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Constraints on water vapor and sulfur dioxide at Ceres: Exploiting the sensitivity of the Hubble Space Telescope

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ABSTRACT

Far-ultraviolet observations of dwarf-planet (1) Ceres were obtained on several occasions in 2015 and 2016 by the Cosmic Origins Spectrograph (COS) and the Space Telescope Imaging Spectrograph (STIS), both on board the Hubble Space Telescope (HST). We report a search for neutral gas emissions at hydrogen, oxygen and sulfur lines around Ceres from a potential teneous exosphere. No detectable exosphere emissions are present in any of the analyzed HST observations. We apply analytical models to relate the derived upper limits for the atomic species to a water exosphere (for H and O) and a sulfur dioxide exosphere (for S and O), respectively. The H and O upper limits constrain the H_2O production rate at the surface to $(2-4) \times 10^{26}$ molecules s^{-1} or lower, similar to or slightly larger than previous detections and upper limits. With low fluxes of energetic protons measured in the solar wind prior to the HST observations and the obtained non-detections, an assessment of the recently suggested sputter-generated water exosphere during solar energetic particle events is not possible. Investigating a sulfur dioxide-based exosphere, we find that the O and S upper limits constrain the SO_2 density at the surface to values $\sim 10^{10}$ times lower than the equilibrium vapor pressure density. This result implies that SO_2 is not present on Ceres' sunlit surface, contrary to previous findings in HST ultraviolet reflectance spectra but in agreement with the absence of SO_2 infrared spectral features as observed by the Dawn spacecraft.

1. Introduction

The shape and low mean density of 1 Ceres, the largest body in the asteroid belt, indicate that between 17% and 27% of its total mass is water ice (see e.g., review by McCord et al., 2011). An earlier theoretical analysis by Fanale and Salvail (1989), however, suggested that the presence of a measurable water-based atmosphere around Ceres is unlikely. Due to the high surface temperatures water ice in the near-surface layers should have been lost by sublimation over the course of its existence leading to low water escape rates of 0.3 kg^{-1} at maximum today. A detection of OH band emission by the International Ultraviolet Explorer (IUE) (A'Hearn and Feldman, 1992) yet indicated that Ceres possesses a water exosphere with production rates of 1.4×10^{26} H_2O molecules s^{-1} or ~ 3 kg s^{-1}. A direct detection of water vapor around Ceres was later provided by the Herschel satellite through absorption at sub-millimeter wavelengths, also suggesting a production rate of $> 10^{26}$ H_2O molecules s^{-1} (Küppers et al., 2014). Other attempts to detect an exosphere at Ceres did not provide confirmation (Rousselot et al., 2011; Roth et al., 2016; McKay et al., 2017).

Various suggestions were put forward on what could produce water vapor at Ceres at such a relatively high rate as derived from the detections. If sublimation derived, the source rate for sublimation of H_2O and hence the exospheric density depend on the amount of ice that is present on or near the surface. Estimations for the stability of ices in the near-surface layers show that it generally depends on the average surface temperatures (Schorghofer, 2008). Hence, a higher stability and pressumably larger presence of ice today is predicted for high latitude regions only (Titus, 2015; Hayne and Aharonson, 2015). Hayne and Aharonson (2015) suggest that seasonal or episodic sublimation of near-surface ground ices could explain the observed water vapor. Formisano et al. (2016) propose that sublimation from large subsurface ice layers, which are only a few centimeters below the surface covered by a porous silicate crust, is a plausible water vapor source mechanism.

Several findings by the Dawn spacecraft were also related to the abundance of near-surface ice and Ceres' exosphere. Dawn's Framing Camera revealed hazes over a bright pit on the floor of crater Occator, which are suggested to arise from sublimation of water ice (Nathues et al., 2015). The Visible-Infrared Mapping (VIR) Spectrometer then detected surface features of H_2O absorption in the mid-latitude crater Oxo (Combe et al.,

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2016). Using topography derived from stereo imaging by the NASA Dawn spacecraft, Schorghofer et al. (2016) estimate that about 0.1% of the surface could be permanently shadowed regions and Platz et al. (2016) found evidence for water-ice deposits adjacent to one permanent shadowed region in VIR data. In addition to ongoing sublimation processes, degassing processes have been suggested for haze and bright material origin in the center of Occator (Nathues et al., 2017). Furthemore, the Gamma Ray and Neutron Detector (GRaND) on Dawn found high concentrations of hydrogen at mid-to-high latitudes, which indicates that water ice near the surface can be stable over the time span of Ceres' age (Prettyman et al., 2017). However, estimations for the water escaping from the surface by Prettyman et al. (2017) and Schorghofer (2016) still indicate significantly lower source rates than the exosphere detections suggested.

In general, it remains difficult to permanently sustain a fast escaping water exosphere at a source rate of 10^{26} H_2O molecules s^{-1} and at the same time to maintain a sufficient amount of ice near a geologically inactive surface providing a water source reservoir over the time span of millions years. Nathues et al. (2017) present a possible solution showing that ongoing surface alteration can indeed provide fresh surface ice as found in the Oxo crater slopes. Other possibly similar crater sites with fresh surface H_2O were reported (Combe et al., 2017).

