Winds in Planetary Atmospheres

Introduction:
The basic circulation of an atmosphere is defined by its pressure, temperature, and wind fields [Holton, 1992]. Pressure and temperature have a direct effect on the passage of electromagnetic radiation through an atmosphere, and so can be measured by remote, passive observations, such as infra-red spectroscopy or occultations, using knowledge of this radiative transfer process. [Chamberlain and Hunten, 1987]. Winds have very little effect on electromagnetic radiation, and hence are much harder to measure, yet are fundamental to the global structures of temperature, pressure, and constituent transport. Measurements of winds on other planets have primarily been made by indirect techniques and are currently limited to lower and middle atmospheres.

Goals:
The goals of the first 12 months covered by this proposal are as follows:

(1) Development of my current work on an innovative technique for deriving upper atmospheric winds using geostrophic balance and measured latitudinal gradients in density [Withers *et al.*, 2002a; 2002b].
(2) Measurement of atmospheric properties, including winds, during the landing of NASA's two Mars Exploration Rovers (MERs) in early 2004 [Squyres, 2001]. I am a member of the Atmosphere Science Advisory Group for their Landing.

Explanation of New Techniques:
My innovative technique for measuring wind speeds from accelerometer or orbiting mass spectrometer density measurements is based on the observation that each such in-and-out pass through the atmosphere is effectively two horizontally separated vertical density profiles acquired simultaneously [Keating *et al.*, 1998; Withers *et al.*, 2002a; 2002b]. The actual flight path typically extends over several tens of degrees in latitude as the spacecraft enters the atmosphere, descends several tens of kilometers to periapis, and rises back up out of the atmosphere. By applying the assumption of hydrostatic equilibrium in a static atmosphere to the inbound (spacecraft descending to periapsis) leg of the pass, as has been done for many vertical density profiles from planetary landers or entry probes, the inbound density profile provides a pressure profile along the same flight path and a value for the pressure at periapsis. Similarly, the outbound (spacecraft ascending from periapsis) leg provides a second, independent measure of periapsis pressure. For Mars Global Surveyor Accelerometer data in the upper atmosphere, I have found that these two measurements of periapsis pressure are generally inconsistent. Scale analysis of the equations conserving momentum in the atmosphere, which originally led to the simple assumption of hydrostatic equilibrium in a static atmosphere, shows that the assumptions need to be relaxed to allow geostrophic balance, or latitudinal density and pressure gradients in response to the Coriolis force [Holton, 1992]. Lower atmospheric wind speeds have been measured using geostrophic balance on temperature/pressure data with complete latitudinal and vertical coverage, but geostrophic balance has never been applied to upper atmospheric density profiles with constrained latitudinal and vertical coverage before [Smith *et al.*, 2001]. Assuming a constant and uniform zonal wind,

geostrophic balance, and requiring the two estimates of periapsis pressure to agree, yields consistent estimates for the pressure profiles and the speed and direction of the zonal wind in this region. The sunsynchronous orbit of Mars Global Surveyor renders this technique sensitive to only the zonal component of the horizontal winds.

On slowly rotating bodies such as Venus or Titan, cyclostrophic balance can be used instead. The Pioneer Venus mission dropped four probes simultaneously into the atmosphere. Latitudinal pressure gradients between the vertical entry paths of the probes were used with cyclostrophic balance to measure the wind speeds [Schubert, 1983]. The results were consistent with winds measured from direct tracking of the probes. Upper atmospheric densities on Earth have been studied with accelerometers in low-Earth orbit, and it is possible that terrestrial upper atmospheric wind speeds could be studied by applying this technique to their datasets [*e. g.*, Marcos and Forbes, 1985]. The ability to measure winds from accelerometer measurements during aerobraking, which will be made on many future NASA missions, extends the scientific breadth of these missions without requiring additional instrumentation. Developing this new technique may well lead to future mission involvement and long-term funding opportunities for me.

