CHAPTER 1

INTRODUCTION

1.1 Preamble

This dissertation is not a single, monolithic research project. Instead it contains most of the diverse research questions that I have studied during my five years at LPL.

Inasmuch as this dissertation has a central theme, that theme is the analysis of accelerometer data. Back when I began graduate school, Mars Global Surveyor was entering its second phase of aerobraking and returning accelerometer measurements from the martian upper atmosphere on a daily basis (Keating et al., 1998). My first hours of research here at LPL were spent processing and trying to analyse the regular data deliveries from the spacecraft. Five years later, I am still trying.

It seems to me that accelerometer datasets are often collected more for engineering reasons than scientific reasons. Judged purely on their scientific return, other instruments probably have stronger cases for being flown into space. However, since the accelerometer data can be essential for the operation of the spacecraft, accelerometers can fly without needing to compete before review boards and advisory committees against radiometers, spectrometers, magnetometers, and so on. For those who decide to analyse accelerometer data, this has the advantage of regular flight opportunities and the disadvantage of inadequate support for data archiving and scientific activities. To illustrate the regular flight opportunities, in the past five years I have worked with the Mars Global Surveyor, Mars Climate Orbiter, and Mars Odyssey accelerometer teams during their missions and with the Beagle 2 and Mars Exploration Rover (MER) teams before launch. To illustrate the lack of scientific exploitation of the data, only three peer-reviewed publications have analysed significant amounts of the data from the Mars Global Surveyor accelerometer (Keating et al., 1998; Bougher et al., 1999; Wilson, 2002). There have been none from Mars Odyssey. This is an astoundingly low number. The same is currently true for entry accelerometers; there are no scientists planning to analyse the MER entry accelerometer data amongst the forty-strong science team.

Since NASA has gone to all the trouble of collecting the data, someone should at least try to analyse it. As those who are involved with proprietary datasets know, there are often simple discoveries waiting to be made by the first scientists who examine a dataset.

Most of the Mars atmospheric science community is busy analysing huge volumes of lower atmospheric data from Mars Global Surveyor's TES and RS instruments, the first significant martian atmospheric dataset since Viking, and they have not taken a great interest in the behaviour of the upper atmosphere (Smith et al., 2001; Tyler et al., 2001). There are many important questions to be answered with TES, but also many clever people working on them. Accelerometer data from a spacecraft aerobraking around another planet form a new kind of dataset, one that had never been collected before Mars Global Surveyor. As such, there are new phenomena to be discovered and studied, ones that are not present in current models or other datasets. Personally, I prefer working with a simple, novel dataset, not knowing what the big questions it can answer are, to working on a vast dataset, which is similar in its basic properties to those returned from previous missions, where the important questions are already known. To expand on what I mean by not knowing the big questions, two of the most interesting features in the Mars Global Surveyor accelerometer dataset are the possibility of using it measuring winds (Chapter 4) and occasional large changes in density over very short times and distances (Tolson et al., 1999; Tolson et al., 2000). Neither of these features was anticipated before the data were analysed.

Mars Climate Orbiter was unfortunately lost before any data were returned, but Mars Odyssey has aerobraked succesfully and I am looking forward to the public release of its accelerometer data. I hope to join in the Mars Reconnaissance Orbiter aerobraking activities as a fully-fledged member of the science team, instead of being mentored by a science team member. Since there are so few scientists working on accelerometer datasets and more flights of accelerometer instruments to come, I hope to have such opportunities in the future.

In an attempt to expand my connections with British and European planetary science, I spent the summer of 2001 working with the Beagle 2 team and developing techniques to analyse accelerometer data from a planetary lander. That snowballed into nearly being funded to join the MER science team to do similar analysis. As a consolation prize, I was invited to join an advisory group for MER, which offers all the data access without any of the funding. I will be in a similar situation with Beagle 2 when it lands — data access without funding. Huygens is also an area of interest. Since Seiff's group at Ames that pioneered this technique has recently dissolved, I am motivated by the chance to establish myself as an expert in the analysis of entry accelerometer data.

