Planetary and Space Science 126 (2016) 34–48

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

IR heterodyne spectrometer MILAHI for continuous monitoring observatory of Martian and Venusian atmospheres at Mt. Haleakalā, Hawaii

Hiromu Nakagawa [a,*], Shohei Aoki [b], Hideo Sagawa [c], Yasumasa Kasaba [a], Isao Murata [a], Guido Sonnabend [d], Manuela Sornig [e], Shoichi Okano [f], Jeffrey R. Kuhn [f], Joseph M. Ritter [f], Masato Kagitani [a], Takeshi Sakanoi [a], Makoto Taguchi [g], Kosuke Takami [a]

[a] Department of Geophysics, Graduate School of Science, Tohoku University, 6-3 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8578, Japan
[b] Istituto di Astrofisica e Planetologia Spazialia (IASP), Istituto Nazionale di AstroFisica (INAF), Via del Fosso del Cavaliere 100, 00133 Roma, Italy
[c] Faculty of Science, Kyoto Sangyo University, Motoyama, Kamigamo, Kita-ku, Kyoto, 603-8555 Japan
[d] Radiometer Physics GmbH, Birkenmaar Str., 10, 53340 Meckenheim, Germany
[e] German Aerospace Center (Deutsches Zentrum fur Luft –und Raumfahrt), Konigswinterer Str., 522-524, 53227 Bonn, Germany
[f] Institute for Astronomy, University of Hawaii, Advanced Technology Research Center, 34 Ohia Ku St., Pukalani, HI, 96768 USA
[g] Rikkyo University, 3-34-1, Nishi-Ikebukuro, Toshima-ku, Tokyo, 171-8501 Japan

ARTICLE INFO

Article history:
Received 9 December 2015
Received in revised form
7 April 2016
Accepted 7 April 2016
Available online 20 April 2016

Keywords:
Spectroscopy
Infrared
Planetary atmospheres
High spectral resolution
Heterodyne

ABSTRACT

A new Mid-Infrared Laser Heterodyne Instrument (MILAHI) with $>10^6$ resolving power at 7–12 μm was developed for continuous monitoring of planetary atmospheres by using dedicated ground-based telescopes for planetary science at Mt. Haleakalā, Hawaii. Room-temperature-type quantum cascade lasers (QCLs) that cover wavelength ranges of 7.69–7.73, 9.54–9.59, and 10.28–10.33 μm have been newly installed as local oscillators to allow observation of CO_2, CH_4, H_2O_2, H_2O, and HDO. Modeling and predictions by radiative transfer code gave the following scientific capabilities and measurement sensitivities of the MILAHI. (1) Temperature profiles are achieved at altitudes of 65–90 km on Venus, and the ground surface to 30 km on Mars. (2) New wind profiles are provided at altitudes of 75–90 km on Venus, and 5–25 km on Mars. (3) Direct measurements of the mesospheric wind and temperature are obtained from the Doppler-shifted emission line at altitudes of 110 km on Venus and 75 km on Mars. (4) Detections of trace gases and isotopic ratios are performed without any ambiguity of the reproducing the terrestrial atmospheric absorptions in the observed wavelength range. A HDO measurement of twice the *Vienna Standard Mean Ocean Water* (VSMOW) can be obtained by 15-min integration, while H_2O of 75 ppm is provided by 3.62-h integration. The detectability of the 100 ppb-CH_4 on Mars corresponds to an integration time of 32 h.

1. General introduction

Recent successful explorations of planetary atmospheres by numerous spacecraft and ground-based telescopes have revealed their highly variable phenomena with spatial variations at various time scales such as diurnal, seasonal, and following the 11-year solar cycle. The characteristics of such spatial and temporal variations are essential for studying the atmospheric dynamics and photochemistry, and for understanding the meteorology, climatology, and the atmospheric evolution. However, many ground-based telescopes, particularly those with large apertures, are operated on a public time-sharing basis; therefore, they are not practical for conducting dedicated, continuous monitoring observations of planetary atmospheres. Spacecraft missions can be used for such observation; however, their spatial coverage is often strongly limited by the instantaneous field-of-view (FOV) of the instrument and the orbit of the spacecraft. Moreover, the monitoring capability is still limited to the mission lifetime. Complementary ground-based observations can probe regions that are not accessible remotely by spacecraft and can obtain global maps

