Chapter 1

INTRODUCTION

In this chapter, I provide some justification for studying dust and I outline some of the past Jovian dust streams studies.

1.1 Why Dust?

Cosmic dust used to be an annoyance to astronomers because of the way that the dust obscures the object that they wish to observe. When the field of infrared astronomy began, those "nuisance" dust particles were observed to be significant constituents of the Universe and found to be vital components of astrophysical processes.

For example, the dust can drive the mass loss that occurs when a star is nearing the end of its life, those particles are an essential part of the early stages of star formation, and they form planets around other stars. In our own solar system, dust plays a major role in the zodiacal light, Saturn's B ring spokes, the outer diffuse planetary rings at Jupiter, Saturn, Uranus and Neptune, the resonant dust ring at the Earth, and the overall behavior of comets.

Dust evolves in the universe. Dust forms in dusty clouds, cycles through solar systems, through a star's late evolution and back into a nebula. During the dust's evolution, a complex interaction of gravitational and non-gravitational forces govern a dust particle's dynamical behavior. For example, when considering the electromagnetic forces on small and charged particles, one must be aware that dust particles can *respond to* forces in their plasma environment as well as *altering* their plasma environment via the process of accumulating and transferring charges. Therefore, small, charged particles are "tracers" of their astrophysical environments.

Within a solar system, dust is formed and destroyed and some dust is locked into a near-pristine state. The lifetimes of these dust particles are very short compared to the lifetime of the Sun. If one finds grains around a star that is older than 10^8 years, then the grains *must* have been recently generated. The sources of interplanetary dust particles in our own Solar System include, at least: asteroid collisions, cometary activity and collisions in the inner solar system, Kuiper Belt collisions, and interstellar medium dust grains.

This thesis investigates another, lesser-known source of dust in our solar system: the Jovian dust streams. Dust from this source is a minor dust source compared to collisions of the main belt asteroids and comet activity, nevertheless, it adds to the variety of dust sources in the solar system. At a velocity of $\geq 200\ \mathrm{km\,s^{-1}}$ (Zook et al. 1996), the Jovian dust stream particles can also leave the solar system to slightly populate the local interstellar medium.

1.2 History of the Jovian Dust Streams

The scientific explorations of Io as a source of dust in the Jovian system and the Jovian dust streams have revealed a long and colorful 20 year history. I present a short summary next of the observational history and publication history (here, addressing the question: *What is the origin of the Jovian dust streams?*), then I describe these historical events in more detail.

- Observational History
  - **1979:** Volcanoes on Io discovered by Voyager 1.
  - **1992:** Ulysses discovers the Jovian dust streams.
  - **1993:** Baguhl, M. et al. found more Ulysses dust streams.
  - $\gtrsim$ **1995:** Galileo observes the Jovian dust streams.
  - **2000:** Cassini & Galileo observe the Jovian dust streams.
- Publication History
  - **1993:** Grün et al. suggest origin in Jovian system.
  - **1993:** Horányi et al. suggest Io.
  - **1993:** Hamilton & Burns suggest gossamer ring.

- **1994:** Grün et al. consider Comet SL-9.
- **1995:** Maravilla, Flammer and Mendis suggest Io.
- **1996:** Zook et al. show streams faster/smaller than reported before.
- **1996:** Ip demonstrates tiny particle sizes ejected from Io.
- **1996-1997:** Horányi, Grün et al. detailed modeling supports Io as origin.
- **2000:** Graps et al. reveal Io via frequencies.

The Jovian dust streams story began when Io's volcanoes were discovered by the Voyager 1 spacecraft in 1979. Upon that discovery (the first time that active volcanism was seen on another body in the solar system), E. Grün, G. Morfill, and T. V. Johnson published a series of papers (Johnson et al. 1980, Morfill et al. 1980*a*, Morfill et al. 1980*b*, Morfill et al. 1980*c*, Grün et al. 1980) giving a theoretical basis for Io dust generation in the Jupiter system. Voyager 1 arrived in the Jupiter system in March 1979, and Voyager 2 arrived in July 1979. No dust detector instrument was onboard either of these spacecraft, but measurements from the other instruments confirmed that dust was in ample supply in the Jupiter system.

