REMOTE SENSING OF THE MARTIAN ATMOSPHERE WITH GROUND-BASED TELESCOPES.

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Introduction:

We are developing techniques for measuring basic properties of the Martian atmosphere using ground-based telescopes. By observing the reflected light spectrum at near-IR wavelengths we can obtain information on the composition and structure of the atmosphere. We use imaging spectroscopy to obtain spectra across the planet's disk and interpret the data with the help of high-resolution radiative transfer models.

Why use ground-based telescopes for such studies when there are a number of spacecraft making remote sensing observations? Ground-based telescopes provide a number of capabilities not currently available from spacecraft. They can provide spectroscopic coverage of the whole visible hemisphere of Mars in a short time and thus provide a global picture of the atmosphere and good coverage of time varying effects due to Martian weather. Ground-based instruments also offer much higher spectral resolution than current spacecraft instruments.

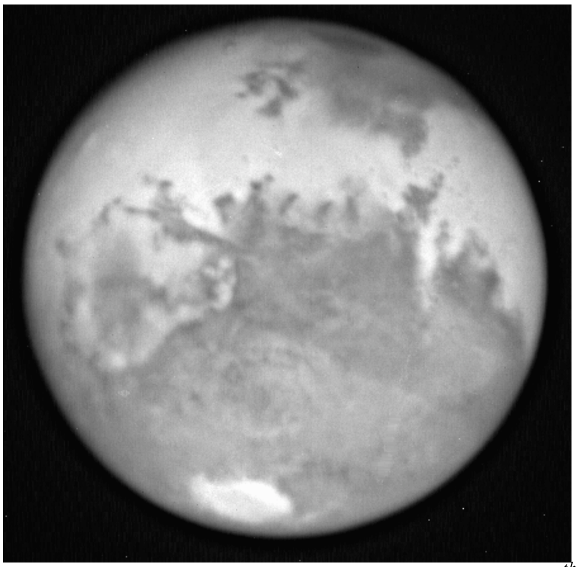

Figure 1 — IR image of Mars obtained on Sep 4th 2003 at a wavelength of 1.64μm.

Observations – 2003:

Observations during the 2003 opposition were obtained with the UIST imaging spectrograph (Ramsay Howat et al. 1998) on the 3.8m United Kingdom Infrared Telescope. This telescope was chosen because the high altitude Mauna Kea site provides excellent seeing, and minimizes terrestrial atmospheric absorption, the telescope has been upgraded to provide excellent image quality (Hawarden et al. 1998), and it has a modern IR spectrograph with a versatile automated observing system. We obtained two types of observations. Narrow band filter images were obtained in four different filters at a pixel size of 0.06 arc seconds (about 16km). A series of short exposure images were taken in each filter. By selecting the best images out of each set we were able to improve on the, already excellent, Mauna Kea seeing (0.3 – 0.35 arc sec) and obtain what we believe to be the highest resolution images of Mars ever taken with a ground-based telescope (e.g. fig 1).

Imaging spectroscopy was obtained by recording long-slit spectra, with the slit stepped through a series of positions across the disk of the planet. These observations were used to build three dimensional "data cubes" with 0.12 arc second pixels along the slit, 0.25 arc second pixels in the scan direction, and 1024 spectral channels. From such data, spectra can be extracted for any position on the disk, or images can be obtained in any spectral feature. Some example spectra are shown in figure 2. These data have a spectral resolving power of 960.

