Direct Observations of Cold Molecular Hydrogen with Infrared Heterodyne Spectroscopy

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ABSTRACT

Direct observations of molecular hydrogen (H_2) in the cold interstellar medium (ISM) and in the atmospheres of the giant planets are feasible with the Cologne Tuneable Heterodyne Infrared Spectrometer (THIS). Molecular hydrogen is the most abundant molecule in space and it plays a major role in many elementary astrophysical processes. Infrared heterodyne spectroscopy is the only tool to investigate cold H_2 in the ISM in absoprtion against warm background sources with ultra high spectral resolution. The fully resolved line profiles will give unique insights to the kinematics allowing to deduce the three-dimensional structure of the distribution of molecular hydrogen. In addition, H_2 can be a tool to investigate Jovian oscillations by identifying Doppler shift variations to reveal the inner structure of Jupiter. Fully resolved H_2 emission lines can also be used to determine temperature profiles of the giant planets' atmospheres.

Subject headings: infrared: ISM — techniques: spectroscopic — line: profiles — ISM: abundances, kinematics and dynamics

1. Infrared Heterodyne Spectroscopy - Technology

Only very few instruments exist worldwide that are capable of ultra-high resolution spectroscopy necessary to observe Doppler-shifted molecular lines in the mid-IR. Direct detection techniques cannot achieve the needed combination of high spectral resolution and high sensitivity. To date the highest spectral resolution instrument using direct detection methods only achieves a spectral resolution of $\frac{\nu}{\Delta\nu} \leq 10^5$ (Lacy et al. 2002). IR heterodyne spectroscopy has been proven to be a valuable tool for astronomy since the 1970's with extensive observations done by a group at NASA Goddard Space Flight Center (Mumma et al. 1982; Kostiuk et al. 2001). THIS is the only tuneable system using for the first time recently developed quantum-cascade lasers as local oscillators (Sonnabend et al. 2005) allowing broader

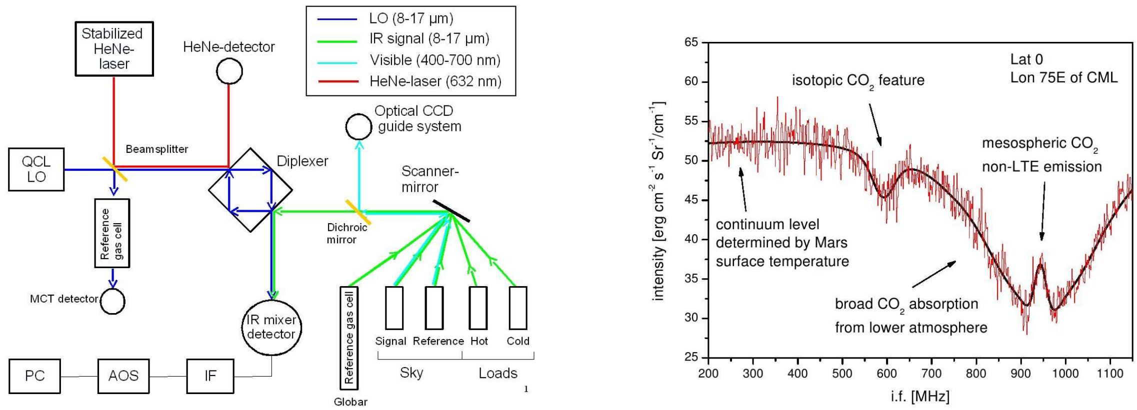

Fig. 1.— left: Schematic of THIS; right: Martian CO_2 features measured with THIS

application and less limitations in the choice of target lines and usable observing periods. Also THIS was the first IR heterodyne instrument to provide a spectral resolution of better than $3{\times}10^7$ at 10 μm.

