Mid-infrared Observations with the Tuneable Heterodyne Infrared Spectrometer "THIS"

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ABSTRACT:—THIS (Tuneable Heterodyne Infrared Spectrometer) is a mid-infrared heterodyne receiver with sensitivity close to the theoretical quantum limit. A Quantum Cascade Laser (QCL) is used as local oscillator and a HgCdTe photovoltaic detector as mixer. The spectral information is derived from a broadband Acousto-Optical Spectrometer (AOS) with 3 GHz bandwidth and 1 MHz resolution. A dual sideband (DSB) system noise temperature has been found near 2400 K at 10 µm wavelength. The stability of the system has been determined at an Allan variance minimum time of 50 seconds. Very good frequency stability has been found with less than 1 MHz rms error within several hours. The quality of the instrument has been demonstrated during observing campaigns at the McMath-Pierce observatory on Kitt Peak and at the IRTF on Hawaii. Measurements of Winds on Mars and Venus are discussed as an example of the merits of THIS.

I. Introduction And Background

THIS (Tuneable Heterodyne Infrared Spectrometer) is a versatile mid-infrared heterodyne receiver, which opens the field of atomic or molecular line spectroscopy in the infrared at very high frequency resolution. An important feature of the instrument is the implementation of tuneable Quantum Cascade Lasers (QCL)[1]. Accordingly, the signals of many new and important molecules are now accessible at very high frequency resolution, such as CH_4, HCCH, H_2CCH_2, H_3CCH_3, CO_2, or H_2 for example, which are not visible in the far-infrared. The lines of cold interstellar material are mostly rather narrow and can only seen in absorption so that high spectral resolution is required as is available with heterodyne methods. For very cold gas we expect line widths near 1 km/sec, and, in order to resolve such lines sufficiently, one needs at least a velocity resolution of 0.5 km/sec, i.e. a relative resolution of $R = \nu/\Delta\nu = 6{\cdot}10^5$. For the $S_0(0)$ H_2 line at 28 µm the corresponding frequency resolution is about 18 MHz, which matches perfectly well to the capabilities of a heterodyne instrument.

In general, high resolution spectroscopy of cold gas in the infrared is a rather difficult undertaking. Decisive for the detection of weak signals is the rate of available photons. The required minimum observing time for the signal of a thermal source at temperature T is given by :

$$t_{Int} \geq (\kappa_h{\cdot}T_Q)^2 /\Delta\nu \cdot [\exp^{-h\nu/kT} - 1]^2$$

$\Delta\nu$ ist he resolution bandwidth of the receiver, $\kappa_h{\cdot}T_Q$ is the system noise temperature with T_Q=hν/k the quantum limit. For THIS we have κ_h= 1.5 … 2. A source at physical temperate of, say, 117 K delivers 235 photons per second at a frequency resolution $R = 6{\cdot}10^5$ ($\Delta\nu$=50 MHz at a wavelength of 10 µm). On the other hand, the quantum limit T_Q is responsible for an equivalent rate of $5{\cdot}10^7$ photons within the same resolution bandwidth. Thus, one would need 1 hour of on-source integration time to detect such signal with a signal to noise of unity (assuming κ_H = 2). For a 176 K source this time shrinks to 1 second. At 28 µm the corresponding temperatures reduce to about 44 K (1 hour) and 67 K (1 sec). It is obvious that the mid-infrared region is not extremely useful for the detection of the emission of very cold material at very high frequency resolution, but in some cases, there is no other choice like with H_2 or other molecules without permanent dipole moment. Cold material can then be seen only in absorption.