Objectives:
The specific objectives for each goal are:

(1A) Extract synthetic density profiles, representative of the environmental conditions (season, time of day, longitude, phase in the 11-year solar cycle, latitude range, and altitude range) of past and anticipated datasets, from general circulation model simulations of the martian upper atmosphere, then compare the actual wind speeds in the simulation to those I derive from the synthetic density profiles. These simulations have been made available by my current PhD supervisor [Bougher *et al.*, 1999].
(1B) Extend the technique to generate vertical profiles of zonal winds by applying the principles of geostrophic balance at each individual altitude level [Holton, 1992]. The current implementation of the technique, which is discussed later, applies geostrophic balance to all altitudes together, which strongly weights the derived wind speed to the lowest altitudes.
(1C) Apply the improved technique to Mars Global Surveyor and Mars Odyssey Accelerometer data from the martian upper atmosphere to derive zonal wind speeds from each pass through the atmosphere, quantify how the zonal wind speed varies with altitude, latitude, season, longitude, and time of day, and then compare these results to existing predictions [Keating *et al.*, 1998; Plaut and Saunders, 2001].
(1D) Instead of geostrophic balance, which is appropriate for rapidly-rotating bodies like Earth or Mars, use the principles of cyclostrophic balance to develop an analogous technique for measuring wind speeds from measured latitudinal density gradients on slowly-rotating bodies such as Venus or Titan [Holton, 1992].
(1E) Apply this version of the technique to Pioneer Venus Orbiter Neutral Mass Spectrometer data, quantify how the zonal wind speed varies with altitude, latitude, season, longitude, and time of day, and then compare these results to existing predictions [Schubert, 1983; Bougher, 1995].

(2A) Extend my current work on generating vertical profiles of density, pressure, and temperature from accelerometer measurements of linear acceleration made during the atmospheric entry of a lander or entry probe to include simultaneous gyroscopic measurements of angular accelerations and solution for profiles of atmospheric winds based on their effects on the spacecraft trajectory [Seiff and Kirk, 1977, Withers *et al.*, 2002c].

(2B) Apply these techniques to the atmospheric entry of NASA's MER spacecraft in early 2004 [Squyres, 2001].

(2C) Compare the derived atmospheric properties, especially wind speed and direction, to existing predictions, and other measurements.

Timeline for Research and Publication:

I plan to spend my first four months working on the first goal, the second four months working on the second goal, and the final four months working on both goals as appropriate based on my research progress. If renewed for a second year, I would study winds in Titan's atmosphere using Cassini and Huygens data. If renewed for a third year, I would study winds in the martian atmosphere using Mars Reconnaissance Orbiter data. These plans are discussed further at the end of this proposal. The results will be published in the peer-reviewed literature; my current plan is for a comprehensive paper on objectives 1A – 1C, a paper on objectives 1D – 1E, and a short paper on objectives 2B – 2C in conjunction with the MER team. Objective 2A is more suited to a detailed, pedagogical publication that will be useful to researchers who have to analyze similar datasets in the future. More detailed papers on objectives 1D – 1E and objectives 2B – 2C may follow, if justified, after the first 12 months of this proposal.

Background and Previous Work:

Wind affects the martian climate by transporting energy, momentum, condensable species, and radiatively important aerosols. Direct wind measurements on Mars are limited to two vertical profiles of horizontal winds from the entry of the Viking Landers and surface winds measured at their landing sites [Zurek *et al.*, 1992]. Indirect wind measurements derived from temperature gradients via the thermal wind equation have greater spatial and temporal coverage, but are only constrained relative to an unknown reference wind speed [Smith *et al.*, 2001]. The two MER vertical profiles of horizontal wind speed and direction will double the number of wind profiles with vertical resolution of less than half a scale height. Unlike the Viking Landers, these entry profiles will be collected in conjunction with extensive orbital remote sensing of the atmosphere from Mars Global Surveyor, Mars Odyssey, and the European Mars Express. This is a unique opportunity to cross-calibrate the many instruments and obtain a snapshot of the martian atmosphere at both local and global scales. My proposed work on winds will be a small part of the research in the planetary science community enabled by this opportunity. Analysis of data from entry accelerometers, an essential instrument on landers and entry probes, was led for many years by a group that has now retired, so successful involvement in the MER mission could lead to future mission involvement and long-term funding opportunities for me [Young and Magalhaes, 2001].