* Corresponding author.
E-mail addresses: rom@pat.gp.tohoku.ac.jp (H. Nakagawa), shohei.aoki@iaps.inaf.it (S. Aoki), sagawa@cc.kyoto-su.ac.jp (H. Sagawa), kasaba@pat.gp.tohoku.ac.jp (Y. Kasaba), murata@pat.gp.tohoku.ac.jp (I. Murata), sonnabend@radiometer-physics.de (G. Sonnabend), sornig@ph1.uni-koeln.de (M. Sornig), okano@pparc.gp.tohoku.ac.jp (S. Okano), kuhn@IfA.Hawaii.Edu (J.R. Kuhn), ritter@IfA.Hawaii.Edu (J.M. Ritter), kagi@pparc.gp.tohoku.ac.jp (M. Kagitani), tsakanoi@pparc.gp.tohoku.ac.jp (T. Sakanoi), taguchi@rikkyo.ac.jp (M. Taguchi), takami@pat.gp.tohoku.ac.jp (K. Takami).

http://dx.doi.org/10.1016/j.pss.2016.04.002
0032-0633/

across the planetary disk. Continuous observation by a dedicated telescope for planetary science will be helpful for understanding the variable nature and spatial variations of planetary atmospheres.

We relocated our Tohoku 60 cm telescope (T60) from Fukushima, Japan, to the summit of Mt. Haleakalā, Hawaii, in September 2014. This telescope is designed to achieve continuous observations of planetary atmospheres through remote operation. In addition, we are currently conducting the Polarized Light from Atmospheres of Nearby Extra-Terrestrial System (PLANETS) project, in which a new 1.8 m telescope will be installed at the summit of Mt. Haleakalā for planetary science, including analysis of exoplanets, under an international consortium (http://kopiko.ifa.hawaii.edu/planets/index.html), see Sakanoi et al. (2014). The Mid-Infrared Laser Heterodyne Instrument (MILAHI) has been developed as a facility instrument for these planetary science-dedicated telescopes at the summit of Mt. Haleakalā, which is well suited for infrared (IR) spectroscopy at an altitude of 3055 m owing to low humidity and low atmospheric absorptions.

A number of rotational and vibrational transitions of atmospheric molecules in the mid-IR wavelength enable observation of many of the most important species and their isotopes in planetary atmospheres. IR heterodyne spectroscopy provides the highest spectral resolution at 7–12 μm with resolving power $R=\lambda/\Delta\lambda>10^6$ and sensitivity close to the quantum limit. These features enable us to fully resolve the line shape of molecular transitions, which provides unique information of the atmosphere: (i) It allows to obtain vertical profiles of dynamics and thermal structure retrieved from single molecular line. (ii) It permits the study of local winds and temperature in the planetary upper atmosphere by using direct measurements of non-local thermodynamic equilibrium (LTE) emission. (iii) High-resolution spectroscopy is suitable for directly observing minor constituents in the planetary atmospheres without any ambiguity for reproducing the terrestrial atmospheric features. Notable successes on Venus, Mars, Jupiter, Titan, and Earth have been accomplished by *National Aeronautics and Space Administration* (NASA) Goddard Space Flight Center (GSFC; Kostuik and Mumma, 1983; Livengood et al., 1993; Kostuik, 1994; Kostuik et al., 1996; Fast et al., 2002), the University of Cologne (Sonnabend et al., 2010; Sornig et al., 2013), and Tohoku University (Okano et al., 1989; Fukunishi et al., 1990; Taguchi et al., 1990).

The present study proposes continuous observation of the atmospheric dynamics, thermal structure, and compositions on Mars and Venus and investigation of the nature of atmospheric activity on various time scales. In Section 2, we describe the IR heterodyne spectrometer technique and instrumentation. Next, we discuss the scientific objectives on Mars and Venus, which are focused on the benefit of high-resolution spectroscopy in Section 3. In Section 4, we address the scientific capabilities and measurement sensitivities by using modeling and predictions from the radiative transfer code. Finally, we summarize our conclusions in Section 5.