When comparing with direct detection methods, it is clear that their sensitivity can be higher due to the missing influence of the quantum limit, but it is also clear that the sensitivity for the detection of narrow molecular line signals becomes reduced due to the frequency dilution in case the observed lines are smaller than the resolution bandwidth of the spectrometer. At longer wavelength, frequency dilution problems become inevitable. In case of large undersampling of a line signal with width δ_S the signal reduces proportional to $[\delta_S/\Delta\nu]^{1/2}$ so that equ.(3) reduces to

$$t_{Int} \geq (\kappa_d{\cdot}T_Q)^2/\Delta\nu \cdot [\exp^{-h\nu/kT} - 1]^2 \cdot (\Delta\nu/\delta_S)^2$$

Again, κ_d is the ratio of the effective noise temperature of the direct detection system and the quantum limit, and is supposed to be significantly smaller that unity for a good receiver. Typical values are near 0.5 at 10 µm. When comparing one finds that the square of the ratio of instrumental and signal width becomes important, which is disadvantageous for a direct detection system. Therefore, the longer wavelength regime is not very attractive for high frequency resolution with a direct detection receiver.

It is also obvious that the system efficiencies κ_h and κ_d are critical. At longer wavelength, the contribution of background radiation to the noise makes κ_d identical or even larger than κ_h, because the effective throughput of a highly dispersive filter in front of the detector is usually fairly small. This is in contrast to a heterodyne system, which provides excellent coupling to the source. On the other hand, at shorter wavelength, the background contribution becomes negligible, which calls for a direct detection system. The crossover point depends largely on the details of the compared systems. A detailed analysis tells that above 20 µm wavelength heterodyne detection at ground-based observatories is advantageous for signals with a linewidth of the order of 3 km/sec. At shorter wavelength, heterodyne detection is still competitive at signal widths ≤ 0.3 km/sec even at wavelengths near 10 µm.

II. The THIS receiver

Major differences to a standard heterodyne receiver are the local oscillator source (LO) and the mixer itself. In contrast to

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far-IR mixers, mid-IR mixers have no antenna structure. The detector has a relatively large surface area when comparing with the wavelength. A typical HgCdTe mixer has a diameter of about 100 µm and the coupling to the radiation field is completely determined by the amplitude distribution of LO field at the surface of the detector.

In the past, mainly gas-laser sources like CO_2-lasers have been used, which have the disadvantage that one depends fully on the accidental availability of pump laser lines. Quantum Cascade Lasers (QCLs) have now changed the situation drastically. These lasers provide power above 1 mWatt up to several hundred mWatt, which is more than sufficient to pump a HgCdTe-mixer diode into saturation. The required pump power is of the order of 0.5 mWatt, which is, when considering the number of photons involved, more or less equivalent to the pump power of a few µWatt needed for a SIS-mixer in the sub-mm frequency range. Since the QCLs are tuneable in frequency, virtually all infrared frequencies can now be reached. Lasers around 5 µm and between 8 and 13 µm are readily available, and it is foreseeable that lasers between 4 and 20 µm can be procured from various sources soon. Extension to longer wavelengths is still a challenge, because new materials need to be investigated. Nevertheless, most of the above listed molecules and many others as well are now accessible.

Single mode QCLs in the mid-IR are usually manufactured with distributed feed-back structures. This provides reliable single mode operation, but the tuning range near 2 % is rather limited. In order to extend the tuneability of the lasers we have started to use multimode lasers which are forced to single mode oscillations by means of a dispersive external cavity using a grating (see Fig.1).[2] Rotation of the grating provides coarse frequency selection while fine tuning is achieved controlling laser current and external cavity length simultaneously, since both have direct influence on the resulting laser frequency. A typical absorption spectrum observed with our laser system is shown in Fig.2.

A scheme of the optics of THIS is presented in Fig.3. QC-laser and HgCdTe-mixer are operated at liquid Nitrogen temperatures in two separate Dewars. The laser is either a QCL with distributed feedback structure (DFB), which operates automatically in single mode, or a multimode laser with external cavity. The central part of the optics is a travelling wave Fabry-Perot interferometer (FPI), which is operated in a confocal configuration. It serves as a diplexer for LO and signal. For this the laser is coupled in transmission and the signal in reflection. The FPI is made of two elliptical mirrors and two 90% reflectivity beam splitters. The resulting finesse with measured values between 15 and 20 is rather low, but high finesse would not be very helpful anyway. The free spectral range is 2.5 GHz, but, when coupling exactly in plane of the FPI, only every second resonance appears so that in total 5 GHz bandwidth can be used. Our mixer provides a useable IF-band between 0.3 and 3.3 GHz, which fits well into the available bandwidth of the diplexer. The advantage of the confocal FPI is that all transversal modes are degenerate so that all resonance frequencies are nearly independent on the spatial field distribution of the input electromagnetic field. Cavity matching is achieved by imaging the laser beam into the ring cavity, so that location and size of the laser waist are practically identical with position and size of the ring cavity waist.