There are no measurements, direct or indirect, of martian wind speeds in the upper atmosphere. These winds affect the upward propagation of atmospheric tides and other wave phenomena, which can break and deposit their energy and momentum locally [Forbes, 1995]. Atmospheric tides are immensely important in the upper atmosphere; Mars Global Surveyor accelerometer data revealed longitudinal density variations by a factor of two or more due to tides [Keating *et al.,* 1998]. Measurements of wind speeds will help us understand how these tides propagate and amplify, and why some tidal modes are stronger than others.

On Venus, the atmosphere super-rotates with a period of about four days. This super-rotation is not well-understood [Schubert, 1983]. Super-rotation has been inferred in the upper atmosphere from nighttime buildups of light molecules such as helium, but has not been directly observed [Niemann *et al.,* 1980]. Direct measurements of wind speeds and their variability over altitude and the 11-year solar cycle will test current theories of the super-rotation.

Contribution to GISS Mission:
These research goals contribute towards the mission of GISS. By studying atmospheric processes in atmospheres beyond Earth, we can understand what is universal and commonplace, and what is special and unique to Earth. Insight into a process from studies of one planet can be applied to long-standing problems on other planets. By studying climates and atmospheres in conditions different to those we live in on present-day Earth, we improve our abilities to forecast changes in terrestrial climate as conditions on Earth change. Winds are a common field of study for GISS researchers interested in other planets. Allison, Del Genio, and Rossow all are, or have been, members of spacecraft instrument science teams with responsibilities for studying winds [*e.g.* Allison *et al.,* 1994]. Allison's Co-Investigator status on the Huygens Doppler Wind Experiment and the Mars Reconnaissance Orbiter Mars Climate Sounder (a reflight of the ill-fated PMIRR instrument) experiment, both of which will measure winds, complements my research goals and experience.

If this proposal is renewed for a second year, I will study winds in Titan's atmosphere, comparing the results of the Huygens Doppler Wind Experiment from its measurements in the lower atmosphere in early 2005 to wind measurements in Titan's upper atmosphere from application of my innovative technique to density profiles from Cassini's Ion and Neutral Mass Spectrometer. I am currently investigating possible results of these upper atmospheric measurements with Roger Yelle, a Co-Investigator on the Cassini Ion and Neutral Mass Spectrometer. The lower atmospheric winds will be derived by other members of the Science Team [Bird *et al.,* The Huygens Doppler Wind Experiment, in press at *Space Science Reviews*]. These two sets of observations can be compared to published predictions and other Cassini/Huygens results.

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Previous and Current Research

When I started graduate school at the University of Arizona in August, 1998, I had no experience in identifying, researching, developing, and successfully achieving independent research goals. Learning how to do that has been the most satisfying achievement of my PhD studies. Supported by my advisor, I have pursued research goals in several different areas of planetary science and in two summer internships.

Weather in the Martian Upper Atmosphere:

- University of Arizona, Tucson, Arizona, USA
- 1998 – present
- Graduate Research Assistant and Associate, supervised by Steve Bougher
- References 5, 15

