HIGH SPECTRAL RESOLUTION OBSERVATIONS OF CO_2 AS A PROBE FOR MARS ATMOSPHERIC DYNAMICS.

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Introduction:

Recently, various Mars global circulation models (GCMs) have been developed from observational data acquired by the Mars Global Surveyor (MGS) and Mars Express spacecrafts and are used to predict the structure of the Martian wind field (Forget et al. 1999; Newman et al. 2001). Observations however, especially from the high atmosphere of Mars are rare. Mid-infrared high spectral resolution spectroscopy of CO_2 offers a unique possibility to probe wind speeds in the mesosphere of Mars (Sonnabend 2005). Non-LTE emission from a narrow layer around 60-80 km altitude in the upper atmosphere can be analyzed in combination with absorption in the lower atmosphere allowing direct measurements of zonal wind speeds in those atmospheric regions (Betz et a. 1976; Deming et al. 1983; Mumma et al 1981; Roldan et al. 2000; Kutepov et al. 2003).

The observed non-LTE features are very narrow (<40 MHz) and the line-shifts are in the order of only a few MHz therefore very high spectral resolution observations are required. Heterodyne spectroscopy offers such capabilities with spectral resolution of better than 10^7 at 10 μm. The Cologne Tuneable Heterodyne Infrared Spectrometer (THIS) is currently the highest spectral resolution instrument and perfectly suited to carry out those observations (Sonnabend 2002, Wirtz 2003).

A first test of the proposed method was carried out with THIS during December 2003 at the 1.5 m McMath-Pierce solar telescope on Kitt Peak where we observed the P(30) transition of CO_2 at 9.6 μm. The data yields a wind speed of 74 m/s at 70 km altitude for 15 degrees northern latitude and Ls=330. This result is in good agreement with model predictions of zonal winds in the mesosphere of Mars based on MGS data. Extended observations are scheduled for the period of November 29th to December 9th 2005 again using the McMath telescope.

The Tuneable Heterodyne Infrared Spectrometer (THIS):

Over the past 30 years IR heterodyne spectroscopy has proven to be a powerful tool for astrophysical studies (Kostiuk 1983; Betz et al. 1976; Kostiuk et al. 1996 & 2001). To achieve highest spectral resolution and sensitivity as well as compact instrumentation heterodyne systems are advantageous over direct-detection methods. Many useful information was gathered in the Earth's atmosphere as well as in the atmospheres of other planets of the solar system.

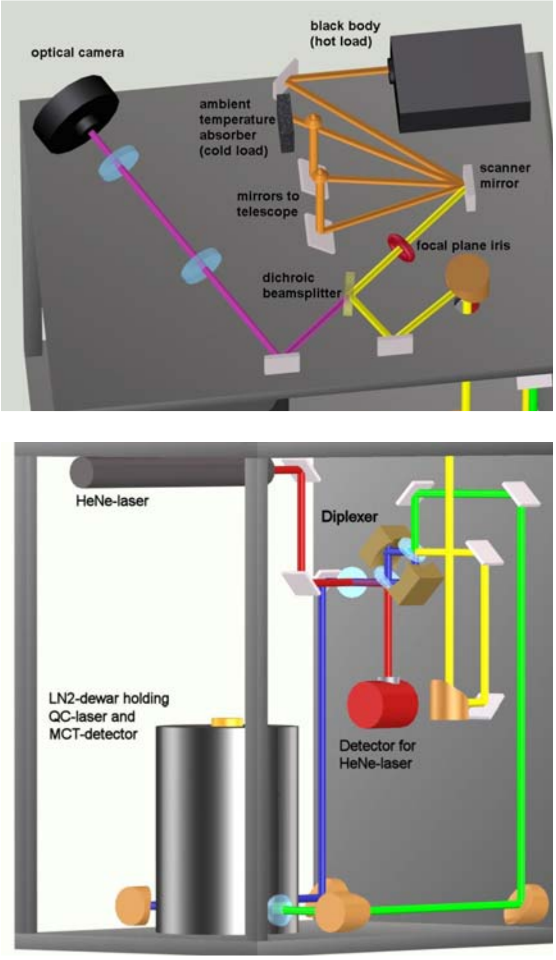

Fig. 1. *Top: Coupling optics for telescope use. A mirror mounted to a scanner motor selects either one of the calibration sources (black body at 400° C, ambient absorber) or one of two positions on the sky.*
Bottom: Model of the receiver showing the beam path. The signal from the telescope enters on top and is combined with the LO laser signal on a Fabry-Perot diplexer. From there it is focused onto the detector.

