pages 205-220). A discussion of the image-processing technique that I call the "coma-fitting method" appears in a paper first-authored by my co-investigator Dr. C. M. Lisse, published in *Icarus* in July 1999 (volume 140, pages 189-204).

DEDICATION

To the two constants of my Universe, Mom and Dad.

ACKNOWLEDGEMENTS

This thesis is formally credited to one person, but it is not completed without the assistance of many other people, of course. Mike A'Hearn has guided me through the bulk of my graduate career and to him I owe many thanks, not only for mentoring me through the scientific aspects of my apprenticeship, but through the sociological and political ones as well. The first scientific talk I heard him give was at the Donn Symposium in Charlottesville, VA, in November of 1995. Until then I had been waffling about deciding on a concentration for my thesis, but after hearing him speak about his database paper, and seeing his enthusiasm about these new breakthroughs that finally revealed themselves after studying seven dozen (!) comets, I really started to understand some of the excitement and allure of studying these buggers. So thank you so much, Mike, for all your help.

Casey Lisse has been my other close collaborator in this scientific journey. I am grateful for his quick mind, infinite patience with my questions, and wacky humor. And of course who can forget the Red Pen? I will always look fondly back on these very scientifically productive years with him.

I also owe a deep debt of thanks to Dennis Wellnitz, who is such an expert on things mechanical and electronic. The smashing success of the Hale-Bopp occultation adventure – in a trash-dump in upstate Utah – would not have happened

without his expertise and quick thinking at the critical moments. Yet again, I think how fortunate I am to have entered Mike's Comet Group just when all these terrific people were there to help me out.

I am very grateful to Lucy McFadden for allowing me to start work on an asteroid project in 1994 and finally allowing me to realize that I really did like planetary science much more than studying clusters of galaxies! And she has continued to be a great teacher through my graduate career. Thanks Lucy!

Lastly (on the scientific front) I have to thank both NASA and NSF for there consistent financial support throughout these last years; the telescope allocation committees and staffs of IRTF, KPNO, CTIO, ESO, VLA, Lowell Observatory, and MKO, for there helpful service and positive attitude; Mike Ressler, Bill Hoffmann, and Ulli Käufl, for granting us permission to play with their instruments. Without all of these people, I would not have been so successful in gaining the necessary data to complete this thesis. Among other things I've learned: you can have oodles of fun with only 60% oxygen in your lungs; form-fitting foam is a godsend; there's nothing like jicama and asparagus salad to help you figure out how to drive a stick-shift.

Now planetary science has been good to me: if I had not been studying comets I would not have been able to travel all over the world and experience more of our planet than I had imagined. It makes you realize how much of Earth's culture and nature is still left to explore. Twenty-eight trips in grad school, and I have only scratched the surface, from strolling along Victoria Harbor among the bright lights of Hong Kong, to bathing in a giant waterfall in Waipi'o Valley on the Big Island, to being the highest human for miles around at the tip of Mt. Lassen, to watching the

rainbows appear and reappear on a misty summer's day in Stockholm. (I could go on for a while.) Unfortunately now I have no choice but to submit to this wanderlust I've picked up and spend the rest of my life traveling the nooks and crannies of our planet.

One repercussion of all this scampering around has been to instill in me a great sense of appreciation for how lucky I am. Though the physical distance between me and that subsistence farmer in central Chile, that family selling trinkets in Nogales, and those poor homeless blokes near Constitution Avenue may be small, what an incredibly fortunate person I am to be able to go to my warm house, my well-supplied grocery, my steadily paying job. We are all just a few small but critical events away from any of these predicaments.

And now, for the other important people of my time here: Thanks to Arunav, Kartik, and Laura. I wouldn't have been able to finish this tome without all of their support and understanding through this crabby and grumpy time, especially near the end. Mes amis, your friendships mean more to me than you imagine. The mid to late 1990s would have been quite a bit more difficult to slog through without you all. Let's all find enough inner peace and gumption to make the XXIst century better than the XXth. AK: Thank you for keeping my head on straight. KS: Thank you for keeping me honest. LW: Thank you for giving me self-confidence.

Continuing with the important people: thanks Don for (among other things) bringing ice cream and going sledding, thanks Leslie for (among other things) playing racquetball and finding my bike, thanks Amy for (among other things) going to see offbeat movies with me, thanks Doug for (among other things) making me stay loyal to the Padres, thanks Steve for (among other things) having practical knowledge in a institute full of geeks, thanks Pete for (among other things) endlessly quoting "The Simpons," thanks Alison for (among other things) endlessly quoting "Star Wars."