The main project that I have worked on in the last five years is analyzing accelerometer data from the aerobraking of Mars Global Surveyor to better understand weather in the martian upper atmosphere. I have participated in peer review of the accelerometer dataset for NASA's Planetary Data System public archive, and have been invited to participate in the peer review of the Mars Odyssey Accelerometer dataset. In addition to scientific research, I supported Steve Bougher in Atmospheric Advisory Group activities for Mars Global Surveyor, Mars Climate Orbiter, and Mars Odyssey. These typically included a daily teleconference during the aerobraking period of these spacecraft with scientists around the country, reviewing the available data, and making daily weather predictions to the mission operations staff to guide safe and timely aerobraking. The Mars Global Surveyor Accelerometer unexpectedly discovered large (factor of two) variations in upper atmospheric density with longitude at constant altitude, latitude, season, and time of day. My research has quantified this longitudinal structure and the effects on it of altitude, latitude, season, and time of day. By comparing these observations to predictions from classical tidal theory, I have identified what the dominant tidal modes, generated at the planet's surface, are in the upper atmosphere. I am developing a novel technique to measure winds in the upper atmosphere from this dataset, based on geostrophic balance and observed latitudinal gradients in density. Winds are challenging to measure, yet play a crucial role in a planet's climate. Once validated, this can be applied to many existing and anticipated datasets to measure atmospheric circulation at high altitudes on many planets.

Age of Lunar Crater Giordano Bruno:

- University of Arizona, Tucson, Arizona, USA
- 2000 – 2002
- Independent Research
- References 2, 3, 11

The first independent research project that I devised and followed to completion was an investigation of the age of the young lunar crater Giordano Bruno. Based on a dramatic description in a medieval chronicle of the "Moon spewing fire, hot coals, and sparks," it has been suggested that the chronicle records an eyewitness account of its formation. This would make it astoundingly young for a 22-km diameter lunar crater. I investigated the formation of this crater, its ejection of 10 million tonnes of debris from the Moon, and the subsequent meteor storm on Earth from the arrival of some of the ejected debris. Based on the expected, but not observed, spectacular meteor storm, I concluded that Giordano Bruno did not form in historical times and that there must be some other explanation for the striking medieval text.

Enigmatic Northern Plains of Mars:

- NASA Goddard Spaceflight Center, Greenbelt, Maryland, USA, later continued at the University of Arizona, Tucson, Arizona, USA
- 2000 – present (summer of 2000 spent at Goddard following successful application to the competitive Goddard Summer Student Program)
- Research Assistant to Greg Neumann while at Goddard, collaboration continued after my return to the University of Arizona and later collaborating also with Jay Melosh of the University of Arizona.
- References 4, 13

Topographic measurements from the Mars Orbiter Laser Altimeter (MOLA) have revolutionized our understanding of martian geology and geophysics. I spent the summer of 2000 as a summer intern with the leaders of the MOLA group, investigating a low-lying area of Mars that appears bland and featureless on existing images, and discovered a large network of ridges within it. We rejected an earlier, highly stimulating, interpretation that some of these ridges were once shorelines on a vast martian ocean and identified them as tectonic features, records of large impacts and the growth of volcanoes on Mars. These results were presented at several meetings of the MOLA Science Team. I later planned to study these features in more detail to learn about the history of martian volcanism, writing a funding proposal to NASA's Mars Data Analysis Program as a Co-Investigator (with Principal Investigator Jay Melosh). This was not funded, but the experience I gained then has improved my subsequent proposals.

Entry Accelerometer Data Analysis:

- Open University, Milton Keynes, Great Britain, later continued at the University of Arizona, Tucson, Arizona, USA
- 2001 – present (summer of 2001 spent at the Open University)
- Consultant to John Zarnecki while at the Open University, collaboration continued after my return to the University of Arizona
- References 7, 10

The Mars Express and Beagle 2 missions to Mars, due to arrive in late 2003, represent major new commitments to planetary science by Europe and Great Britain, respectively. To discover how this is affecting planetary science in Great Britain and establish collaborations there, I spent the summer of 2001 with the Beagle 2 team in Great Britain. Building on my work on analyzing accelerometer measurements from aerobraking, I developed the programs that will process Beagle 2's entry accelerometer data into vertical profiles of atmospheric density, pressure, and temperature. These programs have been made publicly available to stimulate other groups interested in such projects. After returning to Arizona, I submitted a proposal as Principal Investigator to become a Participating Scientist on NASA's Mars Exploration Rover mission. This was highly rated, but not funded. Subsequently, I was invited to join the mission's Entry, Descent, and Landing Atmosphere Science Advisory Team with responsibilities for advising the

JPL engineers in assessing the performance of the spacecraft during its atmospheric entry. I have also been invited to participate in a Huygens Descent Trajectory Working Group meeting by the Group Chair, David Atkinson.

