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Retrieval of water vapor column abundance and aerosol properties from ChemCam passive sky spectroscopy

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ABSTRACT

We derive water vapor column abundances and aerosol properties from Mars Science Laboratory (MSL) ChemCam passive mode observations of scattered sky light. This paper covers the methodology and initial results for water vapor and also provides preliminary results for aerosols. The data set presented here includes the results of 113 observations spanning from Mars Year 31 $L_s = 291°$ (March 30, 2013) to Mars Year 33 $L_s = 127°$ (March 24, 2016).

Each ChemCam passive sky observation acquires spectra at two different elevation angles. We fit these spectra with a discrete-ordinates multiple scattering radiative transfer model, using the correlated-k approximation for gas absorption bands. The retrieval proceeds by first fitting the continuum of the ratio of the two elevation angles to solve for aerosol properties, and then fitting the continuum-removed ratio to solve for gas abundances. The final step of the retrieval makes use of the observed CO_2 absorptions and the known CO_2 abundance to correct the retrieved water vapor abundance for the effects of the vertical distribution of scattering aerosols and to derive an aerosol scale height parameter.

Our water vapor results give water vapor column abundance with a precision of ±0.6 precipitable microns and systematic errors no larger than ±0.3 precipitable microns, assuming uniform vertical mixing. The ChemCam-retrieved water abundances show, with only a few exceptions, the same seasonal behavior and the same timing of seasonal minima and maxima as the TES, CRISM, and REMS-H data sets that we compare them to. However ChemCam-retrieved water abundances are generally lower than zonal and regional scale from-orbit water vapor data, while at the same time being significantly larger than pre-dawn REMS-H abundances. Pending further analysis of REMS-H volume mixing ratio uncertainties, the differences between ChemCam and REMS-H pre-dawn mixing ratios appear to be much too large to be explained by large scale circulations and thus they tend to support the hypothesis of substantial diurnal interactions of water vapor with the surface. Our preliminary aerosol results, meanwhile, show

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the expected seasonal pattern in dust particle size but also indicate a surprising interannual increase in water–ice cloud opacities.

1. Introduction

The Mars Science Laboratory's (MSL) ChemCam spectrometer (Wiens et al., 2012; Maurice et al. 2012) measures atmospheric aerosol properties and gas abundances by operating in passive mode and observing scattered sky light at two different elevation angles. ChemCam was designed primarily for laser induced breakdown spectroscopy (LIBS) of Martian surface materials (Wiens et al., 2015; Maurice et al. 2016), but it has been used extensively for both imaging (Le Mouélic et al., 2015) and passive spectroscopy (Johnson et al., 2015). This paper covers the methodology and initial results of ChemCam passive sky spectroscopy with ChemCam's VNIR (visible and near infrared) spectrometer, focusing on water vapor abundances and providing preliminary results for aerosols. We also retrieve molecular oxygen, but further data analysis refinements will be required before we are ready to report detailed O_2 results.

Other than ChemCam passive sky spectroscopy, our most direct information about water vapor at MSL's work site in Gale Crater comes from MSL's Rover Environmental Monitoring Station (REMS) humidity sensor (Harri et al., 2014b), which provides routine in-situ monitoring of *relative* humidity at a height of 1.6 m above the surface and yields estimates of absolute mixing ratio when relative humidity values are sufficiently high. Water vapor on Mars has of course been measured extensively from orbit and from Earth, and the most densely sampled and high-resolution orbital measurements can provide a useful amount of Gale-Crater-specific information. In this paper we compare ChemCam results with the Gale-specific information that can be provided by the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) data set (Smith et al., 2002) and by Mars Reconnaissance Orbiter's (MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Smith et al., 2009; Toigo et al., 2013).