Where would we be without the department staff shielding us from the three-toed sloth that is the university administration? To John T., Mary Ann, and Maggie, thanks for your protection. Where would I be if I hadn't babysat the PDS machine during S-L 9 impact week? To Anne: thanks for that job 5 years ago and for your humor in the meantime.

Where would I be if I were not able to go to Giant at 3 o'clock in the morning and buy Pop-Tarts? What a country.

Finally, thanks to:

• ...Carl Sagan for writing *Cosmos*;

• ...Halley's Comet, for being visible right when I was so impressionable – may I see you again when I'm ninety;

• ...Voyager 2, for sending back very cool pictures of Uranus and Neptune.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Cometary Nuclei: Their History and Importance

1.1 A Brief Rundown

Most studies of the comet phenomenon focus on the coma and tail of the object, usually the most obvious parts that one sees. However this thesis presents a study of the nuclei of several comets, which are in general much harder to observe. While much work has been done to understand the nuclei indirectly by studying the gas and dust around them, I have tried to directly probe their physical and thermal properties. It is only in the last two decades that this has been observationally and computationally possible; the recorded history of the study of comets extends back a few millenia but for the vast majority of that time the very existence of a cohesive body in the middle of the coma, never mind its properties, was not known.

Though Seneca seems to have had the correct idea in the 1st century A.D., for much of history a comet seen in the sky by the ancients was not even recognized as an astronomical phenomenon until the 16th century, when Tycho Brahe set an upper limit on the comet's parallax that put it far from Earth; previously comets were believed to be atmospheric phenomena. The comets' basic place in the planetary system – moving on parabolae or on ellipses typically crossing the orbits of several major planets – was of course noted by Halley using Newton's then-new universal gravitation idea, through his accurate timing and astrometric prediction of the 1758 return of the comet now bearing his name. Aside from, most notably, work by Bessel, investigations into the physical nature of comets – as opposed to just orbital or astrometric studies – began in earnest only in the late 19th century, with detailed studies of morphology and apparent luminosity, and the advent of photography and then spectroscopy.

The study of a comet's nucleus specifically was fraught with uncertainty. As Bobrovnikoff (1931) wrote in reference to comet 1P/Halley's appearance around 1910, "[t]he term nucleus has no precise significance. Sometimes the nucleus was perfectly star-like without any measurable diameter. Sometimes it looked like a small planetary disc. Sometimes there was nothing that could be interpreted as a nucleus. It is questionable whether most observations of the diameter of the nucleus refer to the real nucleus." A paper by Vorontsov-Velyaminov (1946) gives no less than seven separate operational definitions of the nucleus. The rampant confusion of nuclear nomenclature is indicative of the lack of understanding of exactly what is at the heart of a comet. That is not to say that we are fully enlightened now, but in hindsight we can see fundamental misconceptions.

The dominant model for the comet's nucleus for about a full century, from the mid-1800s to the mid-1900s, was the sandbank model, whose tenets were most recently championed by Lyttleton (1953, 1963). The main motivations for postulating the nucleus as an unbound agglomeration of meteoritic solids and not a monolithic model were (a) a cometary coma contracts as the comet approaches the Sun, (b) meteor streams are coincident with cometary orbits, (c) nuclei tend to fluctuate in apparent size and brightness, sometimes even disappearing, and (d) comets are often as much as an arcminute away from predicted ephemeris positions, even for well determined orbits. The obvious choice to make, at least back then, was to assume that there is no one central body in the photocenter of the comet, but rather just a cloud of dust grains, and that what one observes as the nucleus is just the place where the optical depth or the concentration of particles is higher. The complicated patterns that emerge in the near-nuclear coma of some of the more active comets made it attractive to assume that there is just an amorphous cloud of dust grains deep inside the coma. For example, the head of comet 1P/Halley during its apparition in 1910 (Bobrovnikoff 1931) showed many centers of brightness with tendrils and sheets of coma pointing in multiple directions. The mass of the comet would be spread out over much of the coma, not just in the photocenter, but all of the particles in the comet are on independent orbits of all more or less the same period – there is no gravitational binding but also they are not tidally disrupted as they pass close to a planet or the Sun.