One piece of advice I have seen often in career books as I plan my post-PhD future is that scientists should focus on problems, not on techniques. The reasoning behind this advice is that existing techniques, be they experimental or computational, are always superceded by new ones. The same fate befalls the antiquated experts as befalls the antiquated techniques. This dissertation seems to ignore that advice by being dominated by analysis of data collected with a single type of instrument. My feeling on this point is that the advice is good in the long-term, but that I should become established as a competent scientist in one area before I try to move into too many others. I have chosen accelerometer data analysis as this launchpad because of its regular flight opportunities and relative shortage of established scientific leaders. Luckily, it also contains interesting scientific questions that are sufficiently close to those addressed by other instruments or theoretical models to allow me to develop related research interests elsewhere in the study of planetary atmospheres after I graduate.

Owing to NASA's current focus, this dissertation is heavily weighted toward studies of the dynamics of the martian atmosphere using accelerometer data. In Sections 1.2 and 1.3 I outline the current state of our understanding of martian atmospheric dynamics and how accelerometer data analysis can improve it.

1.2 Introduction to the Martian Atmosphere

My three main sources for this Section are Kieffer et al. (1992), Haberle (1997), and Leovy (2001). I have not referenced these sources explicitly at each appropriate occasion in this Section because that would fill the printed page with citations. Instead it should be understood that information from these sources has been used throughout the entire Section. I make exceptions to that rule when I provide an explicit reference for direct quotations.

The martian atmosphere is predominantly composed of CO_2. N_2 and Ar are present at the percent level and H_2O is a trace constituent. Suspended aerosols such as micron-sized dust and condensates of CO_2 and H_2O have a large effect on the transfer of radiation within the atmosphere. Mars is farther from the Sun than Earth is; its orbital semi-major axis is about 1.5 AU. A martian year is about twice as long as a terrestrial year. Its orbit is quite elliptical with an eccentricity of nearly 0.1, which causes solar insolation at perihelion to be 40% more than at aphelion. The martian obliquity is very similar to Earth's, which makes the effects of seasons similar. Seasonal effects are complicated by the changing Sun-Mars distance. The martian day is also similar in length to Earth's. The mean column mass of the martian atmosphere is about 20 g cm^{-2}, one fiftieth of Earth's. The martian atmosphere is cold, and its temperature at the surface varies between approximately 145 K and 275 K. The surface pressure is so low, a mean value of 7.5 mbar, that liquid water, pure or contaminated, is short-lived on the martian surface. Interestingly, the atmospheric pressure is close to that of the triple point of water, the minimum surface temperature is the freezing point of CO_2 at that pressure, and the maximum surface temperature is close to that of the triple point of water. In contrast to the great cycle of H_2O which drives the Earth's climate, the martian climate is driven by the condensation and sublimation of CO_2 at the polar caps. Tens of percent of the atmosphere's mass flows back and forth between the two hemispheres each year. Even in the absence of CO_2 condensation, there would still be an appreciable hemispheric flux due to the extreme pole-to-pole gradient in topography and the changing atmospheric scale height with the seasons. There are many possible past states of martian climate depending on variations in obliquity and other orbital parameters.

The vertical temperature structure of the martian atmosphere differs significantly from the Earth's. Latent heating due to H_2O is negligible and there is no heating from the absorption of solar UV by ozone. The martian troposphere is heated by dust, whereas Earth's is heated by H_2O. On Earth, H_2O freezes out at the tropopause and limits the height of the troposphere to around 10–15 km. On Mars, the dust is not trapped in this way and it can be lifted to several tens of kilometres altitude, so the martian troposphere extends higher than Earth's. The dust content and distribution in the martian atmosphere can vary significantly over the seasons and during a dust storm. This causes variability in the height and temperature gradient of the troposphere. Above the martian troposphere, there is the near-isothermal mesosphere. This is capped by the thermosphere, a region where temperature increases with altitude due to extreme UV heating. The martian atmosphere has a much smaller mass per unit heating than Earth's with which to buffer diurnal and other subseasonal changes in heating. Departures from a mean state are common with many types of atmospheric waves and tides prominent. The main cycles governing martian climate are those of CO_2, dust, and H_2O. The effects of H_2O are the weakest of the three under current climatic conditions, being limited to its radiative effects as a vapour or a condensate and its potential to trap CO_2 and dust as it condenses.

