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Mesospheric CO_2 ice clouds on Mars observed by Planetary Fourier Spectrometer onboard Mars Express

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ABSTRACT

We have investigated mesospheric CO_2 ice clouds on Mars through analysis of near-infrared spectra acquired by Planetary Fourier Spectrometer (PFS) onboard the Mars Express (MEx) from MY 27 to MY 32. With the highest spectral resolution achieved thus far in the relevant spectral range among remote-sensing experiments orbiting Mars, PFS enables precise identification of the scattering peak of CO_2 ice at the bottom of the 4.3 μm CO_2 band. A total of 111 occurrences of CO_2 ice cloud features have been detected over the period investigated. Data from the OMEGA imaging spectrometer onboard MEx confirm all of PFS detections from times when OMEGA operated simultaneously with PFS. The spatial and seasonal distributions of the CO_2 ice clouds detected by PFS are consistent with previous observations by other instruments. We find CO_2 ice clouds between $Ls = 0°$ and 140° in distinct longitudinal corridors around the equatorial region (± 20°N). Moreover, CO_2 ice clouds were preferentially detected at the observational LT range between 15–16 h in MY 29. However, observational biases prevent from distinguishing local time dependency from inter-annual variation. PFS also enables us to investigate the shape of mesospheric CO_2 ice cloud spectral features in detail. In all cases, peaks were found between 4.240 and 4.265 μm. Relatively small secondary peaks were occasionally observed around 4.28 μm (8 occurrences). These spectral features cannot be reproduced using our radiative transfer model, which may be because the available CO_2 ice refractive indices are inappropriate for the mesospheric temperatures of Mars, or because of the assumption in our model that the CO_2 ice crystals are spherical and composed by pure CO_2 ice.

1. Introduction

One of the peculiar phenomena of the Martian climate is the existence of carbon dioxide (CO_2) ice clouds. These clouds are formed by condensation of the major constituent of the Martian atmosphere, CO_2. Recent observations have revealed the presence of the CO_2 ice clouds at remarkably high altitudes (above 40 km; mesosphere). The existence of mesospheric CO_2 ice clouds on Mars was first suggested by the infrared spectra recorded by Mariner 6 and 7 (Herr and Pimentel, 1970) although the low altitude of the detection (25 km) argues in favor of CO_2 fluorescence (e.g. Lellouch et al., 2000). Clancy and Sandor et al. (1998) discussed the mesospheric CO_2 ice clouds formation based on vertical temperature profiles measured by Pathfinder during its descent (Schofield et al., 1997) and those by the James Clerk Maxwell Telescope. Subsequently, Montmessin et al. (2006) detected several mesospheric detached layers at an altitude of around 100 km at [32°S, −178°E, $Ls = 134°$], [36°S, 134°E, $Ls = 135°$], [15°S, 15°E, $Ls = 137°$], and [15°S, −83°E, $Ls = 137°$] from the nighttime measurements by SPectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM) ultraviolet (UV) channel onboard Mars Express (MEx). These detached layers were attributed to the presence of CO_2 ice crystals because of the simultaneous detection of a supersaturated cold pocket just above the aerosol layer.

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A global view of these mesospheric CO_2 ice clouds has been provided by Observatoire pour la Minéralogie l' Eau les Glaces et l' Activité (OMEGA) onboard MEx and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) onboard Mars Reconnaissance Orbiter (MRO) daytime observations (Montmessin et al., 2007; Määttänen et al., 2010; Vincendon et al., 2011). From the OMEGA data, mesospheric CO_2 ice clouds were identified through a more straightforward approach. A distinct peak was detected at the bottom of the 4.3-μm CO_2 gas band, caused by scattering of CO_2 ice cloud crystals in the mesosphere (Montmessin et al., 2007). The fundamental ν_3 band of CO_2 ice is possibly the strongest known infrared band for a molecule (Warren, 1986), and the combination of the dramatic increase of the imaginary part of the CO_2 ice index and large fluctuation of the real part produces a sharp peak around 4.26 μm. From the OMEGA data analysis, a total of 60 occurrences were identified during the period from MY 27 to 29 (Määttänen et al., 2010) and 13 occurrences in MY 30 (Vincendon et al., 2011). Additionally, CRISM daytime measurements detected the mesospheric CO_2 ice clouds via indirect spectral identification. Although CRISM is a similar instrument to OMEGA, it does not observe the distinctive scattering peak at the bottom of the 4.3 μm CO_2 band because of its limited spectral range (0.362–3.92 μm). Instead, cloud features were identified from the CRISM RGB composite images (based on wavelengths of 0.592, 0.533, and 0.492 μm), and CO_2 ice clouds were distinguished from H_2O ice based on the CRISM IR spectra. From the CRISM observations during the period from MY 29 to MY 30, 54 occurrences in total were found (Vincendon et al., 2011). These detections by OMEGA and CRISM are mainly within a distinct longitudinal corridor (−120°E to +30°E) around the equatorial region (20°S to 20°N) during the aphelion season ($Ls = 330$–150°), with the exception of two detections by OMEGA at mid-latitudes at [49.1°S, −138.3°E, $Ls = 54.2$°] and [46.6°N, −74.7°E, $Ls = 246.3$°], one detection by CRISM around 155°E, and one by OMEGA around 120°E.