Depending on the availability of LOs operation is presently possible between 7 and 14 μm. The telescope radiation is superimposed to the LO signal by means of a diplexer and then focused on a fast mercury-cadmium-telluride detector. The detector generates the difference or intermediate frequency (IF) signal at radio frequencies which preserves the spectral information contained in the original IR signal. The IF signal is then analysed by an acousto-optical spectrometer providing a bandwidth of 3 GHz and a spectral resolution of ∼1 MHz. The QCL LO is locked to a transmission maximum of the diplexer.
A frequency stability of ∼ 1MHz of the complete system is provided by locking the diplexer to a stabilized Helium-Neon laser with a specified stability of better than 10^8 in 8 hours. Two calibration loads at known temperatures are integrated into the system for absolute intensity calibration of the observed spectra. An integrated optical guide system provides accurate pointing information and allows active telescope tracking. THIS is flexible and transportable and has been successfully used on various telescopes and observational targets like Earth's atmosphere, the Sun, Mars and Venus (Sonnabend et al. 2002; Sonnabend et al. 2006a; Sonnabend et al. 2006b).

Table 1: *THIS Characteristics (8m-mirror, 1h integration time)*

Wavelength	Bandwidth	Resolution	sensitivity
17 μm	50 km/s	1 km/s	0.3 Jy
17 μm	50 km/s	100 m/s	1 Jy
17 μm	50 km/s	10 m/s	3 Jy

2. Molecular Hydrogen in the ISM

Hydrogen ist the most abundant element in the universe and, next to Helium (and Lithium), one of the primordial elements formed during the big bang. Formation of H_2 in the very early universe started in the recombination era, predominantly with the associative detachment process via H^- ions (Dalgarno et al. 2005). The bulk H_2 formation, however, occured with the collapse of the first cosmological objects, where high densities, needed for the very rare three-body collisions, were reached (Palla et al. 1983; Lepp et al. 2002). In the evolved universe with higher metallicities, it is suggested that H_2 forms on dust grain surfaces, though this process, especially in the diffuse medium is not yet exactly understood (Habart et al. 2005; Habart et al. 2004; Cazaux & Tielens 2002). H_2 is found nearly everywhere in the universe touching most of the important questions in astronomy. H_2 is central to the evolution of the early universe and the formation of galaxies and the interstellar gas. Its chemistry controls the ionisation and thermal balance in the ISM and the mechanisms of star formation. In addition it has a higher efficiency as a coolant compared to the hydrogen atom. As its radiative and collisional properties are reasonably well understood, it is possible to obtain realistic models of the response of H_2 to its environment. Equally important to the discovery of H_2 in different environments is the possible existence of large amounts of undetected H_2. H_2 may go unseen because its standard tracer, CO, is under-abundant (or frozen out) or because the gas is too cold for excitation to occur. Cold H_2 is a candidate for hidden mass or 'dark matter' in the universe, not at a level to change the global cosmological distribution of baryonic matter, dark matter and dark energy, but as contribution to the galactic baryonic dark matter (Combes & Pfenninger 1997; Kalberla et al. 2001 p. 297ff). Because H_2 is a homonuclear diatomic molecule, it does not have an electric dipole moment, which means that only quadrupole transitions are allowed by which the H_2 molecule can radiate. Thus cold H_2 is invisible for radio or sub-mm observations. Hydrogen molecules have been detected in absorption and emission at ultraviolet and infrared wavelenghts, but so far only in emission at lowest pure rotational transitions into the ground states of ortho ($S_0(1)$, 17.035 μm) and para-H_2 ($S_0(0)$, 28.22 μm). While most observations target hot star forming regions or photon dominated regions (PDRs), the main fraction of H_2 is situated in cold gas. It is possible to observe absorptions using the $S_0(1)$ line, although the rotational temperature of J=1 is at $\approx$ 170 K, because the J=1 $\rightarrow$ J=0 transition is highly forbidden. In PDRs for example, the $S_0(1)$ transition is still the brightest H_2 emission line down to 100 K, and only below 30 K nearly all H_2 will exist in the para state (Burton et al. 1992). Consequently, future observations of the $S_0(0)$ absorption with SOFIA (see 5 below) will then probe all of the cold molecular hydrogen. However, already the $S_0(1)$ line alone will return a variety of scientific output on its own and does not need extended preparatory work as all hardware components are already developed and available.