Interest in Gale Crater water vapor has focused on possible exchanges of water vapor with the surface. Savijarvi et al. (2016) argue that the REMS humidity sensor (REMS-H) data are best explained by diurnal adsorption of water on soil grains, and Martín-Torres et al. (2015) have argued that temperature and humidity conditions at Gale are compatible with the formation of liquid brines on the surface via deliquescence. Meanwhile ChemCam LIBS observations show elevated hydrogen in soils but no evidence for diurnal change in the hydrogen (Meslin et al., 2013; Schröder et al., 2015). Elsewhere on Mars, evidence for a near-surface diurnal cycle of water vapor has been found at both Viking Lander sites (Jakosky et al., 1997) and at the Phoenix lander site (Tampari et al., 2010; Savijärvi and Määttänen, 2010).

The possibility of exchange of water vapor with the surface, by adsorption in particular, remains a controversial but potentially significant factor in the global water cycle. Such exchanges are one way to avoid modeled water columns substantially larger than observed (Böttger et al., 2004), but Montmessin et al. (2004) show that a detailed accounting of the effects of clouds can accomplish the same thing. The radiative effects of those clouds are another aspect of the Martian water cycle that has attracted a lot of recent interest. Models with radiatively active water ice clouds have tended to produce a water cycle that is too dry. This situation has been improved to a significant extent with work by Navarro et al. (2014) that includes detailed cloud microphysics, but that model is still too dry relative to TES water columns at low latitudes, making alternative and additional equatorial water vapor measurements such as those provided by ChemCam particularly valuable.

Clearly aerosols have an important influence on the water cycle and vice versa, so obtaining aerosol and water vapor information in tandem is particular valuable. It has also become clear that water and dust aerosol dynamics are strongly coupled to each other, with vertical distributions playing an important role in that coupling (Kahre et al., 2015). Particle size, too, plays an important role in the influence of dust on dynamics (e.g. Kahre et al., 2008). ChemCam passive sky observations provide a valuable opportunity to capture many of these aerosol properties at the same time, although it should be noted that ChemCam is only one of several MSL instruments that play a significant role in monitoring aerosols. Others include REMS UV photodiodes (Smith et al., 2016) Navcam (e.g. Kloos et al., 2016; Moore et al., 2016), and Mastcam (Lemmon, 2014).

We begin this paper with an overview of the ChemCam passive sky observations and our measurement procedures (Section 2.1) and then describe our methods in detail (remainder of Section 2). We analyze the sensitivity of our results to various input assumptions in Section 3, then present and discuss our results in Section 4 and summarize our conclusions in Section 5. The appendices (Appendices A–C) provide additional information which, although necessary for any replication or extension of the results in this paper, is not essential for understanding them: Appendix A addresses external data sets, Appendix B addresses methodological details, and Appendix C shows how to identify ChemCam passive sky data in the Planetary Data System. Data tables covering the complete water vapor and aerosol data set presented here can be found in the supplemental materials. This data set includes the results of 113 observations spanning from Mars Year 31 $L_s = 291°$ (March 30, 2013) to Mars Year 33 $L_s = 127°$ (March 24, 2016).

2. Methods

2.1. Overview

Fig. 1 illustrates the ChemCam passive sky observing strategy. We observe at two different elevation angles, collecting scattered skylight that has traced two significantly different path lengths through the atmosphere, and then ratio the low elevation signal to the high elevation signal to eliminate solar spectral features and instrument response uncertainties. Figs. 2 and 3 show an example of the raw signal levels as well as the resulting ratio and continuum-removed ratio, with and without a correction for spatially-variable detector background. Using a discrete-ordinates multiple-scattering radiative transfer model, we fit the continuum of the ratio to solve for aerosol properties (Fig. 4) and then the continuum-removed ratio to solve for gas abundances (Fig. 5). Lastly, we use the known CO_2 abundance to correct the gas abundances and derive an aerosol vertical profile parameter (Fig. 6.).

The following subsections present the four major steps of the ChemCam passive sky measurement process in order, together with a brief overview of their technical details.

2.1.1. Fit the continuum ratio to solve for aerosol properties

We fit the continuum at 15 evenly spaced wavelengths ranging from 550 to 830 nm. The aerosol property parameters used to fit the continuum ratio are dust particle effective radius, ice particle effective radius, and the fraction of 880 nm opacity contributed by

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