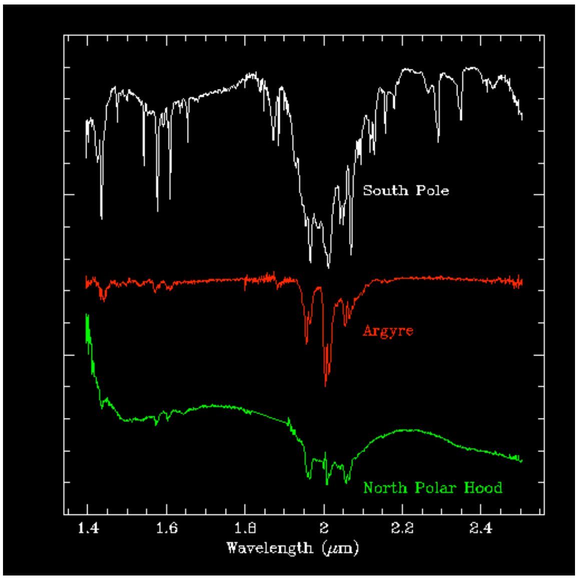

Figure 2 — Near IR spectra of three regions of Mars from the spectral cube obtained on 2003 Sep 4th. Top – spectrum of the south polar cap showing CO_2 ice absorption. Middle – spectrum of the Argyre impact basin showing atmospheric CO_2 absorption. Bottom – spectrum of the north polar hood clouds showing water ice absorption.

Observations – 2005:

Observations during the 2005 opposition were obtained with the CSHELL instrument on the 3m

NASA Infrared Telescope Facility at Mauna Kea, Hawaii, and with GNIRS on the 8m Gemini South telescope at Cerro Pachon, Chile. The observations cover the CO_2 bands with much higher spectral resolution than the 2003 UKIRT observations. Imaging spectroscopy was obtained in the same way as for the UKIRT Mars observations. An image of Mars at 1.6 μm extracted from a high resolution spectroscopic cube is shown in figure 3.

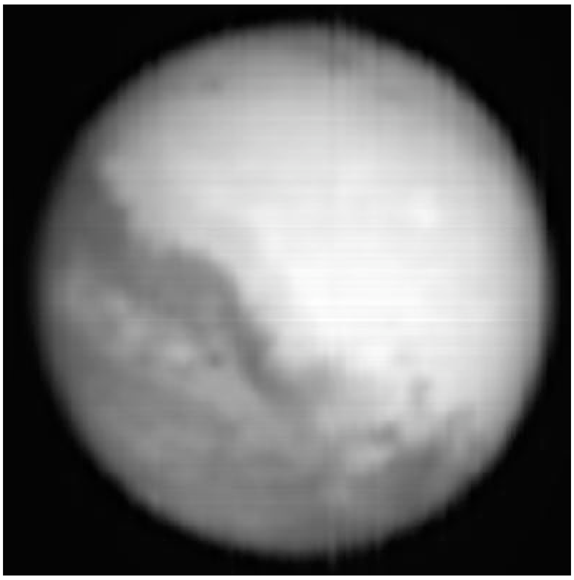

Figure 3 — Image of Mars obtained with GNIRS on Gemini South on Nov 14th 2005. The image is a slice out of a spectral cube obtained by recording 100 long-slit spectra of Mars as the spectrograph slit was stepped across the planet.

Effect of the Earth's Atmosphere:

All ground-based observations are made through the Earth's atmosphere and therefore are affected by the absorption of atmospheric gases. This is a particular problem for observations of Mars as the Earth's atmosphere contains many of the same gases that we are interested in observing in the spectrum of Mars. For some species, such as H_2O and CH_4, which have much higher column densities for the Earth, observations can only be made when Mars has a signficiant radial velocity, doppler shifting the Martian lines away from the telluric lines. For other molecules such as CO_2 and CO, which have higher column densities in the Martian atmosphere, observations can be made near opposition (when the radial velocity is small), but it is still necessary to account for the effects of the telluric lines. Normally astronomers remove these features from their spectra by observing a standard star with a smooth spectrum, and dividing the spectrum of the science target by that of the standard. However, this technique does not work for observations of Mars, because it fails to properly account for the unresolved structure of the bands, which are composed of many narrow, and often saturated, individual lines. The standard star technique assumes Beer's law applies over relatively broad spectral bands, when in fact it only applies monochromatically. We have carried out simulations using high-resolution radiative transfer models for the Mars and Earth atmosphere, that show that applying the standard star technique to Mars data would lead to errors of up to 50% on the strongest CO_2 bands (figure 4). Further details are given in Simpson et al. (2006).

