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Upper limits for phosphine (PH₃) in the atmosphere of Mars

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ABSTRACT

Phosphine (PH₃) is proposed to be a possible biomarker in planetary atmospheres and has been claimed to have been observed in the atmosphere of Venus, sparking interest in the habitability of Venus’s atmosphere. Observations of another biomarker, methane (CH₄), have been reported several times in the atmosphere of Mars, hinting at the possibility of a past or present biosphere. The Atmospheric Chemistry Suite on the ExoMars Trace Gas Orbiter has a spectral range that includes several absorption lines of PH₃ with line strengths comparable to previously observed CH₄ lines. The signature of PH₃ was not observed in the 192 observations made over a full Martian year of observations, and here we report upper limits of 0.1–0.6 ppbv.

1. Introduction

Phosphine (PH₃) is an essential molecule for all forms of life on Earth. Phosphine (PH₃) is a very reactive, rapidly photolysed, and highly variable component of the terrestrial atmosphere. Found at parts per trillion by volume (pptv) to parts per billion (ppbv) volume mixing ratios (VMRs), it accounts for approximately 10% of Earth’s atmospheric phosphorus (Glindemann et al. 2003; Elm et al. 2017). It does not play a direct role in Earth’s biology but acts as an exchange path for phosphorous, being emitted from the biosphere, oxidized to phosphoric acid (H₃PO₄), and then taken up again in biological systems. The dominant sources of phosphine in the terrestrial atmosphere are emissions from soils, sediments, and marines (Glindemann et al. 2005a). In contrast, abiotic PH₃ production may be ongoing in the hot and reducing deep atmospheres of Saturn and Jupiter (e.g. Bregman et al. 1975; Burgdorf et al. 2004; Fletcher et al. 2009).

Phosphine may play a role in the anaerobic biological systems of anoxic environments, where it will not be readily oxidized (Bains et al. 2019; Sousa-Silva et al. 2020). One such proposed environment is the cloud decks of Venus (Seager et al. 2020). Thus, when the first detection of a phosphine absorption line (at 1.123 mm) in the Venusian atmosphere was announced (Greaves et al. 2020a), it was hailed as evidence of a possible microbial habitat in the upper atmosphere of Venus. The result has since been criticized on technical grounds (Snellen et al. 2020; Villanueva et al. 2020; Thompson 2021; Akins et al. 2021; Lin- cowski et al. 2021), and other observations did not corroborate it (Encrènaz et al. 2020; Trompet et al. 2021); however, the original team stands by their findings (Greaves et al. 2020b,c) and has reported revised mixing ratios of 5–20 ppbv.

On Mars, methane is another possible biomarker that has been tentatively detected (Formisano et al. 2004; Krasnopolsky et al. 2004; Mumma et al. 2009; Webster et al. 2015; GIuranna et al. 2019), though not confirmed by the ExoMars Trace Gas Orbiter (TGO; Korabiev et al. 2019), and thus measurements of phosphine may be able to help identify its source. For example, identifying methane and phosphine would hint towards a biological source of methane, whereas finding methane alongside sulphur species would imply a geologic source of both trace gases.

2. Observations

ACS is a suite of three spectrometers: The thermal infrared channel (TIRVIM) is a compact Fourier transform spectrometer with a spectral range of 1.7 to 17 μm; the near-infrared channel (NIR) combines an echelle grating with an acousto-optical tunable filter and covers the range 1 to 1.7 μm; and ACS MIR is a cross-dispersion spectrometer consisting of an echelle grating and a secondary, steerable reflecting diffraction grating. ACS MIR has the finest spectral resolution of any remote sensing mission to...
Fig. 1. Spectral range of ACS MIR containing PH$_3$ absorption features. Panel a: Modelled transmission spectrum contributions from 10 ppbv of PH$_3$ from a 20 km tangent height. Panel b: Single spectra extracted from orders 142–145 for 12 consecutive tangent heights (2–26 km) in the lower atmosphere of Mars using ACS MIR secondary grating position 9. All visible absorption lines result from CO$_2$, which also impacts the broad continuum that decreases transmission towards lower wavenumbers, where the CO$_2$ $\nu_3$ vibration-rotation band is centred. Boxes in panel a indicate the spectral windows covering PH$_3$ absorption features in order 143 used to determine upper limits.

Fig. 2. HITRAN 2016 line strengths for the $\nu_1$ vibration-rotation band of CH$_4$ (panel a) and the $\nu_3$ vibration-rotation band of PH$_3$ (panel b). The spectral ranges of important ACS MIR diffraction orders are indicated in grey.