The literature is full of measurements of the size of the "nucleus" that range from a few tens to a few thousand kilometers (e.g., Chambers 1909, p. 222; Vorontsov-Velyaminov 1946; Lyttleton 1953, pp. 45-46). Frequently observers would measure the angular size of whatever resolved disk was at the center of the comet, if any. A few published reports give values within the same order of magnitude of the modern values, i.e., a few kilometers, but the majority are similar to the case, e.g., of a specific comet mentioned by Richter (1963) with a diameter lower limit that is 10 times bigger than the currently accepted value. Of course there was also the problem of a then-totally unknown albedo and then-undetermined phase effect that complicated matters. The observation of comets transiting the solar disk (Finlay and Elkin 1882, Bobrovnikoff 1931) placed upper limits on the diameter of roughly 50 to 100 km, but in the context of the sandbank model this was taken to confirm the idea that there were several smaller bodies at the heart of the comet rather than one single body producing the coma and tail phenomena.

This then was the heart of the problem for the sandbank model: the actual diameters of cometary nuclei – and here I do mean the central monolithic body – are much smaller than was commonly thought a century ago. As I will show in later chapters, most comets seem to be on the order of just a few kilometers in radius. This is not to say that comets do not have multiple sources for the dust and gas we see, for of course there are a couple dozen cometary nuclei that have been known to split into pieces, some for not obvious reasons (Sekanina 1982, 1997). However, usually the pieces evaporate away (or cease activity) in short order so that at any given moment a comet's nucleus is usually just a singular object with a radius on the order of 1 to 10 km. This should not belittle the work of the 19th and early 20th centuries; I merely point out that in hindsight many conclusions were based on incorrect precepts. Indeed, the main problematical situation in observing cometary nuclei still remains: when the comet is close by, the nucleus is shrouded in the coma, but when it is far away and the coma is not so strong, the nucleus is faint and difficult to measure. The recent journals contain many estimates of the size of cometary nuclei, but the error bars are usually large, and if they are not, then many times they probably should be!

The late 1940s and early 1950s saw the publication of significant papers on several cometary phenomena: the nucleus (Whipple 1950), the plasma tails (Biermann 1951), the reservoir of long-period comets (Oort 1950), and the source of the Jupiterfamily comets (Edgeworth 1949, Kuiper 1951). For my immediate purposes here, Whipple's work is the most significant. The nucleus is a single body, a "conglomerate of ices... combined in a conglomerate with meteoric materials," to use the original wording, with ices subliming off due to insolation. Quantitative studies of the sheer magnitude of gas mass in cometary comae and tails at the time indicated that a huge reservoir of ice was needed in the comet – far more than could be supplied by the grains in a sandbank even if the grains did adsorb volatiles on their passage through space. The ejection of material would, over time, leave an insulating mantle on the nucleus' surface and also measurably push the nucleus in a reaction force. This latter point made Whipple's model superior to the sandbank model in that both acceleration and deceleration could be explained by the sense of rotation of the central body. The sandbank model used solar radiation pressure and collisions within the bank to explain acceleration but not deceleration. The idea of a single body for the nucleus was not totally new in 1950; e.g., Wurm (1939) mentions it in the context of the formation of the gas coma.

Whipple was the first to make an extensive analysis of the rotation states of many cometary nuclei; he (1982) has given a summary and historical and contextual review. However his method for determining rotation periods, based on the timing of features moving through the coma, appears frequently to give misleading results. Whipple himself states that his method either gives exactly the right answer or something totally specious. The photoelectric measurement of the brightness of a comet's photocenter as a function of time was first done only in 1976. The determination of a cometary rotation state is a difficult problem – a good review of the pitfalls is given by Belton (1991) – and it has not been done satisfactorily even for the nucleus of comet 1P/Halley, a comet visited by several spacecraft! I will elaborate on the methodology of rotation period determination later.

In the mid- to late-1980s a series of ground-based experiments were performed that gave us size and reflectivity information on cometary nuclei for the first time. Much of my work elaborates on the same principle, i.e., combining the information from the thermal radiation and reflected light of a nucleus. The advent of sensitive germanium-gallium bolometers to detect 10 to 20 μm radiation made this method possible. I will describe the method fully in Chapter 3. The work gave our first indication that cometary nuclei are some of the blackest objects in the solar system, with geometric albedos of just a few percent. Previously the consensus was to assume a much higher value, something comparable to the icy satellites of the outer Solar System.