Since the restriction of gas lasers to fixed laser frequencies, which allows observations only within a small range around the few laser lines, has been overcome by the use of tunable lasers the whole mid-infrared spectral region can be targeted now by heterodyne techniques. The Cologne Tuneable Heterodyne Infrared Spectrometer (THIS) is to this day the only astronomical receiver to incorporate these new techniques.

Heterodyne receivers in every wavelength regime work in a common way: The broadband radiation to be analyzed is superimposed with the radiation of a monomode local oscillator (LO). THIS is at present equipped with quantum-cascade-laser (QCL) LOs emitting around 10.4 and 9.6 μm wavelength. The power provided by these devices ranges up to several tens of mW (Faist et al. 1994; Beck et al 2002). As a mixer we use a fast mercury-cadmium-telluride (MCT) photovoltaic detector which is optimized for a wavelength between 9 and 12 μm (Spears 1977). Through combined detection of LO and broadband signal the mixer generates an IF-signal that is in a first stage amplified by a cooled high-electron-mobility-transistor (HEMT) amplifier. All three devices (laser, mixer and amplifier) are placed in a LN_2 cooled dewar. The frequency analysis is done by an (in-house built) 2048 channel acousto-optical spectrometer (AOS) with a total bandwidth of 1.4 GHz. (An update to a 3 GHz spectrometer is currently under way).

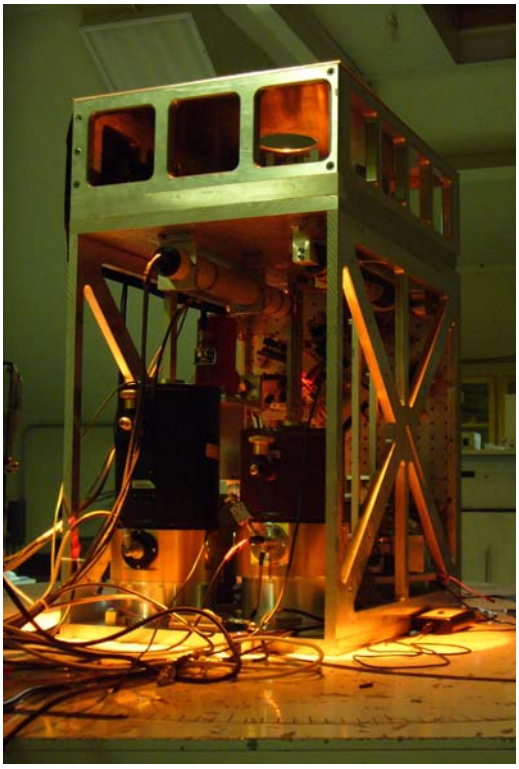

Fig. 2 *THIS at the McMath main observing table at sunset. The size of the aluminum cube is roughly 80 x 60 x 42 cm^3 weighing about 80 kg. The instrument is designed for use on all kinds of telescope including Cassegrain foci.*

The transportable instrument depicted in Fig. 1 and 2 consists of the receiver (containing the LO, mixer/detector matching mirrors and a visual telescope guide system) and two 19"-racks housing the control electronics (including the RF-chain, the AOS-backend, control computer and power supplies).

Performance

The system noise temperature T_{sys} is commonly used to describe the sensitivity of a heterodyne instrument especially in the sub-mm and radio regime. In the lab as well as at the telescope system noise temperatures of 3500 K are typically reached which is less than a factor of three from the quantum limit.