Another measurement by Dawn was suggested to provide indirect evidence of the presence of an exosphere at Ceres. During Dawn's Survey orbit phase, GRaND measured energetic electrons moving toward the spacecraft from the direction of Ceres. These electrons were interpreted to orignate from a bow shock thought to be generated when the solar wind interacts with an exosphere around Ceres (Russell et al., 2016). Using a magnetohydrodynamic model Jia et al. (2017) find that an exosphere source rate of 0.6×10^{26} H_2O molecules s^{-1} is sufficient to produce a shock surface upstream of Ceres. A coincident event of high solar wind energetic protons flux was observed simultaneously with this GRaND observation. Villarreal et al. (2017) showed that an increase of energetic solar wind proton fluxes also occurred prior the previous neutral gas detections by IUE and Herschel, while the non-detections coincided with low energetic proton fluxes. Villarreal et al. (2017) conclude that a transient exosphere might be generated by proton sputtering only during solar energetic particle events, which would provide an explanation that reconciles the measured high source rates with the continued presence of water ice near or at the surface.

However, Tu et al. (2014) estimate a maximum production rate of $\sim 10^{23}$ H_2O molecules s^{-1} from sputtering at an average solar wind flux, i.e., three orders of magnitude below the derived source rates. Ice sputtering yields upon proton impact peak near proton energies of ~ 100 keV (e.g., Johnson, 1990). According to Villarreal et al. (2017), protons require an energy of 100 keV to penetrate the surface. If only protons near or above 100 keV are the main sputtering agent at Ceres, the fluxes are orders of magnitude lower than, e.g., at Jupiter moon Europa, where sputtering still provides insufficient yields on the order of only 10^{24} H_2O s^{-1} (Cassidy et al., 2013). Additionally, globally there is no ice on the surface but instead any larger ice patches are at least covered by layers of dust (Formisano et al., 2016), which will further reduce total sputtering yields depending on the depth of the ice. Thus, more studies are required to estimate whether sputtering can really be sufficient to produce the required water source rates during solar wind energetic particle events.

Recent HST observations of Ceres' UV reflectivity pointed to the existence of sulfur dioxide on the surface, with higher abundances in the polar regions (Hendrix et al., 2016). Despite the fact that SO_2 exhibits several absorption bands at IR wavelengths, the presence of SO_2 could not be confirmed by Dawn's VIR instrument (Stephan et al., 2017). Due to the low melting point of SO_2 of 201 K, SO_2 is not stable at the average surface temperature of Ceres, except possibly for cold trap regions. Hendrix et al. (2016) suggest that the SO_2 frost derived from their observations could be deposits from recent outgassing of sulfurous materials.

If SO_2 is present today on Ceres' surface, high vapor pressure and thus high abundances of gaseous SO_2 are expected due to the low sublimation temperature of SO_2. For comparison, the SO_2 atmosphere of Jupiter's moon Io, which is the third densest atmosphere of a minor Solar System body, is maintained primarily by sublimation of SO_2 frost (Lellouch et al., 2007; Tsang et al., 2016). Because the average surface temperature at Io of 110 K is significantly lower than at Ceres (167 K), the SO_2 vapor pressure at Ceres is several orders of magnitude higher (e.g., Matson and Nash, 1983).

Here we analyze far-UV observations by Hubble's Cosmic Origins Spectrograph (COS) and Space Telescope Imaging Spectrograph (STIS) taken in 2016 and 2015, respectively. Results on the oxygen abundances from a first COS observation visit from 2015, with Ceres located in the COS field-of-view (FOV), were reported by Roth et al. (2016). In 2016, COS observed Ceres again, but pointing slightly off the body in order to constrain neutral gas emissions without interference of reflected sunlight from the surface. In addition to this 2016 COS visit, we search for neutral emissions in spectra taken by STIS in 2015 within the HST program of Hendrix et al. (2016) for investigations of Ceres' surface UV reflectivity. Although no emissions are detected in these COS and STIS observations, we derive constraints for brightness and abundances of O, H, and S. Using a simple Haser model (Haser, 1957) for the radial profiles of parent and daughter species, we relate the O and H upper limits to an H_2O source rate. We also investigate the energetic proton fluxes in the days leading up to each observation to test the hypothesis of Villarreal et al. (2017) of a transient sputter-generated exosphere. Finally, we relate the O and S upper limits to a sulfur dioxide exosphere constraining the surface abundance of SO_2 frosts based on the expected vapor pressure.

2. Observations

2.1. HST/COS spectra

Ceres was observed with COS and the G130M grating over a 5-orbit visit by HST (Table 1). Using the central wavelength of 1327 Å, the wavelength coverage of 1172–1313 Å on detector segment A and 1328 –1469 Å on segment B included a sulfur transition near 1429 Å in addition to the oxygen lines at 1304 Å and 1356 Å and the hydrogen Lyman-α line (1216 Å). Five exposures were taken, one per orbit. HST pointed at an offset of 1.95 arcsec to the center of Ceres (1.6 arcsec to the limb) during the first 4 orbits. This offset was chosen to search for neutral gas emissions near the body but without interference of reflected sunlight from the surface. The last exposure was taken at an offset of 20 arcsec from Ceres in order to provide a background sky measurement under the same conditions.

For the lines mentioned above, the strongest emissions are expected for OI 1304 Å and HI Lyman-α, which are also most affected by scattered light from the geocorona. The visit was carried out on October 26, 2016 just one day after Ceres' opposition to Earth, maximizing the night time during a Hubble observing orbit and thus providing optimal conditions. Scattered sunlight from the geocorona is still present throughout the exposures at HI Lyman-α and at the beginning and end of each exposure (when HST is closest to the terminator) at the OI 1304 Å multiplet. We use the TIME-TAG data to monitor the geocoronal background and select exposure portions such that the background is similarly low during all