The study of cometary nuclei received a boost in 1986 with the data taken by the flotilla of spacecraft that flew by comet 1P/Halley, most especially by *Giotto*. For the first time ever a resolved image of a nucleus was produced, and I show a representation in Fig. 1.1 (taken from a review article by Keller [1990]), which is the combination of several high-resolution images. The flybys confirmed many of our basic suspicions: Halley's nucleus is a cohesive body and not a sandbank, its visual geometric albedo is very low (a few percent), it is approximately prolate and elongated by about 2:1, there are regions on the surface that are more active than their neighbors are; these regions produce jets similar to what is seen in the ground-based images; an active region is active apparently only on the sunlit side, not on the night side; but a good fraction of the gas and dust does not come from these active regions. While the study of Comet 1P/Halley revolutionized cometary science, it of course left many questions still unanswered. Most obviously, it would be wise to obtain similarly detailed close-up data of other nuclei. Fortunately this will probably happen in the next decade; there are several spacecraft missions with cometary targets scheduled to fly in the coming years and we hope not all of them will suffer from the budget axe or system failure. The near future will bring exciting scientific knowledge to us about these denizens of our Solar System.

This short history should make it clear how difficult observations of the nucleus can be. In general, if the comet is close to Earth, it is also close enough to the Sun to be outgassing, and the light from the gas and dust coma competes with and often swamps the light from the nucleus. On the other hand, if the comet is far from the Sun, where it is not outgassing and we have an easier view of the nucleus, the comet is also far from Earth, and the nucleus is difficult to observe due to its faintness. Furthermore once the comet is several AU away it becomes extremely difficult to tell the difference between a little bit of comatic flux and no comatic flux, since there is no set distance known *a priori* at which one can declare the comatic activity negligible. . This "Catch-22" problem exists in both the infrared and optical regimes. In the radio, there is some hope because there are not enough grains in the coma to produce enough radiation to compete with the nucleus. However at these wavelengths the PSF – "beam" in this case – is so large as to make spatial differentiation of the coma and nucleus very difficult – it is even harder to tell how much flux is comatic and how much is nuclear. Interferometric observations can be used to improve the spatial resolution, as I will show in Chapter 4, but then one needs a large nucleus since the wavelengths are so far down on the Rayleigh-Jeans side of the Planck function. The fact that our knowledge of cometary nuclei was almost non-existent all the way up into the mid-1980s dramatically indicates the difficulties in approaching the study of these objects.

1.2 The Role in the Solar System

1.2.1 Origins

In the mid-18th century, Kant speculated that the non-astrological and non-

Figure 1.1: Current "canonical" cometary nucleus. This is a processed image of the nucleus of comet 1P/Halley, taken by the *Giotto* spacecraft in March 1986 (Keller 1990). This image represents our current view of the "typical" cometary nucleus.

anthropic reason for the comets' existence was tied to the origin of the Solar System. To this day, among the largest unanswered questions in comet science are: "What exactly was the role of the comets in the Solar System's formation?" and "How is the currently-observed group of comets related to the original population?" The comets are some of the best probes we have for studying Solar System origins, since they are some of the least processed observable objects.

The story apparently begins before the Solar System was born. Recent studies of the bright comets Hyakutake and Hale-Bopp have indicated an interstellar origin for the ices, based on the isotopic ratios (Meier *et al.* 1998a, 1998b) and unusual hydrocarbon abundances (Mumma *et al.* 1996). The ices were in the solar nebula as the gas giants were forming, and the comets are remnants from the accretion process that created the gas giants. There is much debate about the exact method of gas giant formation – gravitational stability (Boss 1998) or core accretion (Pollack *et al.* 1996) – but low-speed collisions of grains undoubtedly played some role in the agglomeration of the cometesimals. The existence of the ice implies that the comets we see today formed in the 5 AU range and beyond, since closer to the Sun they would not have retained the volatile component.

Currently there are four major ideas for the structure of the nucleus as a result of the formation process. Whipple's (1950) icy conglomerate model is the original. Variations on that idea have been created by Donn (1990), who created a fractalized, fluffy aggregate; by Weissman (1986), who created a primordial "rubble pile" of a cometesimal collection with low tensile strength; and by Gombosi and Houpis (1986), who postulated a collection of closely-packed boulders held together with "icy glue." This is by no means exhaustive, and extensive reviews of the models of the bulk structure of cometary nuclei have been written by, e.g., Donn (1991). The main variations among the models are: the density of packing of the cometesimals from which they formed, and the makeup of the ice-rock matrix of which they are made. There are apparently testable predictions for the models, based on how they suffer collisions and the physics and hydrodynamics of the gas and dust ejection. Work on split comets (Sekanina 1982, 1997) seems to indicate a very low tensile strength for the bodies, but in general differentiating between the models may have to wait until we have many very close observations of several nuclei by spacecraft. Notable among the future missions is *Deep Impact*, which will fire a missile at a comet and simulate a meteorite impact, and thus allow us to observe crater formation on the surface.