High frequency stability is crucial for a high-resolution instrument. To control the frequency of the QCL we use a three-stage strategy. Coarse tuning of the laser is performed by changing the temperature of the device and monitoring its output frequency. For that purpose a small percentage of the laser power is coupled out by a beamsplitter in front of the diplexer, passed through a reference gas cell and focused to a detector. By modulating the laser current (and therefore its frequency) an absorption spectrum from the gas cell is observed and the desired frequency can be set. The accuracy is better than 20 MHz. Determination of the precise absolute frequency is done by either analyzing a heterodyne reference spectrum or if available a telluric spectrum. Once the laser is set to the desired frequency the modulation is turned off. Now the diplexer is tuned so that a transmission maximum coincides with the output frequency of the laser. The length (and therefore transmission frequency) of the diplexer is actively controlled by a feedback loop which uses an error signal generated by a small modulation of the device's length and analyzing the reflected signal from a frequency stabilized helium-neon laser with a lock-in amplifier. At the same time the modulation of the diplexer causes a minimal intensity modulation of the QCL's signal to the main detector which is also measured by a lock-in amplifier and likewise used in a feedback loop to actively stabilize the laser output frequency. The influence of the modulation to the overall stability is negligible. Tests of the frequency stability of the LO using absorption measurements of methanol and ammonia from a gas cell yielded an accuracy better than 1 MHz per hour. The laser linewidth at the same time was determined by direct heterodyne techniques to be better than the AOS resolution of 1.53 MHz (Sonnabend et al. to be published).

First Observations:

High spectral resolution is necessary to fully resolve molecular features from planetary atmospheres. By analyzing the shape of emission or absorption lines various information on the physical parameters of the gas can be gathered. Non-LTE CO_2 emission from the atmospheres of Mars and Venus is not only an interesting phenomenon by itself but can be used to probe the regions of the atmospheres where the emission occurs.

THIS was used at the 1.5 m McMath-Pierce solar telescope on Kitt Peak/Arizona in November and December 2003. To evaluate the system performance various solar system and extra-solar objects were observed.

Special emphasis was put on the non-LTE CO_2 emission features from the mesosphere of Mars. From the Doppler-width of these features temperatures in the altitude were the emission is formed can be derived. Highest spectral resolution is crucial to reduce the uncertainty in the determination of the width and therefore the calculated temperatures. Also the lines can be used to determine wind speeds down to an accuracy of a few m/s. In the spectral region around 9.6 μm used for the presented observations the high-resolution also allows us to peek through the many telluric lines that contaminate the spectra and prohibit ground based observations with coarse resolution.

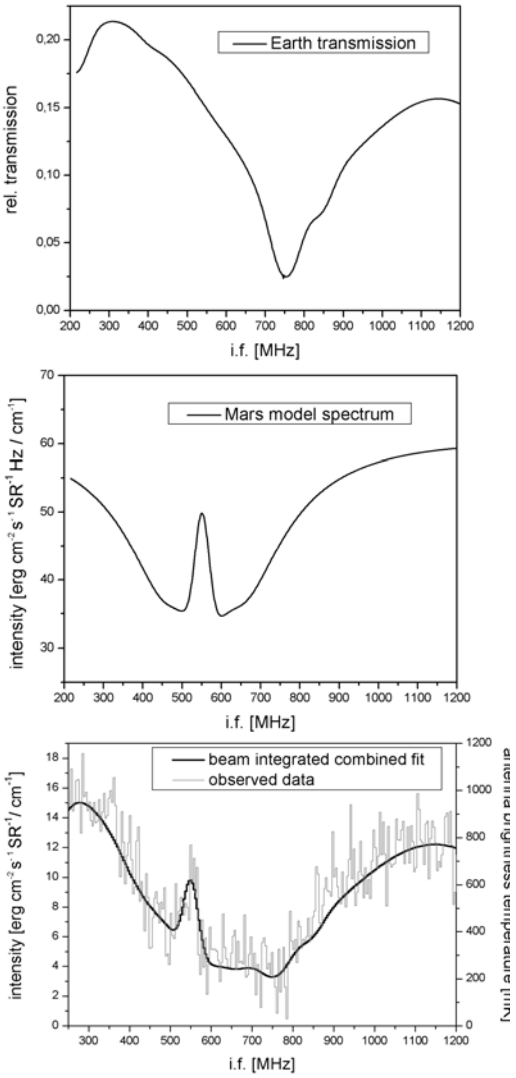

Fig. 3. *top: CO_2 P(30) absorption and emission line at 1037.4 cm^{-1}. The spectra are double sideband, binned to a 4 MHz resolution and highly contaminated by telluric ozone absorption. The combined fit (black line) yields the telluric and Mars spectra shown separated in the center and bottom respectively. The width of the emission peak was determined to be 42 MHz +/- 4.0 MHz (FWHM) suggesting an altitude of 60-80 km as the origin of the line. The offset of the emission peak from the center of the absorption line of 7.5 MHz can be explained by zonal wind in the high atmosphere.*