The lower atmospheric circulation has been well-studied by observations and theory. "The mean meridional atmospheric circulation is nearly zonally-symmetric. At equinoxes, two Hadley cells share a common rising branch near the equator, extending upwards to ~30 km altitude and poleward to ~ 30°. At solstices, the Hadley cells intensify and merge into one cross-equatorial cell with air descending in the winter hemisphere, moving across the equator, and rising in the summer hemisphere" (Haberle, 1997).

"In the tropics, the winds are westward at all seasons. Winds are also westward in the summer hemisphere at solstices. Winds are eastward in the winter hemisphere at solstices and at extratropical latitudes during the equinoxes. Jet streams can reach speeds on the order of 200 m s^{-1}" (Haberle, 1997).

Superimposed on this pattern is the seasonal flux of CO_2 to and from the poles. Winds at the edge of the southern polar cap become strongest in springtime, close to perihelion, as CO_2 sublimates off the cap. These strong surface winds can lift significant amounts of dust into the atmosphere, sometimes initiating planet-encircling dust storms.

"Eastward travelling planetary waves with zonal wavenumbers of 1 to 3 occur during winter and spring in mid and high latitudes of both hemispheres. Stationary planetary waves, with zonal wavenumbers 1 and 2, are generated by the interaction of eastward zonal winds and topography. Thermal tides are common in equatorial to mid-latitudes. Most of them migrate westward with the Sun, but some travel eastward. The breaking of these disturbances as they reach the middle and upper atmosphere deposits energy and momentum into the atmosphere and will alter the circulation" (Leovy, 2001). The nature of the circulation in the middle and upper atmospheres has not been well-studied observationally.

Various large-scale wave motions are present in the martian atmosphere. These motions are of interest because of their intrinsic nature, their relationship with the averaged general circulation, and their effects on the transport of aerosols and trace constituents. They are generated by atmospheric instabilities and external forcings such as solar heating, topography, albedo, and thermal inertia. The long-duration surface pressure records from the two Viking landing sites revealed transient eddies, similar to travelling cyclones and anticyclones at terrestrial mid-latitudes, with periods of a few days and zonal wavenumbers of 2 or 3 travelling eastwards with phase speeds of 10–20 m s^{-1}. Global-scale oscillations, or tides, are also common. Migrating diurnal and semidiurnal tides, modes which have the same phase speed as the Sun, cause regular surface pressure variations of a few percent. The relative strengths of these two modes depends on atmospheric dust loading. The frequencies of some non-migrating tidal modes, modes which are generated by the interaction of solar heating and topography, are close to atmospheric resonant frequencies, which encourages their amplitudes to become relatively large. One of these, the diurnal Kelvin wave (see Chapter 2), has been detected in Viking surface pressure records, vertical temperature profiles in the lower atmosphere measured by orbiting IR spectrometers, and Mars Global Surveyor accelerometer data at 130 km altitude (Wilson, 2002). Many other transient waves are probably present in the martian atmosphere. This paragraph follows Section V of Zurek et al. (1992) closely.