The current domicile of a comet within the Solar System depends strongly on its birthplace 4.5 Gyr ago. According to numerical simulations, comets born near Jupiter and Saturn predominantly found themselves either crashing into the Sun or being ejected from the Solar System entirely, due to the strong gravitational influence of the two largest gas giants. A small percentage collided with the terrestrial planets; i.e., Jupiter and Saturn provided the impetus for some of the heavy bombardment suffered by Earth in its early history. It should be noted that even today it is thought that a typical short-period comet – with a 6-year period and aphelion passing less than 1 AU from Jupiter's orbit – can expect to survive less than a million years before being strongly perturbed into the Sun, out of the Solar System, or into a near-Earth asteroid-like orbit (Wetherill 1991).

Then there are the comets born near Uranus and Neptune. The lower mass of these gas giants (compared to Jupiter and Saturn) prohibited them from completely ejecting the comets into interstellar space. However, they were apparently very good at populating the Oort Cloud (Weissman 1991). Once a comet had been flung outward by Uranus or Neptune, it would spend several thousand years barely held by the Sun's gravity and subject to significant perturbations by passing stars, giant molecular clouds, and the Galactic tides. One net effect was to raise the perihelia and aphelia distances of these comets and, hence, keep them out of the inner Solar System (Weissman 1991); the residents of the Oort Cloud live between about 5×10^3 AU and 1×10^5 AU from the Sun. However the perturbative sources also tend to destroy the Oort Cloud over time, sending the comets into interstellar space. The existence of an Inner Oort Cloud has been invoked to resupply the outer cloud, since apparently few outer cloud members could survive 4.5 Gyr at the edge of the Sun's gravity. Duncan *et al.* (1987) have done numerical calculations to show that an inner cloud would be populated by ejected members of the Uranus-Neptune region and could help to preserve the outer cloud's population.

Lastly I will mention the Kuiper Belt, originally filled with comets that were born beyond Neptune. With no large planet to shepherd them, the planetesimals remained planetesimals. Many of the Kuiper Belt objects discovered in the past seven years reside in a resonance with Neptune – as Pluto does – that keep them safely orbiting over Gyr timescales. However, Fernández (1980; no relation) was one of the first to numerically explore the idea that the short-period comets originally came from this region, and recently Levison and Duncan (1997) have performed extensive numerical calculations to model the currently observed orbital spread of Jupiter family comets by integrating the orbits of particles in the Kuiper Belt.

1.2.2 Classification

I will give here a brief description of the relation between cometary dynamics and nomenclature. Historically, a comet has either a "short-period" (SP) or a "long-period" (LP), the dividing line being at 200 years. An LP comet can either be new or old in the "Oort sense" depending on whether or not it is passing for the first time through the inner Solar System. An SP comet can either be a member of the Jupiter family (JF) or Halley family (HF). JF comets originally come from the Kuiper belt; HF ones came from the Oort Cloud. Both JF and HF comets have been perturbed by the gas giants into orbits that keep them mostly in the inner Solar System. The usual distinguishing characteristics between JF SP and HF SP comets are the inclination and period. In my opinion one can make a case for the existence of an Encke family of SP comets (EF), for comets in orbits similar to the majority of near-Earth asteroids (NEAs). Levison (1996) has come up with a similar categorization, but currently this family is populated by only 2 known members. Recent observations have found comets residing in the Main Asteroid Belt (Marsden 1996b, Lien 1998), but these objects represent exceptional cases and are probably caused by colliding asteroids rather than independent outgassing, so it is likely that this is not a separate dynamical class of comets.

With the publication of a paper by A'Hearn *et al.* (1995) detailing molecular gas species abundances in seven dozen comets, we may have entered the era of cometary taxonomy based on compositional differences instead of just dynamics. Such categorizations are just starting to be found and understood, but continuing surveys of cometary comae and improved remote sensing techniques may allow us to obtain more accurate determinations of the compositional differences from comet to comet.