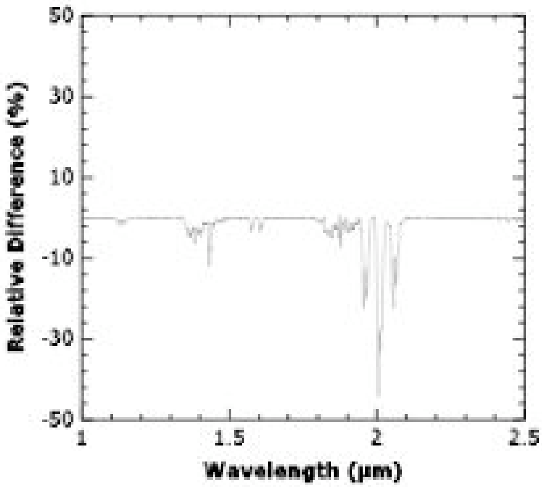

Figure 4 — Result of a simulation showing the errors introduced into a spectrum of Mars by using the "standard star" method to remove telluric absorption.

Modeling:

The effects of the Earth's atmosphere can be dealt with by adopting a forward modeling approach. We model the entire light path through the Mars and Earth atmospheres to the observer using high-spectral-resolution radiative transfer models. This involves first using a model for the Mars atmosphere to predict the radiance at the top of the atmosphere, and then passing this through an Earth atmosphere model to account for the telluric absorption. The predicted spectrum can then be compared with that observed.

We have used two radiative-transfer modeling codes for this work, the SMART code (Meadows and Crisp 1996) and the VSTAR code (Bailey 2006). Both of these codes model a plane parallel atmosphere using a line-by-line treatment of the molecular absorption and solving the radiative transfer equation by the discrete ordinate method (Stanmes et al. 1988). The Mars atmosphere model includes absorption by CO_2, CO, H_2O, O_2 and O_3 with line data coming from the HITRAN database (Rothman et al. 2003) as well as scattering form Martian dust.

Results:

Figure 5 shows an image extracted from the UKIRT spectral cube in the 2.0μm CO_2 absorption band. An image in the deepest part of the band has been divided by one just outside the band, giving the CO_2 band depth variations. The variations in CO_2 band depth are primarily due to the difference in atmospheric path length resulting from Martian surface topography.