Comparison of Martian Topography Between Viking Lander and MOLA Data:

- University of Arizona, Tucson, Arizona, USA
- 2002
- Independent Research in loose collaboration with Greg Neumann and Ralph Lorenz
- References 6, 12

Having a broad range of research projects stimulates novel ideas. Whilst working on entry accelerometer data analysis, I found that one product of that analysis for the Viking landers was a topographic profile, derived from radar altimetry, beneath the non-vertical path of the descending spacecraft. I compared this measurement of martian topography to the MOLA data I had been studying the previous summer and discovered a one to two kilometer difference between the two. This is most easily explained by uncertainties in the altitude of the radar attached to the Viking lander, which affects the vertical profiles of atmospheric density, pressure, and temperature generated by the Viking entry accelerometer data analysis.

Simple Climate Models:

- University of Arizona, Tucson, Arizona, USA
- 2001
- Collaborator with Ralph Lorenz
- References 1, 14

Current models of planetary climate are based on general circulation models, which are highly computer-intensive and contain many uncertain parameterizations of physical processes. It has been suggested that complicated thermodynamic systems, like a planet's climate and atmosphere, can be understood by the application of some kind of extremal principle analogous to the principle of least action in physics. Ralph Lorenz has investigated the hypothesis that fluid motions within an atmosphere act to maximize the rate of change of entropy within the system. I collaborated with him by deriving analytical expressions for how this would affect a simple atmosphere.

Others:

- References 8, 9

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2. Nockolds, P, and **P Withers** (2002) Comment and reply on "Meteor storm evidence against the recent formation of lunar crater Giordano Bruno" by Paul Withers, *Meteoritics and Planetary Science*, **37**, 465-466.
3. **Withers, P**, (2001) Meteor storm evidence against the recent formation of lunar crater Giordano Bruno, *Meteoritics and Planetary Science*, **36**, 525 - 529.

4. **Withers, P**, and GA Neumann (2001) Enigmatic northern plains of Mars, *Nature*, **410,** 651.
5. **Withers, P**, SW Bougher, and GM Keating (2002, submitted) The Effects of Topographically-controlled Thermal Tides in the Martian Upper Atmosphere as seen by the MGS Accelerometer, under review by *Icarus*.
6. **Withers, P**, GA Neumann, and RD Lorenz (2002) Comparison of Viking Lander descent data and MOLA topography reveals kilometer-scale error in Mars atmosphere profiles, *Icarus*, **159,** 259-261.
7. **Withers, P**, MC Towner, B Hathi, JC Zarnecki (2002, submitted) Analysis of Entry Accelerometer Data: A Case Study of Mars Pathfinder, under review by *Planetary and Space Science*.

Selected Conference Presentations and Other Unrefereed Papers:

8. Grier, JA, and 28 coauthors, including **P Withers**, (2002) Setting Goals and Priorities for Education and Public Outreach, in *The Future of Solar System Exploration 2003-2013: Community Contributions to the NRC Solar System Exploration Decadal Survey* (ed. Sykes) Volume 272 of the Astronomical Society of the Pacific's Conference Series.
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14. **Withers, P**, and RD Lorenz (2001) Simple Tests of Simple Climate Models *Eos, Transactions of the American Geophysical Union, Fall Meeting Supplement,* **82,** Abstract #U32A-05.
15. **Withers, P**, SW Bougher, and GM Keating (2002) Measurements of Winds in the Martian Upper Atmosphere from the MGS Accelerometer, *Bulletin of the American Astronomical Society,* **34,** Abstract #5.05. (1 of 9 first-author conference presentations on weather in the martian upper atmosphere)