Thirteen years later, when Ulysses was at its closest approach to Jupiter, in March 1992, the dust detector instrument, built by E. Grün and his colleagues, recorded six periodic bursts of submicrometer dust particles with durations ranging from several hours to two days and occurring at approximately monthly intervals (28 ± 3 days) (Grün et al. 1993*a*; Grün et al. 1993*b*). The dust streams were observed in interplanetary space within 2 AU from Jupiter, and the particles arrived at Ulysses in collimated streams, radiating from close to the line of sight to Jupiter, suggesting a Jovian origin.

In 1993, more detailed work on the Jovian dust streams was published and many investigators began to suggest theories for the dust streams' origin with physical models.

Grün et al.'s (1993*b*) article established the Jupiter system as the origin of the dust streams. Horányi et al.'s (1993*b*) work suggested Io as a source for the dust streams. Their model could explain the 28 day periodicity of the data, if the dust grains were small (sizes: 0.03–0.1 μm) and they exhibited speeds in the range:

$30 < v_{exit} < 100$ km s^{-1}. Their model suggested that the periodicity arose from a resonance between the Io orbital and the Jupiter rotational periods.

Hamilton & Burns (1993) presented an alternative model for the origin of the dust streams; they suggested that the masses and velocities of the detected particles were better explained by an origin in Jupiter's gossamer ring.

Baguhl et al.'s (1993) work relaxed the rigid noise requirements of the Ulysses dust instrument and allowed better statistics. After they reanalyzed their data, a much larger number of impacts for the Jupiter dust streams were seen. One clear indication that the Jupiter system was the origin of the streams was that there was a 180° shift of stream mean impact directions before and after the Jupiter flyby.

Horányi et al.'s (1993*a*) work expanded on their model for the dynamics of charged particles in Jupiter's magnetosphere and they considered both Jupiter's rings (ring/halo and gossamer) and Io as a source for the dust streams' particles. Their work favored Io as the source.

Two important events occurred in the Jovian dust streams story in the years 1994–1995. In July 1994, comet Shoemaker-Levy-9 impacted Jupiter, and in December 1995, the Galileo spacecraft arrived in the Jupiter system.

Grün et al. (1994) considered the possibility of comet SL-9, before its time of tidal disruption in 1992, as a source of the dust streams' particles. They found that only two of the eleven Ulysses dust streams would have the right timing and speeds to be the source of Ulysses's dust stream measurements, but they concluded, after further investigation of stream characteristics and dust accelerations mechanisms, that the comet most likely *added* some dust to the Ulysses-detected dust streams, but the comet wasn't a source.

Maravilla et al. (1995) obtained analytic results characterizing grain orbits launched with different velocities and locations in the Jovian system. They conclude that Io is the most likely source of the Ulysses dust stream measurements.

Galileo's dust detector instrument, which is identical to Ulysses' dust detector instrument, observed the Jovian dust streams, both on its way to Jupiter, and in the years since 1995, while in the Jupiter system.

Work continued on the Ulysses dust stream data in 1996, with a paper: (Zook et al. 1996). In their paper, they simulated dust streams detected by Ulysses, tracing trajectories back in time to Jupiter's location using actual solar wind plasma and magnetic field data, in order to determine the size and speed the particles would have to have in order to arrive at the Ulysses dust detector instrument. From their simulations, they determined that the particles must have been *smaller* and *faster* than previously reported. The new sizes were $\sim 10^{-18}$ g with speeds of > 200 km s^{-1}. Their results were consistent with Horányi et al.'s (1993) model, but not completely consistent with Hamilton and Burns' (1993) model (Hamilton and Burns' particle sizes were larger).

