CHAPTER 11

CONCLUSIONS

Each Chapter of this dissertation ends with its main conclusions. I summarize those here and then try to draw together some common threads that link the diverse research questions that I have studied during my five years at LPL.

In Chapter 2 I studied the sol-to-sol variability in the martian upper atmosphere at fixed latitude, altitude, longitude, times of day, and season. This variability is not due solely to solar flux variations, and further modelling and studies of lower atmospheric observations are needed to understand its cause and make useful predictions about it.

In Chapter 2 I also looked at zonal structure in the martian upper atmosphere due to thermal tides. These observations, together with classical tidal theory and observations from other instruments, have been analysed to identify the dominant tidal modes. A simple explanation has been outlined for why topography is the most likely cause of the thermal tides.

The density profiles remain almost unexamined (Keating et al., 2001a). Every bump and wiggle on them has a story to tell about the small-scale dynamics in the upper atmosphere and there are many hints of significant changes in density over very short distances that seem to defy reason. Comparison of data with general circulation models is also at an early stage. Models provide a way of filling the gap in time and space between measurements, so if the models do an adequate job of reproducing the data then it is possible to examine the model's results and determine which physical mechanisms are most important.

Dust storms on Mars are unique in their planetary scale. Their effects on the upper atmosphere are not well-known. Further analysis of this dataset will let us watch the upper atmosphere during the rapid rise and slow decay of a dust storm.

The upper atmosphere sits atop the lower atmosphere. Many phenomena in the upper atmosphere are influenced by the state of the upper atmosphere. As models progress and become able to reproduce upper atmospheric observations reliably, it may be possible to infer information about the state of the lower atmosphere from upper atmospheric measurements alone. For example, some tidal modes require specific wind conditions in the lower atmosphere to propagate to the upper atmosphere and be detected there. The ability to indirectly study the lower atmosphere during aerobraking would greatly extend the scientific usefulness of accelerometer data.

Chapters 3 and 4 have possibly the most important conclusions of this dissertation: Accelerometer data from aerobraking or neutral mass spectrometer data from orbit can be used to measure winds. A novel "Balanced Arch" technique for deriving winds from aerobraking data has been derived and applied to MGS data. These are the first measurements of winds in the martian upper atmosphere. This technique also provides a way of deriving consistent pressure and temperature profiles from the MGS data. Neither the archived dataset nor other workers have yet derived pressure or temperature profiles from the data. Coupled density, pressure, and temperature data are much more useful than density data alone and permit the study of a wider range of phenomena. This technique could be applied to several other existing and anticipated datasets from Venus and Titan.

Winds are one of the most difficult atmospheric properties to measure, yet they play a huge role in determining a planet's weather and climate. It is unfortunate that I have not been able to test my "Balanced Arch" technique against GCM simulations. It is important that the technique is tested as much as possible to determine what its limits of applicability are. There are several assumptions in the derivation of the technique that warrant careful scrutiny. In the text, I have tried to emphasize the preliminary nature of the results for the martian upper atmosphere. However, there should be some way to use the combination of inbound and outbound profiles to constrain horizontal gradients in the atmosphere. Separating vertical and horizontal gradients in the density profiles would make them much more useful. The relatively poor agreement between my results and GCM simulations is interesting. Either my results are incorrect, which means that the technique is flawed, or the simulations are incorrect. A combination of those two failures is also possible. There are several possible causes of problems with the simulations. The upper atmospheric simulations are linked to lower atmospheric simulations. These lower atmospheric simulations are well-constrained by data at their lowest altitude levels, but not at the highest levels where they are coupled to the upper atmospheric model. The current coupling is one-way only and does not allow the upper atmosphere to influence the lower. The upper atmosphere is also zonally-averaged and much of this dissertation has discussed longitudinal variability in the upper atmosphere. In the traditional words of graduating students, “more work in this area is needed.”

Chapter 5 represents work whose main usefulness will come after I graduate and use it analyse Beagle 2 and MER entry accelerometer data. By developing techniques to process entry accelerometer data, I have gained a better understanding of what hidden problems and assumptions exist in the processed MGS accelerometer dataset. Section 5.7.3 presents what I believe is a new idea that could radically simplify the first analysis of entry accelerometer data when management and public alike are clamouring for results. Deriving an atmospheric temperature profile without needing an aerodynamic information about the spacecraft is potentially a powerful technique. The problems that have been discovered in the PDS archive are probably not important for the atmospheric structure results or their interpretation. Spencer et al. (1999), using what I believe is a valid entry state, derived essentially identical atmospheric results as Magalhães et al. (1999), whom I believe quoted an invalid entry state. It is not clear that the entry state quoted by Magalhães et al. (1999) was actually used to derive their results.

Chapter 6 is also something of an investment for the future when I am able to analyse entry accelerometer data. It will not provide ground-breaking scientific results, but it offers the chance to obtain very rapid, yet crude, characterizations of atmospheric structure even before the entry is complete. The ability to make a robust estimate of atmospheric temperature at peak acceleration without being overwhelmed by the uncertainties in transmitted frequency is potentially useful. The ability to derive any scientific results from a failed mission might help maintain public support of NASA's exploration program.