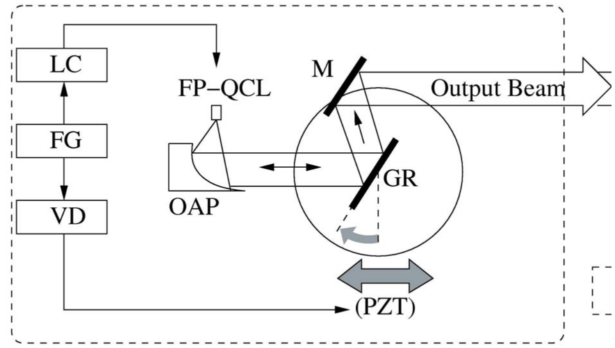

Fig.1 External cavity laser system. The divergent laser beam is collimated by an off-axis parabola (OAP).

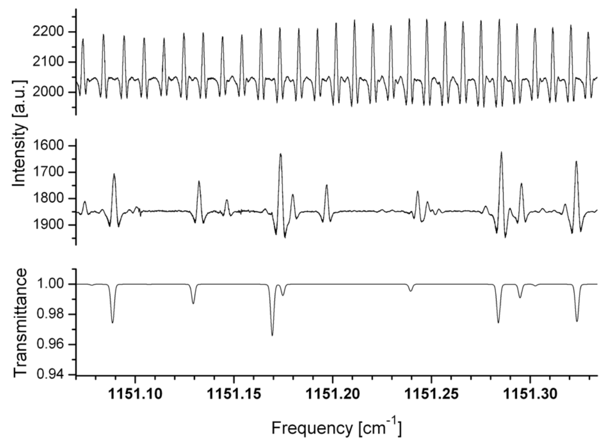

Fig.2 Demonstration of a continuous scan with the. Top scan shows the fringes of Fabry-Perot interferometer (FSR = 300 MHz). The middle scan shows the absorption spectrum of SO_2. At the bottom a HITRAN spectrum is shown for comparison

The FPI diplexer has a couple of advantages in comparison to other coupling schemes:

- The signal response is nearly independent on IF frequency
- The FPI is locked to fringes of a commercial frequency stabilized HeNe laser. In turn, the QCL frequency is now locked to the FPI. Thus, the diplexer serves as a reference for frequency of the QCL as well.
- The laser power transmission is fairly high.
- Feed-back problems with the laser are significantly reduced
- The diplexer suppresses also the signal standing wave, which occurs by reflections between mixer and laser.

It is frequently stated that a good cavity match for a confocal FPI needs fairly fast optics, but this is not really the case! The waist of a confocal FPI with 2.5 GHz free spectral range is about 0.3 mm. The full $1/e^2$ beam divergence of a Gaussian beam is therefore not more than 1.2 degrees, which is a very moderate value

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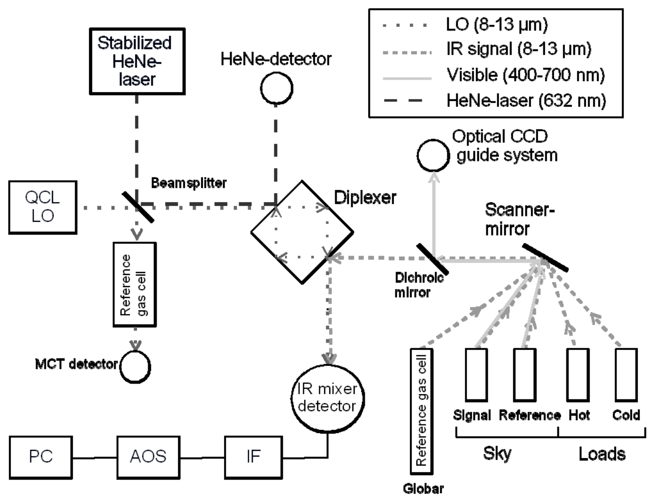

Fig.3: Scheme of the THIS receiver. For details see text.