The formation mechanism of the mesospheric CO_2 ice clouds has been discussed based on the observed spatial and seasonal distributions. Clancy and Sandor (1998) first suggested a scenario whereby the clouds form in supersaturated pockets of air created by the interference of thermal tides and gravity waves. This scenario has been demonstrated by theoretical studies. González-Galindo et al. (2011) showed using a Mars Global Circulation Model that the observed mesospheric CO_2 ice clouds can be found in places where temperature minima are reached in the atmosphere due to the propagation of thermal tides. This study showed that observations were significantly correlated with the seasonal and spatial distributions of these minima caused by the propagation of the large-scale waves, even though the temperature remained just above the condensation threshold. Subsequently, Spiga et al. (2012) showed using a mesoscale model that the locations where clouds are observed are places where gravity waves are not filtered by Martian atmospheric dynamics and can propagate upward into the mesosphere. This study supported the inference that smaller-scale waves allow the creation of supersaturated pockets in the temperature minima created by the thermal tides. Finally, Listowski et al. (2014) demonstrated that temperature profiles that combine the effects of thermal tides and gravity waves in a one-dimensional microphysical bin model enable simulation of mesospheric CO_2 ice clouds that are consistent with observations.

The crystal size of the mesospheric CO_2 ice clouds was constrained by the spectroscopic observations. SPICAM-UV nighttime observations suggested that the effective radii of the CO_2 cloud crystals detected around 100 km are between 0.08 and 0.13 μm (Montmessin et al., 2006). In contrast, larger crystal sizes were estimated from the daytime observations at lower altitudes (~60-80 km) by OMEGA and CRISM. The OMEGA analysis showed that crystal radii are within 1–3 μm, and that their optical depths are between 0.01 and 0.6 at $\lambda = 1\ \mu$m (Määttänen et al., 2010); the CRISM analysis showed that crystal radii are within 0.5–2 μm and, that their optical depths are lower than 0.3 at $\lambda = 0.5\ \mu$m (Vincendon et al., 2011). These estimates were calculated by comparing the measurements and simulations based on the Mie theory (with spherical particle shape assumed). Note that in the OMEGA data analysis, the peak at 4.3 μm was not used directly; the crystal size was derived from ratios between the radiances inside and outside shadows. While understanding of the exact composition of the cloud crystals (pure CO_2 ice or not) and their shapes in the clouds are still poor because there are not direct observations.

In this study, we have investigated these mesospheric CO_2 clouds using the nadir near-infrared spectra of the Planetary Fourier Spectrometer (PFS) onboard MEx. To date, PFS has the highest spectral resolution in the 4.3 μm CO_2 band. Using this unique dataset, a detailed study has been conducted on the spectral position, shape, and intensity of the CO_2 ice cloud scattering peak around 4.3 μm. The high-spectral-resolution observations of PFS provide not only a new dataset to compare with previous observations but also new insights into the optical properties of the mesospheric CO_2 ice clouds (such as crystal size, composition, and shape). The details of the PFS data analysis are described in Section 2. The observational results are presented in Section 3. A comparison between the spectra measured by PFS and synthetic spectra from a radiative transfer model is provided in Section 4, and the results are discussed in Section 5. Finally, concluding remarks are provided in Section 6.

2. PFS data analysis

2.1. Planetary Fourier Spectrometer (PFS)

PFS is a Fourier transform spectrometer onboard the MEx orbiter optimized for atmospheric studies (Formisano et al., 2005). It has two spectral channels: the Short Wavelength Channel (SWC, 2000–8600 cm^{-1}) and the Long Wavelength Channel (LWC, 250–1700 cm^{-1}). The fields of view are 1.6° for the SWC and 2.8° for the LWC. Both channels have a spectral sampling step of 1.0 cm^{-1} and a spectral resolution of 1.3 cm^{-1}. The spectral and radiometric calibration procedure for both channels has been discussed in detail by Giuranna et al. (2005a, 2005b). An advantage of PFS is its wide spectral coverage coupled with its relatively high spectral resolution. In about six Martian years, PFS has collected more than 2500,000 spectra for each channel. With full spatial coverage every year, PFS has been sounding the Martian atmosphere at different local times and seasons, which enables investigation of the diurnal, seasonal, and inter-annual variability of several atmospheric constituents and optical parameters of aerosols.

2.2. Searching for mesospheric CO_2 ice cloud features with PFS

In this study, we have analyzed PFS spectra collected over a period of about six Martian years, from July 2004 to March 2015 (MEx Orbit #634–14,454), which corresponds to the beginning of MY 27 and the end of MY 32, respectively. To detect mesospheric CO_2 ice clouds, the scattering peak of CO_2 ice at the bottom of the 4.3 μm CO_2 band in the SWC spectra was searched. Because the lines of this strong CO_2 band are saturated, no solar reflection signal is expected between 4.2 and 4.5 μm, except in the following three cases (Montmessin et al., 2007): (1) solar reflection from high topographic regions (i.e., partial desaturation of the CO_2 band), (2) non-local thermodynamic equilibrium (non-LTE) emission of CO_2 and CO, and (3) solar reflection by high-altitude aerosols, such as mesospheric CO_2 ice clouds. In the first case, an