Chapter 7 presents a way to improve the atmospheric profiles measured during the entry of the two Viking landers. Errors of 10 – 20% in density and pressure at a given altitude were found and preliminarily corrected for. A topographic profile from the Viking 2 entry, which is not discussed in this chapter, can be found on page 285 of Euler et al. (1979). This work shows topographic elevation above a reference areoid, so comparison against MOLA data requires knowledge of what that reference areoid was. Since Viking 2 landed on flat Utopia, far from the rugged outflow channel terrain of Viking 1, a smaller error is likely.

This is another example of scientifically useful information coming from what might be considered an engineering instrument. Comparing the Viking radar altimeter topographic profiles with MOLA data provides a test of an established dataset that could not have been forseen in the Viking era. The possibility of someone reanalysing the entire Viking entry with the additional constraint of MOLA data is, I think, slim. Many different instruments were used to derive the Viking entry trajectories and the chance that all the necessary data and documentation can be found and understood in the JPL archives is small. Since martian surface atmospheric pressure varies so much, the Viking-derived standard atmosphere is primarily temperature based (Seiff, 1982). Temperature as a function of altitude is specified from the Viking entry data, but pressure and density profiles are derived from the temperature profile, an assumed surface pressure, hydrostatic equilibrium, and the equation of state. Consequently, the likely impact of errors in the original

Viking density and pressure profiles on other work is relatively small.

Chapter 8 continues the theme of martian topography with a concise discussion of the discovery of a network of tectonic features in the otherwise bland northern plains of Mars and their implications for a possible ocean in that area.

This project has received an undeservedly small amount of attention in this dissertation. I began this project in the summer of 2000 after my second year as a graduate student. My orals kept me away from it for much of the subsequent semester. I continued working on it in the spring of 2001 and wrote a funding proposal to support my work. My involvement in entry accelerometer work from the summer of 2001 onwards pushed this project further into the background and the rejection of the funding proposal did not help my motivation either. It has been two years since I worked on this project and my notes are simply not adequate for writing a substantial chapter on this without more work than is justified at this time. I would like to continue with this project in the future. Projects important enough to get published in *Nature* are unlikely to be a steady occurrence in my career and I should take full advantage of them when I have them. To make a significant contribution with this project in the future I need to develop a robust technique for mapping these ridges and measuring their characteristics. I am dissatisfied with the subjectivity of my previous mapping work and think that I would benefit from working closely with someone experienced in this area to develop a more objective and repeatable technique, preferably one that can be automated. The nature of the northern plains is, as *Nature's* editors phrased it, enigmatic. Neither sedimentation in an ocean nor steady influx of material from localized volcanic or fluvial sources as championed in current models seems to explain either the flatness or smoothness of this region or its veneer-like covering of older craters and ridges. Why the plains are closer to level with the pole-to-pole slope than with respect to an equipotential is also perplexing.

Chapter 9 investigates whether the formation of lunar crater Giordano Bruno was witnessed in 1178 AD. The formation of this crater would have caused great meteor storms in Earth's atmosphere that would have merited recording in the many chronicles of the era. Since no such records are known, I concluded that Giordano Bruno did not form in 1178 AD. This means that there is not a large, pristine crater on the Moon that can be studied to give more insight into the important geological process of impact cratering than weathered terrestrial examples.

Chapter 10 presents some studies of simple climate models. Simple, one dimensional climate models are commonly used in the first studies of a planet's climate. While planets in our solar system are nowadays usually modelled by general circulation models, simple climate models, which require minimal observational constraints on the nature of an atmosphere, will be useful in studies of extra-solar planets.

The common thread that runs through this dissertation is the analysis of accelerometer data to derive atmospheric properties. Accelerometer data seem relatively simple to me, just a single scalar measurement as a function of time, when compared to, for example, gas chromatograph measurements or the millions of spectra that TES has measured. I have used two different approaches in this analysis. One approach aims for back-of-the-envelope, order-of-magnitude analysis leading to rapid generalizations about the phenomena present in the data. Chapter 6 and Section 5.7.3 are examples of this. The other approach aims for long-term, methodical, and in-depth analysis to extract every last piece of information from the data. Chapters 2 and 4 are examples of this. The rapid approach favours analytical tools with sweeping simplifications and limited predictive power, whereas the detailed approach favours comparison to other observations and theoretical models to build a comprehensive picture of what is happening. Both styles have their advantages and disadvantages. I believe that the most useful progress can be made by switching back and forth between them.

The datasets that I have analysed or prepared to analyse in this dissertation are not directly concerned with the most pressing scientific questions that drive current programmatic and mission priorities. However, they are in a sense "free data."

Since the measurements are made for engineering purposes anyway, subsequent scientific analysis of them is relatively cheap. The dynamics of the martian upper atmosphere are almost unconstrained by data in comparison with the lower atmosphere. That means that connections to the major questions pertaining to the study of the better-studied martian lower atmosphere or of upper atmospheres in general are weak. Only after collecting new and broad-based observations, such as the Mars Global Surveyor accelerometer data, and surveying and characterizing those data can specific, focused questions be posed that address these issues.

Exploring such a *terra incognita* will always lead to discoveries, even if it is not known in advance what they will be. In the final analysis, the reason why I have spent five years studying these data is for the stimulation of making unexpected discoveries that will influence scientific priorities in the future.