Behind the mixer detector we use a cryogenic HEMT amplifier. In the following warm IF the signal is further amplified, filtered and converted from the mixer IF-band between 0.3 and 3.3 GHz to the input band of an acousto-optical spectrometer (AOS) at a center frequency of 5 GHz [3]. The AOS has 3 GHz instantaneous bandwidth at a resolution of 1 MHz.

The performance of THIS is very satisfying. We find a minimum of the Alan-variance plot near 50 seconds. The frequency stability of the laser is excellent with an rms below 1 MHz over several hours. The best observed noise temperature at 1034 cm^{-1} ($\lambda = 9.67$ µm) was 2400 K which is only 60% above the theoretical limit. When applying corrections for losses in the optics it seems that we operate extremely close to the limit. The receiver is mounted within an aluminium frame of 60 x 80 x 45 cm^3. The weight is approximately 70 kg. Pointing on sky is controlled by an optical guide camera, which is co-aligned to the infrared beam path by means of a dichroic mirror.

III. Results

THIS has been used during a few test runs at small observatories in Europe, for a couple of observing campaigns at the McMath-Pierce observatory on Kitt Peak/Arizona and at the IRTF observatory on Mauna Kea/Hawaii. Observations with THIS were mainly dedicated to studies of the wind distribution and temperatures in the upper atmospheres of Mars and Venus. The narrow width of the non-LTE emission of CO_2 is an excellent tool for wind and temperature measurements. Two examples are shown in Fig.4 and 5.

The velocity resolution for these studies was about 10 m/sec which corresponds to a frequency uncertainty of the line position of 1 MHz. The linewidth provides information about the kinetic temperature. In Fig.4, a spectrum seen on Mars can be seen, which shows pressure broadened absorption on the P(2) CO_2 line at 959 cm^{-1}. A small absorption feature about 350 MHz below the major line is due to isotopic CO_2. The narrow emission line in the center of the main absorption is due to the non-LTE emission of CO_2 in the upper Mars atmosphere. The observed linewidth is about 40 MHz, which leads to a kinetic temperature near 230 K.

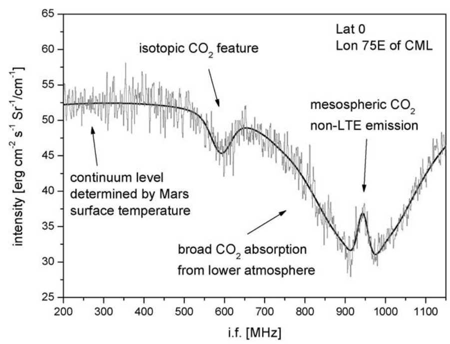

Fig.4: Typical thermal absorption and non-LTE emission spectrum from Mars.

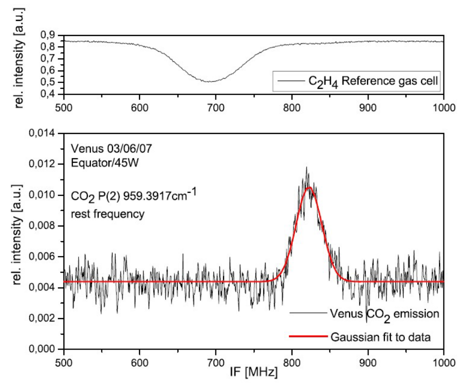

Fig.5: Typical non-LTE emission spectrum from Venus.
Top: spectrum from reference gas cell.

In Mai/June 2007 Venus observations were done to support simultaneous observations of Venus Express. Maps for the wind distribution were determined and compared with model atmospheres. A sample spectrum is shown in Fig.5. Striking is the missing absorption profile in the Venus spectrum, as we see it on Mars. On Mars we observe the thermal emission of the surface, whereas the column density of CO_2 on Venus is too high to see the surface. Obviously, the temperature distribution in the Venus atmosphere is practically constant over a large altitude range, so that no absorption is visible.

IV. References

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