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Research Note

High-resolution observations of Martian non-thermal CO_2 emission near 10 μm with a new tuneable heterodyne receiver

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Abstract. We present first observations with the Tuneable Heterodyne Infrared Spectrometer (THIS). This instrument developed at University of Cologne has the potential to cover the mid-infrared from 7 to 19 μm. By using heterodyne techniques and an acousto optical spectrometer (AOS) as a back-end the frequency resolution achieved is better than 10^7 at 10 μm. A tuneable quantum-cascade laser (QCL) is used as a local-oscillator (LO) and the instantaneous bandwidth supplied by the mercury-cadmium-telluride (MCT) detector and the AOS is 1.4 GHz. The system operates within a factor of two of the quantum limit. During December 2003 THIS was installed at the 1.5 m McMath-Pierce solar telescope on Kitt Peak/Arizona. Observations of molecular line features from the atmosphere of Mars were carried out. We present measurements of narrow non-LTE CO_2 emission from the Martian atmosphere observed with a never before achieved frequency resolution of 1 MHz. The first analysis suggests zonal winds in the mesosphere of Mars in good agreement with model predictions.

Key words. techniques: spectroscopic – planets and satellites: individual: Mars – infrared: solar system

1. Introduction

Over the past 30 years IR heterodyne spectroscopy has proven to be a powerful tool for astrophysical studies and much useful information has been gathered from measurements of the Earth's atmosphere as well as the atmospheres of other planets of the solar system (Kostiuk 1983; Betz et al. 1976; Kostiuk et al. 1996, 2001). To achieve high spectral resolution and sensitivity with compact instrumentation heterodyne systems are advantageous over direct-detection methods. Using gas lasers as local-oscillators restricts observations to the small mixer bandwidth range around the few laser lines. Systems incorporating leadsalt diode lasers as LOs had tuneability but lacked sensitivity due to low power of the lasers (Glenar et al. 1982; Sonnabend et al. 2002). The use of tuneable quantum-cascade lasers (QCL) overcomes this limitations and the whole mid-infrared spectral region can now be targeted by heterodyne methods (Faist et al. 1994; Beck et al. 2002). The Cologne Tuneable Heterodyne Infrared Spectrometer (THIS) is currently the only astronomical receiver to incorporate these new techniques. For a detailed description of the system parameters and its components see Wirtz et al. (2003) and Sonnabend et al. (2002).

High spectral resolution is necessary to fully resolve molecular features from the colder regions of planetary atmospheres. By analyzing the shape of emission or absorption lines various information on the physical parameters of the gas can be retrieved. A particularly interesting phenomenon is the non-LTE CO_2 emission from the atmospheres of Mars and Venus (Betz et al. 1976; Deming et al. 1983; Mumma et al. 1981). While first observed in the mid 1970ies the process of its formation is still a subject of theoretical and observational investigation (Roldán et al. 2000; Kutepov et al. 2003). A better understanding of the formation of these emissions is a valuable addition to modeling planetary atmospheres including our Earth's atmosphere and as a probe of altitude regions of the line formation. Though the features are extremely narrow (approximately 40 MHz *FWHM*) and can only be fully resolved by heterodyne techniques the strongest transitions are at least an order of magnitude above the self emission of the gas and thus contribute substantially to the overall broadband CO_2 spectrum. With NASA's Mars Global Surveyor (MGS) and ESA's Mars Express spacecrafts currently observing Martian CO_2 emission with relatively low spectral resolution, modelling non-LTE effects is crucial to understand atmospheric processes and the observed spectra and therefore a subject of high interest. THIS is also planned to be a second generation instrument for the Stratospheric Observatory for Infrared Astronomy (SOFIA).

2. The instrument

2.1. Setup

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 9.2 and 9.6 μm wavelength. The power provided by these devices ranges up to several tens of milliwatts. As a mixer we use a fast mercury-cadmium-telluride (MCT) photovoltaic detector which is optimized for a wavelength between 9 and 12 μm[1] (Spears 1977). Through combined detection of LO and broadband signal the mixer generates an IF-signal which 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.

The transportable instrument 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).

Figure 1 (bottom) shows a to scale model of the receiver. The rigid aluminum frame is $80 \times 60 \times 40\,\mathrm{cm}^3$ in size and weighs roughly 80 kg which allows easy transport and mounting to the focal plane of a Cassegrain telescope. It contains the optical components as shown. Different parts of the optical path are shown in color: The LO-laser beam (blue) exits one port of the LN_2-dewar and is focussed on a confocal Fabry-Perot diplexer. Here it is very efficiently combined with the incoming signal radiation (yellow) (for further description of the diplexer refer to Wirtz et al. (2003) and Sonnabend et al. (2002). The combined signal (green) is focussed on the mixer/detector again inside the LN_2-dewar. For length-stabilization of the Fabry-Perot a frequency stabilized helium-neon laser is used (red). The adaption to different telescope focal lengths is done by a set of suitable off-axis parabolic mirrors. Such mirrors are also used for matching the beam parameters of the LO, the mixer, and the beam-combining confocal Fabry-Perot diplexer.