On the bottom of Fig. 3 the CO_2 P(30) absorption/emission feature at 1037.4341cm^{-1} is shown. The data was acquired on November 30th 2003 by observing the west limb of the Mars disk at ~15 degrees northern latitude with an integration time of 40 minutes. The spectral resolution of the plot is 4 MHz. The beam size on the sky was calculated to be 1.7 arcseconds. The spectrum is highly contaminated by telluric ozone and CO_2 absorption. The Martian line is only visible from the ground due to the Doppler-shift between Mars and Earth which was calculated to be 1440 MHz at the time of observation. In addition, heterodyne spectra have double-sideband contributions complicating the measured spectra. Both effects result in a fairly complex fitting process involving a combination of BEAMINT, a beam-integrated radiative transfer model code for planetary atmospheres developed at NASA Goddard Space Flight and GENLN2, a radiative transfer model for the Earth (Hewagama et al. to be published; Edwards 1992). To model the observed spectrum with BEAMINT we used a standard CO_2 atmosphere for Mars based on Viking data. Mars surface temperatures from the MGS Thermal Emission Spectrometer (TES) were used to calculate the surface continuum radiation (Smith et al. 2001).

The resulting spectra for the telluric transmission as well as the remote atmosphere are shown on top and in the center of Fig. 3 respectively. While the absorption against the surface brightness of Mars reaches all the way down to the ground thus forming a fairly broad (~400 MHz) absorption line the emission feature is very narrow (FWHM 42 MHz +/- 4.0 MHz) and formed at an altitude of 60-80 km. The emission peak is slightly offset from the absorption feature by 7.5 MHz +/- 2.2 MHz. This offset can be explained by assumption of a mesospheric zonal wind in the atmospheric level where the lines are formed. The observed shift corresponds to a line of sight wind component of 72 m/s +/- 21 m/s or a zonal wind of about 74 m/s +/- 22 m/s if no other effects are involved. This value is in good agreement with recent models of the thermal structure of the Martian atmosphere derived from MGS/TES data which predicts zonal winds of more than 60 m/s for the season and location we observed (Fig.4).

We have currently observing time scheduled at the McMath-Pierce telescope for the period of November 29th to December 9th to carry out detailed observations of the Martian wind field. Data will be taken at different latitudes and Mars universal times to allow for comparison with GCMs. First results from these observations will be presented.