Grün et al.'s (1996*b*) paper reported Galileo's dust detections of the Jovian dust streams for the first time. The spacecraft's dust detector instrument detected the dust streams in interplanetary space on its approach to Jupiter (re-confirming that the source was within the Jovian system), the instrument detected streams within the Jovian system, and it detected dust "storms" as well. The dust streams were similar in duration and intensity to the streams observed by Ulysses, although the streams did not display the one-month periodicity that the Ulysses data of the dust streams displayed. Since Zook et al's recent (1996) work argued for very small and fast dust stream particles, Grün et al. (1996*b*) concluded that the dust streams' particles were outside of the calibrated mass and impact speed ranges. The dust storms, which were detected on the way to Jupiter, were intense (fluctuated by up to a factor 100 in a day), of a month-long duration, with impact rates up to 10 times higher than those rates detected by Ulysses. The authors discussed possible sources of the dust streams in some detail (Grün et al. 1996*b*). They list comet SL9, Jupiter's gossamer ring, or the volcanoes on Jupiter's moon Io, as a potential source of the Jovian dust streams. After ruling out comet SL9, they conclude that the dust streams' source could be either Io, or the gossamer ring.

Grün et al.'s (1997) paper described the dust streams data observed within the Jovian magnetosphere as a continuation of the dust streams observed in interplanetary space out to 2 AU from Jupiter. These data show the same kind of impact magnitude and direction with a smooth transition of the rate from interplanetary space to within the Jovian system. Since Galileo's in-orbit measurements now provide higher time resolution data than the previous dust stream measurements, Grün et al. (1997) could find more detailed frequencies. In particular, they found frequencies that correspond to values of Jupiter's rotation period as seen by Galileo, and a correlation with dust impact rate and Galileo's position in the Jovian magnetic field.

Horányi et al.'s (1997) work and Heck's PhD thesis (Heck 1999) modeled the above Galileo dust detector data for the early Galileo orbits assuming that Io is the only source of the escaping dust grains, and they succeeded in matching the gross characteristics of the Galileo dust detector data. They described a scenario where the Jupiter dawn-dust electric field, which shaped the Io plasma torus, then ultimately shaped the trajectories of the dust ejected from the Io plasma torus. The trajectories of the particles followed a spiral, much like the motion of water from a sprinkler system. Once the grains begin traveling in the Jupiter magnetosphere, the spatial distribution becomes non-uniform and asymmetric.

The work in this thesis continues the Jovian dust streams story since approximately 1998.

1.3 Statement of the Problem and this Thesis

Indirect methods applied by previous researchers have pointed to Io being the simplest explanation for the question of the origin of the Jovian dust streams. Problem: **Can I show by direct methods that Io is, or Io is not, the source of the Jovian dust streams?** If the answer to that question is 'Yes', then: **Please explain some of the physical phenomena of the Jovian dust streams.**

This dissertation is divided to first address the issue of identifying Io directly in the Galileo dust detector data. In (Graps et al. 2000), which I describe more fully in the chapter 'Jovian Dust Streams as Frequencies', I demonstrate that Io is indeed the source of the Jovian dust streams, by applying time-frequency analysis, in particular, Fourier methods, (however, non-Fourier methods support the conclusions), to the Galileo dust data. Some additional frequency signatures to Io's signal also emerge from the time-frequency analysis, and I show a time-evolution view of the 29 orbits of Galileo dust detector data.

The second part of this dissertation shows that a particle carrying a varying charge can explain some of the features of the Jovian dust streams in real-space. To show how a Jovian dust stream particle travels in real-space, I apply a detailed Jovian particles and fields model by M. Horányi, which I adapted for this thesis, which simulates a dust stream particle's trajectory as the particle moves from Io's orbit through Jupiter's magnetosphere and beyond. I describe the complex model in the chapter 'Modeling', and I show the results of applying that model in the chapters: 'Charging' and 'Dynamics'. Through the model, I show some charging effects which influence the particle's dynamical behavior, and I apply the model to match the travel time seen in the December 30, 2000, Galileo-Cassini joint dust stream measurements.

The last part of this dissertation gives a synopsis in the chapter: 'Synopsis of Io Revealed in the Jovian Dust Streams', and I describe some paths for future work in which to advance the Jovian dust streams research in the chapter: 'Going Further'.