1.2.3 Evolution

The cometary nuclei have not been quiet since their formation. Numerical considerations indicate that comets from anywhere – from both the Oort Cloud and Kuiper Belt – have undergone some collisional events in the intervening eons (Stern 1988, Stern 1995, Farinella and Davis 1996); an important question is how many? The observed size and rotation distribution that we measure from the population of nuclei that has managed to penetrate the inner Solar System will likely not be the same as the original distribution with which the nuclei were born. However we would be able to tell if the nuclei are as collisionally relaxed as the main belt asteroids are or if they have not quite reached that stage yet.

There are other effects that have altered the comets, even those that were in the deep freeze of the Oort Cloud. Cosmic rays have bombarded the nuclei and affected the top layer of cometary material, although presumably this is blown off on the first passage of a comet near the Sun. Passing stars and nearby supernovae briefly warm the nuclei from their usual 3-K temperature, and hence motivate some chemical reactions in the ice. Some calculations (Stern and Shull 1988) indicate that at least once during the previous 4.5 Gyr have the Oort Cloud nuclei warmed up to 45 K due to passing stellar or supernova radiation, which could initiate sublimation of the more volatile icy components and induce some otherwise-inert chemical reactions.

The short-period comet population of course is more evolved than their long-period, new (in the Oort sense) counterparts. The aging process is thought to manifest itself, among other ways, in the chemical differentiation of the topmost layers of the nucleus and the creation and thickening of a mantle (Meech 1991). The physical destruction of the comet also contributes: e.g., via splitting or the blowing off of relatively large fractions of the comet's mass during outbursts. These phenomena could affect any observed size distribution and would tend to smear out the small end of the distribution. However, currently there is a much more worrisome problem to overcome, namely the small number of objects about which we have a detailed physical understanding. Also, the evolution of cometary nuclei is a mostly theoretical pursuit at the moment because we have not been able to observe the decay of a nucleus through multiple passages. The most obvious candidate for such a study – Encke's comet – has selfishly guarded its nuclear secrets until recently (see Chapter 5) and we will have to wait a few more years before the effect can be observed on that object. There may be some indication that small comets simply do not exist in great numbers in the inner Solar System (Rickman 2000) and that nuclei disintegrate rapidly once they get below some threshhold size. However the observational bias is strong and until we are more confident of sampling most of the short-period comets we should hold off on any conclusions. Future comet-detection searches or asteroid-searches adapted for comets could help improve the statistics by at least removing the sky coverage bias that currently prevents us from discovering many long period objects.

1.3 Motivation

We need detailed studies of more than just a few cometary nuclei if we are ever to place the nuclei in the correct context of Solar System formation and evolution. Our current knowledge of the nuclei is rather limited, so learning basic physical characteristics such as size, shape, reflectivity, rotation state, and thermal behavior represents a major step. Spacecraft will be busy during the next few years studying a few nuclei in detail, but I hope that we can more rapidly build up a reliable database of information with ground-based observations.

As an indicator of how important thermal studies of nuclei are, as opposed to just using optical data, I show the cumulative size distribution function of the Main Belt asteroids in Fig. 1.2. I have used the database of Bowell (located on the World Wide Web at `http://asteroid.lowell.edu`) to create this graph. One can estimate a radius based on just the optical magnitude by assuming a geometric albedo, in this case 4%, for the asterisks in the graph – and for these 51,517 main-belt asteroids that gives roughly a $R^{-2.5}$ size distribution. I have considered only the high end of the distribution where the sampling is at least reasonably complete. However, if one looks at the actual radii of the objects, measured via the thermal radiation for about 2100 main-belt asteroids with the *IRAS* satellite, one gets a much different distribution of $R^{-3.5}$ in the more complete end. This effect does not depend on the value of the assumed albedo since changing it would merely slide the position of the asterisks left or right. Moreover, the slope is shallower for the bettersampled optical case, whereas if this albedo effect were a manifestation of our incomplete knowledge of the main-belt one would expect a steeper slope since there would be more smaller asteroids known. I do not want to argue the actual value of these slopes; my point is simply that they are very different, and that a similar pitfall could very well occur for the cometary nuclei. Optical data alone cannot necessarily guarantee the validity of size distribution information.