1.3 Observations of the Martian Upper Atmosphere

The martian upper atmosphere has been studied remotely by instruments on flyby and orbiting spacecraft and *in situ* measurements have been made by instruments on landers and aerobraking orbiters (Kieffer et al., 1992). UV spectrometers on the Mariner 6 and 7 (Mars arrival in 1969) flyby spacecraft studied upper atmospheric composition. Mariner 9 (1971) was the first spacecraft to orbit another planet. It studied upper atmospheric composition with a UV spectrometer and ionospheric densities with radio occultations. Mars 4 and 5 (1973) were flyby spacecraft that studied upper atmospheric composition with visible spectrometers and ionospheric densities with radio occultation. Viking 1 and 2 landers (1976) measured *in situ* ionospheric properties and vertical profiles of upper atmospheric composition, density, pressure, and temperature during their descent. A suite of instruments on the short-lived Phobos 2 orbiter (1989) studied ionospheric properties. Phobos 2 also measured two vertical profiles of upper atmospheric temperature from X-ray occultations of solar flares (Krasnopolsky et al., 1991). Pathfinder (1997) measured a vertical profile of upper atmospheric density, pressure, and temperature during its atmospheric entry. Mars Global Surveyor (1997) measured *in situ* upper atmospheric densities during its aerobraking passes and ionospheric densities from radio occultations. Prior to Mars Global Surveyor, all of these observations apart from Mariner 9 came from landers or flyby spacecraft that did not have extended spatial or temporal coverage. How altitude, latitude, season, longitude, time of day, and the phase of the 11-year solar cycle affect upper atmospheric densities, pressures, temperatures, and winds is not well-known.

Volatile escape rates, and their variation over martian history, play a crucial role in studies of the history of the climate and habitability of Mars. An important loss mechanism for oxygen, dissociative recombination, is controlled by the diffusion of hydrogen through the lower thermosphere. The dynamics of the martian upper atmosphere affect escape rates and so this dissertation contributes indirectly to those important scientific questions. The underdeveloped state of our understanding of the physics and chemistry of the martian upper atmosphere was highlighted by the recent Decadal Survey recommendation for a Mars Upper Atmosphere Observer spacecraft (Belton, 2002).

Mars Global Surveyor accelerometer data can be used to improve our understanding of the dynamics of the martian upper atmosphere. This dataset contains profiles of upper atmospheric density between 100 and 160 km altitude at various latitudes, longitudes, seasons, and times of day (Keating et al., 2001a). These density profiles can, in principle, give pressure and temperature profiles as well. Since the density measurements on each aerobraking pass are made at two different latitudes for every altitude, zonal winds can, in principle, be derived as well, as discussed in Chapter 3. There have been no previous measurements of winds in the martian upper atmosphere. MGS measured density profiles on 800 aerobraking passes. This dataset is significantly larger and more extensive in its coverage than previous measurements of upper atmospheric properties. An unfocused initial survey of the dataset will probably yield interesting results and can be followed by addressing specific questions such as which tides are present, what mechanisms are dominating the heat transport, what controls the circulation, or how the upper atmosphere responds to solar variability or lower atmospheric dust storms.

In this dissertation I have studied which tidal modes are present in the upper atmosphere and how they relate to observations and simulations of tides in the lower atmosphere. I have also developed and applied a novel technique for measuring winds with the accelerometer data. Many of the other questions posed in the preceding paragraph remain to be answered; I hope to answer them in future work as I delve deeper into this dataset aided by theoretical predictions, lower atmospheric observations, and similar, subsequent datasets like those of the Mars Odyssey and Mars Reconnaissance Orbiter accelerometers.