2.1. Star Formation and Protoplanetary Discs

Being the most abundant species in molecular clouds, H_2 is crucial for star formation. Its dissociation enables the final collapse to the stellar core (Larson 1969). Therefore it is also dominant in circumstellar discs and in the formation of planets (1). However, most data on circumstellar discs were aquired observing the dust within the disc as it is more easily done, e.g. with the Spitzer satellite (Meyer et al. 2004). Models often assume temperatures of gas and dust to be equal, but at low densities the gas will thermally decouple from the dust. More detailed information about the gas in discs is required to strengthen the models with respect to disc mass or planetary formation processes. The characteristics of the forming planets, particularly giant planets, are directly tied to the evolution of the gas content in the disk. The presence of planets may lead to the opening-up of a gap that stops further accretion onto the star. Conversely, the energetic processes accompanying star formation in the form of jets and winds have a profound influence on the evolution of the circumstellar disk, and may halt planet formation. Recently, H_2 has been detected in circumstellar discs with TEXES (Bitner et al. 2007) and Spitzer (Quanz et al. 2007), while using VISIR resulted in both, detection (Martin-Zaïdi et al. 2007) and non-detection (Carmona et al. 2007). Heterodyne observations will provide the high spectral resolution necessary for example to address the dependency of the dynamics or the chemical composition on the radial distance to the star.

3. Molecular Hydrogen in Planetary Atmospheres

Molecular hydrogen is the main component of the giant planets (Niemann et al. 1998; Kunde et al. 2004). In the inner core of Jupiter and Saturn, H_2 is highly compressed, forming metallic hydrogen. The inner structure, however, is poorly known. It was suggested by Vorontsov et al (Vorontsov et al. 1976) that Jupiter might oscillate similar to the sun. Oscillations were measured by (Schmider et al. 1991) in the troposphere of Jupiter. Such oscillations are a powerful tool for inferring the internal structure, like the radius of the planetary core or the localisation of the transition level from molecular to metallic hydrogen (Chabrier et al. 1992). Infrared Heterodyne Spectroscopy can provide the high resolution needed for observations of planetary oscillations (Mosser et al. 1992). With its bright $S_0(1)$ line (Mosser et al. 1992), Jupiter will also serve as an ideal testbed for later observations of dimmer targets.

THIS (Sonnabend et al. 2007) was already used successfully to measure planetary atmospheric dynamics on Mars (Sonnabend et al. 2006b) and Venus with ultra high spectral resolution equal to a few m/s (Sornig et al. in preparation). This is exactly the resolution