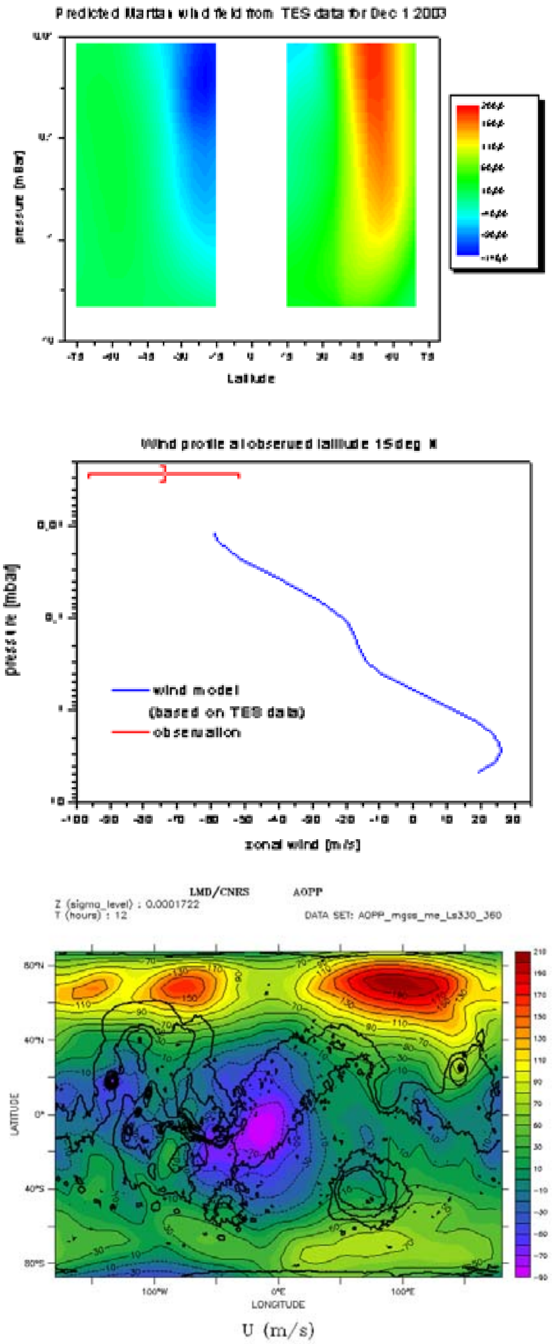

Fig. 4. *top and centre: Comparison of the 2003 meaurement to MGS/TES atmospheric models bottom: model prediction of zonal winds at noon MUT for the 2005 observing period* (http://www-mars.lmd.jussieu.fr/)

Conclusion and outlook:

High resolution heterodyne spectroscopy is a perfect tool to determine wind fields in planetary atmospheres. The first measurement of mesospheric winds in the atmosphere of Mars also proves the capabilities of the new receiver THIS. The first promising results will be followed-up by observations of other seasons of Mars to cover ideally the whole Martian year to verify the predicted variability of the global wind field. Observations will also be extended to Venus in support of the ESA Venus Express mission.

References:

Beck, M., Hofstetter, D., Aellen, T., et al. 2002, Science, 295, 301

Betz, A. L., Johnson, M. A., McLaren, R. A, Sutton E. C. 1976, ApJ, 208, 141

Deming, D., Espenak, F., Jennings, D., et al. 1983, Icarus, 55, 347

Edwards, D. P., “GENLN2: A general line-by-line atmospheric transmittance and radiance model: Version 3. 0 description and user's guide”, Rep. NCAR/ TN-367+ STR, Natl. Cent. for Atmos. Res., Boulder, Colo., 1992

Faist, J., Capasso, F., Sivco, D. L., et al. 1994, Science, 264, 553

Forget, F., Hourdin, F., Fournier et al. 1999, J.Geophys.Res.., 104, 24155-24176

Hewagama, T., Goldstein, J., Livengood, T.A., et al. to be published in J. Quant. Spec. Radiat. Transf.

Kostiuk, T. 1983, Appl. Opt., 22, 2644

Kostiuk, T., Buhl et al. 1996, Icarus, 121, 431

Kostiuk, T., Fast, K. E. , Livengood, T. , et al. 2001, Geophys. Res. Lett., 28, 2361

Kutepov, A. A., Feofilov, A. G. et al. 2003, Astron. Nachr. Suppl., 324, 3

Mumma, M. J., Buhl, D., Chin, G., et al. 1981, Science, 212, 45

Newman, C., Lewis S., Read P, 2001DPS…33.1903N

Roldan, C., Lopez-Valverde, M. A., Lopez-Puertas, M., Edward, D. P. 2000, Icarus, 147, 11

Smith, M. D., Pearl, J. C., Conrath, B. J., Christensen, P. R. 2001 J. Geophys. Res., 106 (E10), 23929

Sonnabend, G., Wirtz, D., Schieder, R. Appl.Opt., 44(33), 7170

Sonnabend, G., Wirtz, D., Vetterle, V., Schieder, R., 2005, A&A 435, 3, 1181

Sonnabend, G., Wirtz, D., Schmuelling, F., Schieder, R. 2002 Appl. Opt., 41(15), 2978

Spears, D. 1977, Infr. Phys. 17, 1, 5

Wirtz, D., Sonnabend, G., Schieder, R. 2003, Proc. SPIE, 5152, 83