1.4 Dissertation Structure

Chapter 2 is an expanded version of a paper accepted for publication by Icarus (Withers et al., 2003). Steve Bougher and Gerry Keating are coauthors. As my advisor, Steve Bougher provided guidance, oversight, and innumerable comments on draft manuscripts. Gerry Keating is a coauthor because of his role as instrument principal investigator. Several other people are acknowledged in the paper for their assistance. Chapters 3 and 4 will be prepared for publication after I graduate. Chapter 5 has been accepted for publication by Planetary and Space Science (Withers et al., 2003). Martin Towner, Brijen Hathi, and John Zarnecki are coauthors. Martin Towner provided insight into real-world issues with instrumentation and commented on many early drafts of this chapter/publication. There are several short passages in this chapter that are more his words than mine. Brijen Hathi provided helpful discussions on the coordinate frames and aerodynamics. John Zarnecki provided supervision and financial support. Several other people are acknowledged in the paper for their assistance. Chapter 6 is work that I will use as a member of the MER Entry, Descent, and Landing Atmosphere Science Advisory Team when the two MER spacecraft reach Mars in early 2004. Chapter 7 has been published in Icarus (Withers et al., 2002). Greg Neumann and Ralph Lorenz are coauthors. Greg Neumann provided expert advice on the MOLA dataset. Ralph Lorenz wrote the Datathief program that extracted data from a figure in another publication. Several other people are acknowledged in the paper for their assistance. Chapter 8 has been published in Nature (Withers and Neumann, 2001). Greg Neumann is a coauthor. He was my supervisor during my summer internship at Goddard when I began this work. Several other people are acknowledged in the paper for their assistance. Chapter 9 and a subsequent Comment and Reply have been published in Meteoritics and Planetary Science (Withers, 2001; Nockolds and Withers, 2002). Several other people are acknowledged in the paper for their assistance. Chapter 10 contains my contribution to Lorenz et al. (2001) and some subsequent work that has not been published. Only one of the projects that I have presented at scientific meetings is not included here — Angle of Repose-limited Shapes of Asteroids. This project, which tried to find how far away from spherical an asteroid could be without requiring strength, has not received enough of my attention in recent years to develop beyond the level of a class project. The question remains interesting and unsolved, but it not discussed further in this dissertation.

I have not tried to keep fully up-to-date with the scientific literature whilst preparing this dissertation. I have not cited any publications that appeared in the LPL library after 2002. Important publications from 2003 will have to wait until my next peer-reviewed publications to be cited appropriately.

1.5 Sources of Support

I have received intellectual support from a great many people in the past five years. Many secretaries, faculty, postdocs, and graduate students at LPL have been generous with their time when I have been seeking help. I single out some of the most important ones here. Don Hunten and Jay Melosh have, in their own inimitiable styles, shaped my ideas of what a scientist should be, what problems should be tackled, and how they should be tackled. Their teachings have influenced how I selected and approached the projects included in this dissertation. Ralph Lorenz's enthusiasm for simplicity in science and understanding of what makes a spacecraft mission work are resources that I have called upon often. Chapters 6, 7, and 10 have been influenced by his ideas. Many discussions with those graduate students whom I met when I arrived at LPL have helped guide me safely through the department, conferences, orals, publications, this dissertation, and job-hunting. Outside LPL, the LPL mafia has given me many networking opportunities. Bob Tolson has saved me from several horrendous mistakes with his occasional emails. His comments have influenced Appendix A and my processing of data in Chapter 4. I have been privileged to see how a science team should work through my association with the MOLA team which led to Chapter 8. The Open University welcomed me back to Britain one summer and helped me catch up on planetary science activities in Europe. Finally, Steve Bougher has let me invest my time (and his money) in projects far afield from his research interests that have helped me reach this stage of my career. The freedom he has given me to make mistakes has been invaluable to me.

I have received financial support from a variety of sources. Steve Bougher's NASA grants were my primary source of funding. LPL has supported me with two semesters of quarter-time teaching assistantships and one semester of a half-time research assistantship after Steve Bougher moved to the frozen north. The University of Arizona's College of Science awarded me a Galileo Circle Scholarship that helped me after two summers away from LPL's doubled summer pay. The Goddard

Summer Student Program in the GSFC Earth Sciences Directorate supported me for one summer. The MOLA team supported my travel to several conferences and team meetings. The Open University supported me for another summer. Jonathan Lunine sent me to an LPSC meeting. JPL partially sent me to a Planetary Science Summer School. The European Union sent me to Italy for two wonderful weeks. Finally, the Deep Space 2 E/PO budget supplied me with a fine computer. Sadly, I am barred from entering the MER naming contest.