Following the signal-path (yellow) from the diplexer outward, one reaches the telescope-coupling optics on top of the receiver cube shown in Fig. 1 (top). A flat mirror mounted to a scanner motor is used to select between the signal of hot and ambient calibration loads and two positions on the sky (all in orange). A dichroic mirror splits the incoming signal: while the IR radiation (yellow) is reflected into the cube the visible light (purple) is focussed onto an optical wavelength camera which allows facility-independent guiding.

[1] An ongoing collaboration with Theodor Kostiuk's group at the Planetary Physics Branch of the NASA Goddard Space Flight Center in Greenbelt, Maryland allowes us to use the current device providing a quantum efficiency of about 60%.

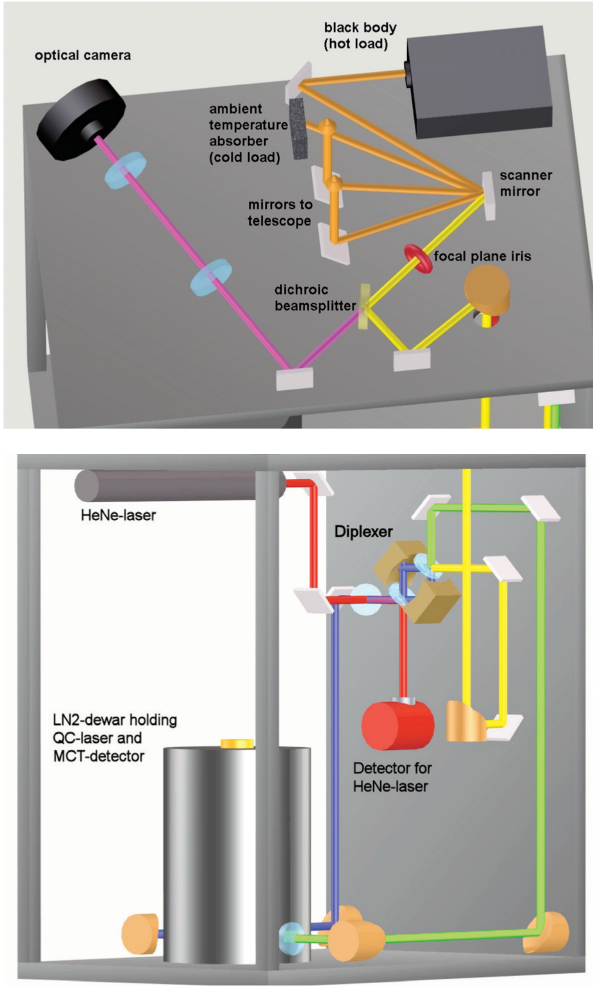

Fig. 1. *Top*: coupling optics for telescope use. A mirror mounted to a scanner motor selects either one of the calibration sources (black body at 400 °C, ambient absorber) or one of two positions on the sky. *Bottom*: to scale model of the receiver. The size of the aluminum cube is roughly $80 \times 60 \times 42$ cm^3 weighing about 80 kg. The different parts of the optical path are marked in colours and described in the text.

2.2. Performance

The system noise temperature T_{sys} is commonly used to describe the sensitivity of a heterodyne instrument. Gaslaser-based instruments have been shown to reach system noise temperatures around 3000 K (which is two times the quantum limit of 1440 K @ 10 μm wavelength. T_{sys} can be converted to a noise-equivalent power using $NEP = k_{\mathrm{B}} T_{\mathrm{sys}} \sqrt{1.3 \cdot \delta_{\mathrm{res}}}$ with k_{B} the Boltzman constant and δ_{res} the resolution bandwidth of the instrument.

In the lab as well as at the telescope system noise temperatures of 3500 K are typically reached with $NEP(\mathrm{THIS}) \approx 7 \times 10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ using $\delta_{\mathrm{res}} = 1$ MHz. A good measure of system stability is the Allan-variance method which describes the time dependent influence of instrumental drift noise contributions to the signal (Schieder & Kramer 2001). Investigation of the system noise using Allan-variance measurements yielded Allan minimum times around 20 s which implies, that one measurement cycle consisting of recording signal from hot- and

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ambient-loads as well as source position on sky and reference position (typically blank sky) has to be finished within 20 s.

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 50 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).

3. Observations

THIS was used at the 1.5 m McMath-Pierce solar telescope on Kitt Peak/Arizona during 10 days in November and December 2003. To evaluate the system performance various solar system and extra-solar objects were observed.

Special emphasis was put on non-LTE CO_2 emission features from the mesosphere of Mars. The Doppler-width of these features can be used to derive temperatures in the altitude were the emission is formed. Having the highest possible 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.

In top of Fig. 2 the CO_2 P(30) absorption/emission feature at 1037.4341 cm^{-1} is shown. The data was acquired on November 30th 2003 by observing the west limb of the Mars disk at ≈20 degrees northern latitude with an integration time of 40 min. The spectral resolution of the plot is 4 MHz. The beam size on the sky was calculated to be 1.7 arcseconds.

