Astrophysics (Planetary atmospheres)

High-resolution imaging spectroscopy of planetary atmospheres

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A B S T R A C T

Imaging spectroscopy at high resolution, in the infrared range, is a powerful tool for monitoring the behavior of minor species in planetary atmospheres and their evolution with latitude and longitude, season or local hour. Using the TEXES imaging spectrometer at the Infrared Telescope Facility (IRTF), this method has been applied for detecting and monitoring hydrogen peroxide and water vapor (using its proxy HDO) on Mars, then for monitoring sulfur dioxide and water (again using HDO) above the H_2SO_4 cloud deck ($z = 65$ km on Venus). Observations of Mars have shown that its atmosphere and climate are well reproduced by the Global Climatic Models. In contrast, strong spatio-temporal variations of SO_2, observed above the Venus clouds, are not understood by the models. As a support of the forthcoming *Juno* space mission, a similar program has started on Jupiter to monitor its dynamics through 3-D maps of ammonia and phosphine.

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1. Introduction

Over several decades, the atmospheres of planets (Venus, Mars, Jupiter and Saturn) have been monitored by numerous spacecraft (orbiters, landers and rovers in the case of Mars). Over the years, these missions have provided us with impressive datasets regarding the planetary atmospheric composition, thermal and cloud structure, and seasonal evolution. Still, ground-based imaging spectroscopy can provide important supplementary information. Indeed, ground-based instruments, being more sophisticated than space-borne instruments, can achieve a higher resolving power, essential for probing the tenuous molecular lines of the Martian atmosphere or the stratospheric emissions in the giant planets' atmospheres. In addition, the development of high-resolution imaging spectrometers now allows us to record instantaneous maps of minor species over the planetary disks, which

gives a unique opportunity for studying daily variations or transient phenomena.

Over the past ten years, we have been using the Texas Echelon Cross Échelle Spectrograph (TEXES), mounted at the 3-m Infrared Telescope Facility (IRTF) at Mauna Kea Observatory, to monitor the atmosphere of Mars and, more recently Venus and Jupiter. In the case of Mars, our first objective was to search for hydrogen peroxide H_2O_2, a key molecule possibly responsible for the lack of organics at the Martian surface. After its detection in 2003, we have monitored its abundance (as well as HDO, simultaneously recorded as a proxy for water vapor) until 2014 as a function of latitude and season, and we have used these results to constrain global climatic photochemical models. Starting in 2012, we have used the same facility to monitor the behavior of sulfur dioxide and water vapor at the H_2SO_4 cloud-top ($z = 65$ km) and within the clouds (z about 60 km). In addition, in November 2011, we have used the Atacama Large Millimeter Array (ALMA) to obtain maps of SO, SO_2, HDO and CO in the submillimeter range. These data probe the upper mesosphere of Venus, at an altitude

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of about 90 km. Finally, since February 2014, we have started a program on Jupiter to monitor two key tracers of its tropospheric dynamics, ammonia and phosphine, at different atmospheric levels, with pressures ranging from 0.1 bar to a few bars. This program will continue over the coming years as a support to the forthcoming *Juno* space mission, launched in August 2011 for an encounter of Jupiter in July 2016.

In this paper, we first present our results on the Martian atmosphere (Section 2), then on the Venus mesosphere using both ALMA (Section 3.1) and TEXES (Section 3.2). In Section 4, we briefly describe the Jupiter program and we discuss the perspectives of this work.

2. The atmosphere of Mars

Since the Mariner 9 and Viking era in the 1970s, the atmosphere of Mars has been repeatedly monitored by orbiters, landers and rovers. We now have a very good knowledge of the seasonal atmospheric evolution (chemical composition, thermal and cloud structure, dynamics, photochemistry). Global climatic models have been developed, especially at the Laboratoire de météorologie dynamique (LMD, Paris; Forget et al., 1999); they generally provide very good data fitting, at least below an altitude of about 50 km.

After the negative results of Viking regarding the presence of organics at the surface of Mars, the question was raised about the nature of the agent responsible for the oxidation of the surface. Hydrogen peroxide was suggested (Atreya and Gu, 1995; Clancy and Nair, 1996), although the amounts predicted by photochemical models appeared by far insufficient to destroy all organics (in particular those of meteoritical origin). Hydrogen peroxide was unsuccessfully searched for (Encrenaz et al., 2002; Krasnopolsky et al., 1997) until it was discovered through two ground-based experiments in 2003, first in the submillimeter range (Clancy et al., 2004), then by imaging spectroscopy (Encrenaz et al., 2004). The latter dataset is described below.