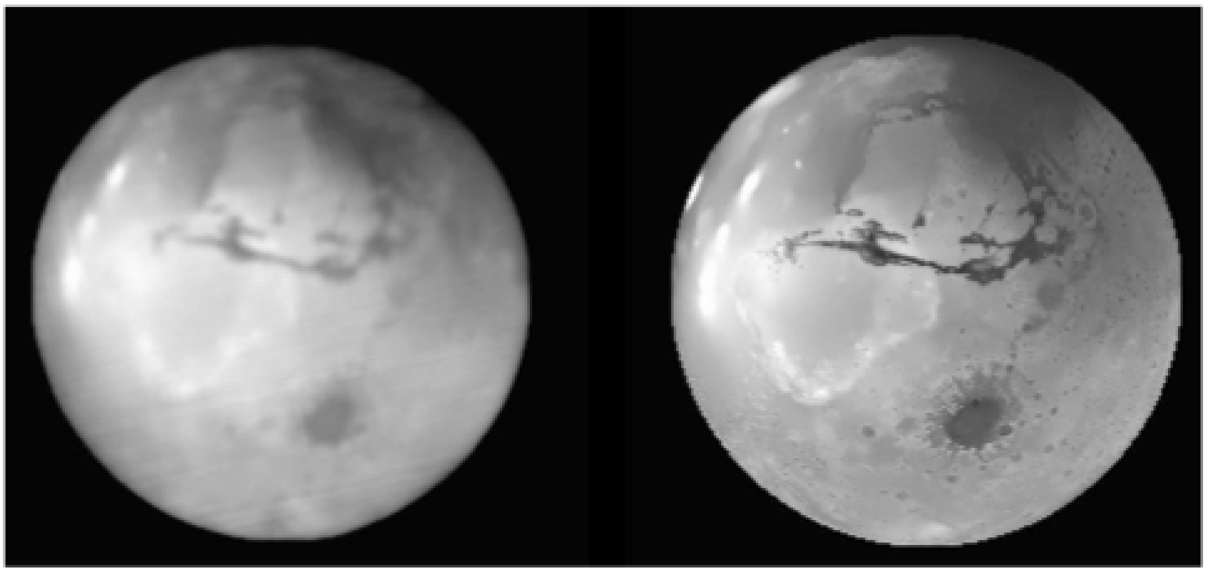

Figure 5 — Left – image of Mars in the 2.0μm CO_2 band, extracted from the UKIRT spectral data cube observed on Sep 4th 2003. Right – Mars Global Surveyor MOLA topography data plotted on an orthographic projection with a similar orientation to that of the UKIRT data. The CO_2 band data shows essentially all of the topographic features visible in the MOLA data, and is quite different from the albedo image (figure 1).

This image shows many topographic features that are absent or poorly seen in the direct albedo images (figure 1). Thus the Valles Marienris canyon system, the Argyre impact basin, the Tharsis highland region, and the three volcanoes Ascraeus Mons, Pavonis Mons and Arsai Mons are all clearly seen. Further examples of such data can be seen in Chamberlain et al. (2006).

While topography is the main signature visible in this data, the CO_2 band depth is effectively a measure of surface atmospheric pressure. The topographic signal is the largest pressure effect, but such data should also show effects due to weather systems on Mars. Pressure measurements by the Viking 1 and 2 landers showed that, in addition to a seasonal variation of pressure (due to condensation and sublimation of the CO_2 polar caps) there are significant pressure variations on timescales of a few days. These variations have been interpreted as baroclinic waves (Barnes 1981, Collins et al. 1996). Variations with amplitudes up to around 50Pa in a total pressure of about 800Pa are seen.

Weather systems of this type should be easily visible in CO_2 band observations of the type presented here. However, a simple CO_2 band depth index as we have used here, is unlikely to be sufficient for retrieval of surface pressure in the general case, since dust content and temperature also have effects on the CO_2 band depth and shape. To better separate such effects we are investigating the use of higher spectral resolution observations that can resolve the individual lines within the CO_2 bands. With a range of line strengths ranging from weak lines, that should be linear in pressure to strong saturated lines that will be most sensitive to dust, it should be easier to distinguish the various effects. This is the motivation behind the recently obtained Gemini GNIRS and IRTF CSHELL observations.

Future Developments:

Current observations of Mars are limited by the effects of seeing in the Earth's atmosphere to spatial resolutions, of at best, about 100km when Mars is nearer opposition, and considerably poorer for the rest of its orbital cycle. In principle much higher resolution should be possible. Many large telescopes are now equipped with adaptive optics (AO) systems enabling diffraction limited resolution in the near IR. The diffraction limited resolution of an 8m ground-based telescope at a wavelength of 2μm is about 16km (Bailey & Crisp 2003) when Mars is at a perihelic opposition. Extremely Large Telescopes of 30m or greater aperture now under development could provide resolutions on Mars down to a few km.

However, currently available astronomical AO systems do not work on planets like Mars as they require a guide star close to the science target. A planet such as Mars is too large to be used a guide star, and too bright to allow a nearby guide star to be used. However, there are a number of ways in which diffraction limited observations of Mars could be achieved. One approach might be to exploit the communications laser system in future Mars orbiter missions using optical communication as an AO reference beacon (Bailey 2004). Another approach would be to use the correlating Shack-Hartmann technique for wavefront sensing allowing the planet itself to be used as an AO reference source, a method successfully used in solar AO systems.

New developments in spectrographs will also add to the capabilities of ground-based observing systems. The CRIRES spectrograph currently under development for the ESO VLT will provide spectral resolving power up to 100,000 in the near-IR. However, even higher resolutions could usefully be applied to Mars. The low temperatures and pressures mean that lines are very narrow and resolving powers up to ~one million could be usefully applied to studies such as the detection of trace gases, and direct measurements of winds by looking at the Doppler shifts of lines such as the O_2 airglow emission. The large echelle spectrographs needed for such observations are feasible instruments for large ground-based telescopes, but would be currently impractical to fit within the constraints of space missions.

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