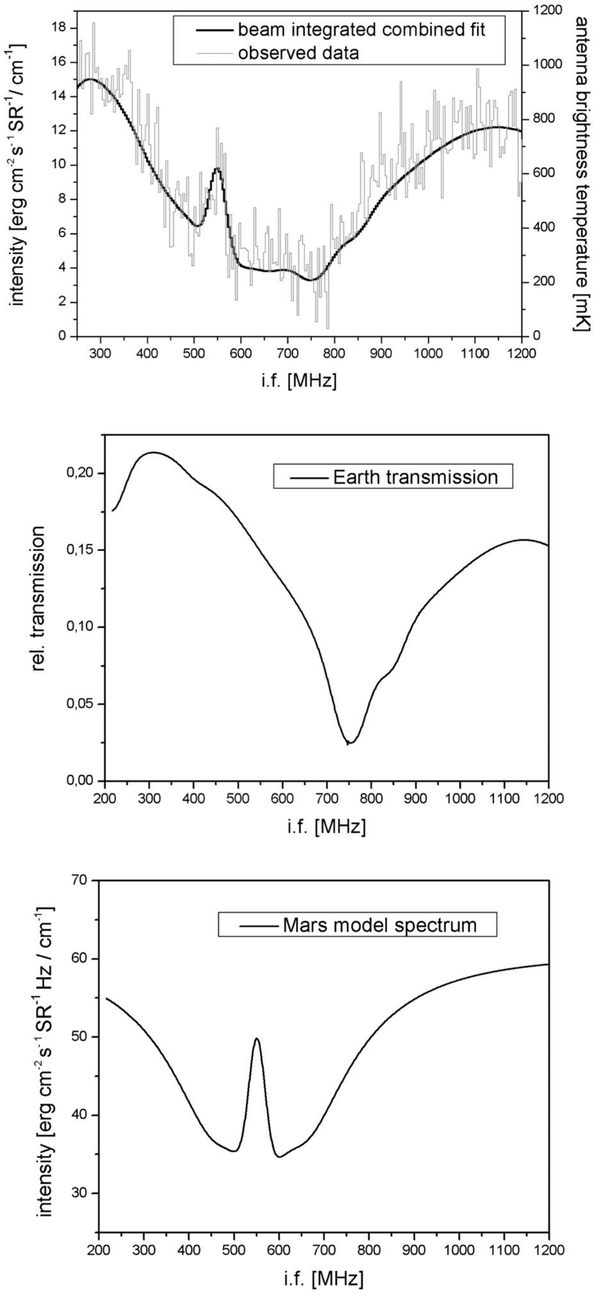

Fig. 2. *Top*: CO_2 P(30) absorption and emission line at 1037.4 cm^{-1}. The spectra are double sideband, binned to a 4 MHz resolution and highly contaminated by telluric ozone absorption. The combined fit (black line) yields the telluric and Mars spectra shown seperated in the center and bottom respectively. 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 is most likely caused by zonal wind in the higher atmosphere.

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. Also heterodyne spectra have double-sideband contributions complicating the measured spectra. Both effects result

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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 Center (Hewagama et al. in preparation) and GENLN2, a radiative transfer model for the Earth (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.

The resulting spectra for the telluric transmission as well as the remote atmosphere are shown in the center and bottom of Fig. 2 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. The reason for that has yet to be determined but one possible explanation is an additional molecular feature not included in the model atmospheres used. However, no responsible feature could be identified. Therefore more likely explanations are vertical wind shear between lower and upper atmosphere or mesospheric zonal winds in the atmospheric level where the lines are formed or a combination of both. In the case of zonal winds the observed shift would correspond 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 (Smith et al. 2001).

4. Conclusion

The capabilities of the new receiver THIS have been successfully demonstrated. With the availability of QCLs operating at wavelength from 7 to 19 μm as local oscillators in heterodyne receivers a whole new spectral region becomes accessible for highest-resolution spectroscopy. Exciting questions can be addressed not only in planetary sciences but also in stellar astrophysics or the chemistry and dynamics of the interstellar medium.

First analysis of the acquired data shows the value of highest spectral resolution for the non-LTE emission features of CO_2 that are not only seen on Mars but also on Venus. The phenomenon of non-LTE emission is not only interesting by itself but non-LTE observations can also be used for various other projects. Of interest are for example simultaneous observations of many transitions from the same molecular band to characterize the rotational temperature of the material from the distribution of line intensities. The lines can also be used to search for spatial variations of line position as a probe for global dynamics and mesospheric winds on both planets (Goldstein et al. 1991). A third important experiment would be to look for global density waves in the atmosphere which are not only of scientific interest but could also effect future space missions to Mars and Venus for they can effect the trajectory of landing probes.

Non-LTE features are expected to exist also in the Earth's atmosphere. Due to the high absorption of low altitude CO_2 those emissions are not detectable by ground based observations but may be observed by a future Earth orbiting spacecraft thus revealing more information on the physical conditions in our home planet's atmosphere.

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