2. Instrument

2.1. Principle

The IR heterodyne detection is analogous to a spectroscopy technique in the radio frequency range. An IR source from the planet is combined with a laser local oscillator (LO) and is focused onto a mercury cadmium telluride (MCT) photodiode mixer. The resultant intermediate frequency (IF) in the radio region preserves the intensity and spectral information of the IR spectrum. Heterodyne detection is a coherent technique, and the detected electric field is the sum of the electric fields of the source and LO, $E(t)$:

$$E(t)=E_S\exp(i\omega_S t)+E_{LO}\exp(i\omega_{LO}t), \tag{1}$$

where radiation from the source (frequency ω_S, electric field $E_S\exp(i\omega_S t)$), and the output of an LO (frequency ω_{LO}, electric field $E_{LO}\exp(i\omega_{LO}t)$). The nonlinear response of the photodiode mixer is

$$R(t)\propto EE^*=E_S^2+E_{LO}^2+2|E_SE_{LO}|\cos[(\omega_S-\omega_{LO})t], \tag{2}$$

where $\omega_s-\omega_{LO}$ is a cross-product term generated at IF.

Table 1
Instrumental specifications.

Size	W600 × D1200 × H450 mm for optics
Weight	80 kg
Wavelength	7–12 μm
Operating spectral range	7.71–7.73 μm (1293–1297 cm^{-1}) 9.54–9.59 μm (1043–1048 cm^{-1}) 10.28–10.33 μm (968–973 cm^{-1})
Detector	Mercury–Cadmium–Telluride photo diode
Detector elements	0.1 mm diameter
Detector bandwidth	3000 MHz (~0.10 cm^{-1}) (3 dB cut off)
Backend spectrometer	Digital Fast Fourier Transform spectrometer
Backend bandpass	1000 MHz (~0.03 cm^{-1})
Backend resolution	61 kHz (1.8 × 10^{-6} cm^{-1}) or 16,384 channels
Noise level	System noise temperature 3000 K
Resolving power	more than 1.5 × 10^6
Diffraction-limited FOV	4.32″ with 60 cm-telescope (10.3 μm) 1.44″ with 1.8 m-telescope (10.3 μm)
Focal plane operation	Coude or Nasmyth mounted

2.2. Specifications

The instrumental specifications of MILAHI are summarized in Table 1, and its optical configuration is shown in Figs. 1 and 2. MILAHI is currently composed of three LOs that cover the wavelength ranges of 7.71–7.73 μm (1293–1297 cm^{-1}), 9.54–9.59 μm (1043–1048 cm^{-1}), and 10.28–10.33 μm (968–973 cm^{-1}) and of one backend spectrometer. Previous systems have used large-sized CO_2 lasers, which allow observations in only a small portion of 9–12 μm. In contrast, recent applications of the quantum cascade laser (QCL) to the IR laser heterodyne have opened new spectral regions to exploration in 7–13 μm (Sonnabend et al., 2005; Stupar et al., 2008; Stangier et al., 2013). Because the current LOs in the system are easily exchangeable, observable molecules can be extended by handling with additional LOs. In our system, a newly designed room-temperature-type QCL manufactured by Hamamatsu Photonics is adopted for use as a LO. Temperature sweeping between −30 °C and 30 °C strongly increases the total tuning range, which is five times larger than the liquid nitrogen type QCL at 5 cm^{-1} for each wavelength region. Fig. 3 shows an example of the emission spectra of LO obtained using Fourier Transfer Spectrometer (FTS) with 0.0035 cm^{-1} resolution without any apodization. Due to the discontinuity of the interferogram-edge, the oscillation occurred around the peak line, which caused negative excursions and brunch of low-level features. The typical output power of LO is of 30–100 mW. We also applied a compact CO_2 gas laser manufactured by Access Laser Co. as a LO in MILAHI for complementary use in 10 μm. The CO_2 gas laser covers wavelength ranges of 9.20–9.34 μm (1071–1087 cm^{-1}), 9.45–9.69 μm (1032–1058 cm^{-1}), 10.15–10.34 μm (967–985 cm^{-1}), and 10.47–10.71 μm (934–955 cm^{-1}).

The optical beam from the celestial signal is combined with the LO on the ZnSe beam splitter and is fed into the MCT photodiode mixer, manufactured by Raytheon vision systems. We used four detector elements on a chip in the form of a 2 × 2 matrix. Each individual detector is circular with a diameter of 0.1 mm and 0.1 mm edge-to-edge spacing between each element. Each