TEXES (Texas Echelon Cross-Échelle Spectrograph) is a high-resolution imaging spectrometer (Lacy et al., 2002), operating between 5 and 25 μm, that combines both very high spectral resolution (R = 80,000 at 8 μm in the high-resolution mode) and good spatial resolution (about 1 arcsec). At 8 μm, the 1.1 × 8 arcsec slit of the instrument, aligned along the north–south celestial axis, is moved from west to east with 0.5 arcsec steps. The size of Mars typically ranges between 6 and 15 arcsec. Two scans (north and south) are usually necessary to map the whole planet, which takes about 15 min. We choose an interval of about 7 cm^{-1} of bandwidth, centered at 1240 cm^{-1}, which contains several transitions of the strong ν_6 H_2O_2 band. In June 2003, the areocentric longitude was 206° (southern spring), corresponding to a high H_2O_2 content according to photochemical models. All H_2O_2 transitions were detected, together with CO_2 transitions (both strong and weak) and a couple of HDO transitions.

In order to map the H_2O_2 mixing ratio on the Martian disk, we selected a H_2O_2 doublet which brackets a weak CO_2 line at 1241.6 cm^{-1}, and we simply compute the ratio

of the line depths of the H_2O_2 transitions versus the CO_2 transitions. Radiative transfer calculations show that this line depth ratio is a very good indicator of the H_2O_2/CO_2 mixing ratio as it eliminates, to first-order, effects due to geometry and thermal structure. Fig. 1 shows the spectrum of the H_2O_2 doublet observed in June 2003 (Ls = 206°) at the time of the first detection, and the first H_2O_2 map recorded for this season.

Since 2003, we have been observing H_2O_2 in November 2005, June 2008, October 2009 March 2014, and July 2014, to monitor its behavior as a function of time and season (Encrenaz et al., 2005, 2008, 2012a,b). As an example, Fig. 2 shows the H_2O_2 map retrieved with this method in March 2014 (Ls = 96°), compared with the H_2O_2 map calculated using the LMD-GCM (Forget et al., 1999), including a photochemical model developed at LATMOS (Lefèvre et al., 2008). It can be seen that the H_2O_2 distribution over the disk is far from being uniform, and globally well fitted by the model. The disk-integrated H_2O_2 mixing ratio typically ranges between a few ppb and about 30 ppb. The conclusion of these observations is that the H_2O_2 behavior is well reproduced by the models. In particular, Fig. 3 shows the evolution of the H_2O_2 content as a function of Ls, compared with various photochemical models. It can be seen that the observations favor the LMD-IPSL model including heterogeneous chemistry on water ice grains (Encrenaz et al., 2012a,b, 2015a; Lefèvre et al., 2008). The same behavior is observed for the seasonal distribution of ozone on Mars, as well as in the terrestrial atmosphere, where the loss of polar ozone in the Earth's stratosphere has been explained by interactions between gaseous chemical species and ice cloud particles (Lefèvre et al., 2008).

Using weak HDO transitions in the 1237–1244 cm^{-1} range, we have simultaneously retrieved maps of water vapor, using HDO as a tracer of H_2O. We made the assumption that D/H was constant over the Martian disk, with a value of 5.0 times the terrestrial value (Krasnopolsky et al., 1997). This is actually a first-order approximation, as theoretical calculations predict variations associated, in particular, with condensation (Montmessin et al., 2005). We assume a constant D/H value in the lack of precise measurements. The water vapor seasonal cycle is generally well understood on Mars since the Viking measurements and, more recently, the TES monitoring aboard the MGS orbiter (Smith, 2002, 2004), and maps of the water vapor content versus latitude and areocentric longitude are well represented by GCMs. However, no information has been acquired so far on two-dimensional maps of water vapor that would give, for any season, the H_2O distribution versus latitude and longitude, or versus latitude and local hour. This information requires imaging spectroscopic capabilities from some distance, as from the ground or Earth orbit, and has been obtained in the thermal regime for the first time with TEXES. In general, the agreement between the TEXES maps of HDO and H_2O maps predicted by the GCM is satisfactory. An example is shown in Fig. 4 for Ls = 80°, just before the northern summer solstice, when water vapor is expected to be maximum. There is a very good agreement between the data and the model (Encrenaz et al., 2010).