The fruition of such an endeavour is guaranteed, as evidenced by the previously-unknown conclusions from the work of A'Hearn *et al.* (1995). I make no claims that an understanding of the Solar System origins can be teased out of my study of a half-dozen objects, but the revolution in infrared astronomy currently happening will make it technically and observationally feasible to continue studying the small bodies of the Solar System and eventually reach the "holy grail" of comet science, answers to such questions as: How do comets fit into the birth and evolution of the Solar System? How many times have they collided with each other? What accounts for the differences in the reflectivity, the dust-to-gas ratios, the active regions, and the emitted grains? Is there any correlation with dynamical age? How do the comets contribute to the interplanetary medium and the dust population of the Solar System? How does their appearance reflect the alterations they have suffered? Does their composition reflect an interstellar origin for the volatiles?

1.4 A Description of Chapters

I will first describe the methods used to study the nuclei, and then individually discuss each nucleus. Specifically: in Chapter 2 I will discuss my reduction methods for this study. Chapter 3 will have a description of my interpretation methods; this

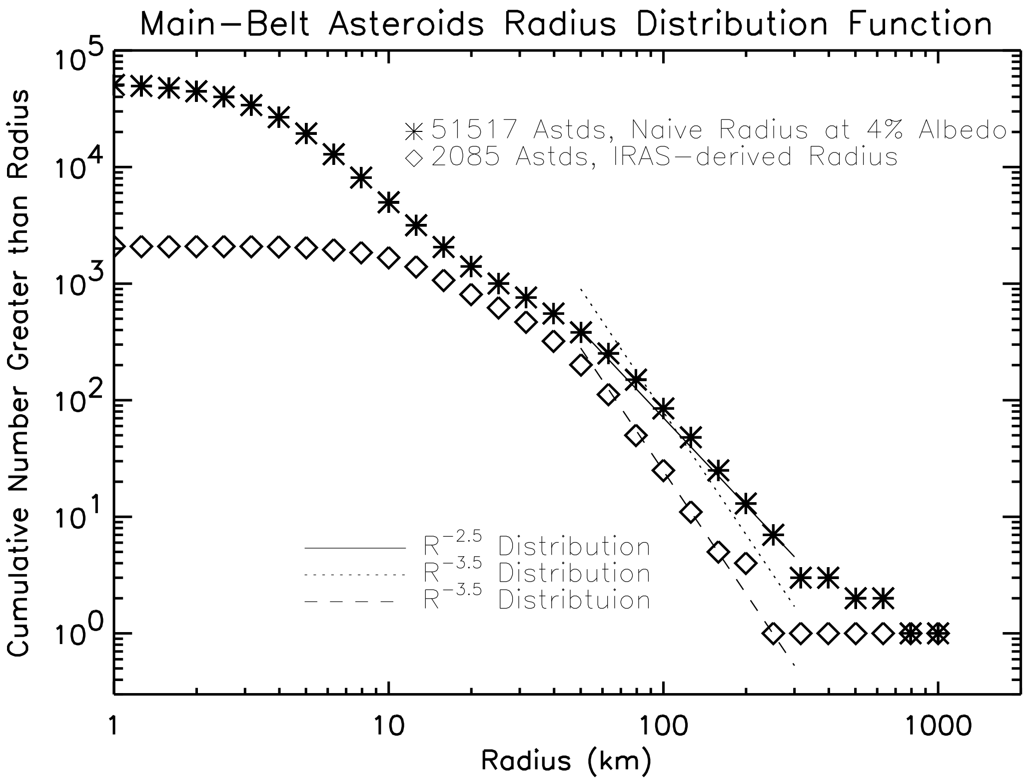

Figure 1.2: Main Belt asteroids' radius distribution function. The asterisks represent the distribution using an assumed albedo, and so give a "naive" radius when combined with the known absolute visual magnitude. The diamonds represent the *IRAS*-derived radii, and so they have the albedo ambiguity removed. Note that the slopes of the two distributions in the large particle, well-sampled end are quite different.

chapter will explain how I have taken advantage of the new generation of sensitive mid-infrared detector arrays to overcome the problems of nucleus observation that I mentioned in Section 1.1. In Chapters 4 through 7, I will discuss the nuclei of comets Hale-Bopp, Encke, Hyakutake, and Tempel-Tuttle, respectively. I will add some information about two other comets (with smaller datasets) in Chapter 8. Finally in Chapter 9 I will combine the results of the previous chapters and make comparisons with other objects of the Solar System, and try to place these results within the framework of Solar System formation and evolution.