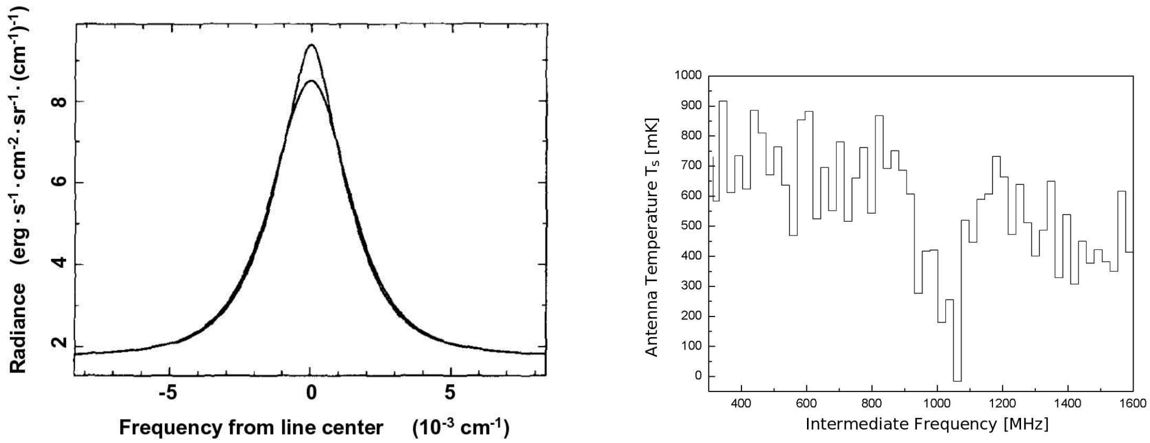

Fig. 2.— left: Expected Jovian $S_0(1)$ line (with and without rotational broadening) from (Mosser et al. 1992); right: Telluric Ozone against α-Ori measured with THIS

needed for the search for jovian oscillations.
Furthermore, high resolution observations of molecular hydrogen will provide detailed temperature profiles of the stratospheres of the outer planets, again also on Jupiter but especially Uranus and Neptune.

4. Preliminary Work - Astronomy

The spectrometer THIS has been used sucessfully on various observation runs in the past. High precision determination of atmospheric dynamics on Mars and Venus were done as well as investigations of molecular features in sunspots and the telluric atmosphere.
A first proof of concept for detecting extrasolar signals with THIS was done in 2003 at the McMath-Pierce Solar Telescope on Kitt Peak/Az, USA (1.5 m mirror). Similar to the planned H_2 observations, an absorption feature was measured against a hot background source, in that case telluric ozone against the continuum radiation of Alpha Orionis (Betelgeuse). The spectrum shown in Fig. 4 is a 20 min observation of an Ozone line at 9.635 μm. From a skydip measurement - solar flux vs. zenith angle - a coupling efficiency between telescope and spectrometer of 55 % and an atmospheric transmission of 18 % was deduced. At 9.6 μm, the brightness temperature difference between sky and Betelgeuse is 2913 K (Bester et al. 1996). Scaled with a beam filling factor of $2.4 \cdot 10^{-3}$ and the coupling efficiency to the telescope, a mean background temperature of 692 mK was expected, in agreement with the measurement. Calculated backwards to the sensitivity of THIS with respect to background sources, we find similar sensitivities than shown in table 1. This

indicates the excellent capabilities of the spectrometer THIS, which are promising to detect absorption of the $S_0(1)$ line for the first time.

5. Goals / Long term perspective

The goal of this project is to perform first time heterodyne observations of pure rotational absorption of cold interstellar molecular hydrogen and to observe jovian planetary oscillations and temperature profiles of Jupiter, Uranus and Neptune using the quadrupole transition at 17.035 μm. Planetary science will be done by investigating the line emission with highest spectral resolution. Observing the interstellar medium (ISM) will be achieved by looking at molecular gas against sources of hot background radiation. Object requirements for background sources are a minimum flux of $\geq$ 10 Jy. This can be a star as well as a star forming region or a bright galaxy. With the ultra-high spectral resolution provided by THIS, the expected linewidth of $\sim$ 1 km/s within the cold interstellar gas can be fully resolved and detailed analysis of the dynamics of the interstellar medium are possible as well as measurements of the abundance of the cold, dense molecular hydrogen.

After observations at 17 μm, the next target will be the $S_0(0)$ line at 28.22 μm. With the ability to measure both ground state transitions of ortho- and para-H_2, it will be possible to precisely determine the ortho/para ratio and to retrieve the temperature information of the interstellar H_2. Due to the low atmospheric transmission, even at excellent sites as Mauna Kea, this is only feasible on board the airborne 'Stratospheric Observatory For Infrared Astronomy' (SOFIA). This modified Boeing 747 SP will be flying at altitudes of 13 km and higher to avoid 99 % of the telluric water vapor to get an unobstructed view of the sky in the mid- and far infrared. THIS is already intended to be a second generation instrument for SOFIA.

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