Mars to date ($\lambda/\Delta\lambda \sim 30,000$) and covers a spectral range of 2400 to 4400 cm$^{-1}$ (2.2 to 4.2 $\mu$m; Korablev et al. 2018).

ACS MIR operates in solar occultation mode, recording a series of spectra with tangent height spacings of 1–2 km by using the Sun as a light source and observing the limb of the atmosphere. The secondary diffraction grating separates diffraction orders that would otherwise overlap in the infrared spectral region. Observations are measured with a two-dimensional detector array. The horizontal axis corresponds to the wavenumber, and the vertical axis corresponds firstly to the diffraction order and secondly to the vertical field of view of the instrument. Each order appears as a stripe across the detector, the width of which covers around 20 rows of pixels, each row producing a unique spectrum recorded ~ 0.2 km above or below the adjacent rows. Thus, at every tangent height several spectra are recorded for each order, representing a vertical range of several kilometres. Details about the instrument and data processing, as well as example detector image frames, can be found in Korablev et al. (2018), Korablev et al. (2019), Trokhimovskiy et al. (2020), and Olsen et al. (2021).

The absorption signature for PH$_3$ can be sought by using secondary grating position 9, which provides access to diffraction orders 142–152, covering the spectral range 2377–2560 cm$^{-1}$; these are the lowest wavenumbers available to ACS MIR. Figure 1 shows modelled PH$_3$ absorption features with ACS MIR spectral resolution, indicating the locations of the most significant PH$_3$ absorption features over orders 142–143. Figure 1 shows example spectra from the same orders recorded during one occultation. At each tangent height, a single spectrum was extracted for each order. The change in baseline transmittance is mainly due to increasing aerosol extinction as tangent heights approach the surface. The left side of the spectrum is dominated by the strong $\nu_3$ vibration-rotation band of CO$_2$, the continuum absorption of which also impacts the transmittance of adjacent orders. While the strongest PH$_3$ lines directly overlap the CO$_2$ $\nu_3$ band, prominent lines free of interference remain in order 143, which is where this study focuses (lines in order 144 are too weak, and interference from CO$_2$ is too strong in order 142; see Fig. 1).

The line strengths of the strongest PH$_3$ lines in this spectral region are about 1.5 $\times$ 10$^{-19}$ in the 2016 edition of the HITRAN database, which is used in the forward modelling in this study (Gordon et al. 2017; we note that Greaves et al. (2020c) used the ExoMol line list for high temperatures). This is comparable to those used by ACS MIR and others to search for methane. Figure 2 shows the line strengths of the $\nu_3$ band of methane and
the $\nu_3$ band of phosphine, with the spectral ranges of diffraction orders used to search for them indicated. The expectation, then, is that ACS MIR should have roughly similar sensitivity to both trace gases, of the order of less than a part per billion. Upper limits for methane from the ACS MIR data are lower than for PH$_3$, around tens to hundreds of pptv (Korablev et al. 2019).

The ExoMars TGO entered Mars orbit in late 2016, and its nominal science phase commenced in April 2018. It is approaching 1.5 Mars years (MYs) of coverage (three Earth years). The dataset analysed here consists of all 192 usable occultations recorded between $L_\lambda = 140–350^\circ$ in both MY 34 and 35 (we note that there was a period between MYs in which position 9 was not used). The majority of observations are at high northern or southern latitudes (around 60°N and -60°S), but several low latitude observations were also made.

3. Results

To make the most accurate measurements of rare trace gases possible, we exploited the vertical field of view of the ACS MIR instrument and considered 12 spectra for diffraction order 143 from each detector frame recorded at each observation in the occultation series. Each spectrum has a unique tangent altitude, with corresponding temperatures and pressures, and some also have a unique instrument line shape (ILS) that needed to be fitted prior to VMR retrievals. The ILS was impacted by an optical aberration that caused the total absorption to be divided into a primary and secondary image (Alday et al. 2019, Olsen et al. 2021a) that had to be accounted for. The accuracy of retrievals using a fitted ILS for ACS MIR was verified by comparing retrieved vertical profiles of temperature, pressure, water vapour, and carbon monoxide with simultaneous observations made with ACS NIR (Alday et al. 2019, Fedorova et al. 2020, Olsen et al. 2021a).

To best account for the observational differences affecting adjacent spectra, each of the 12 detector rows from which spectra were extracted was treated as a unique solar occultation sequence and analysed independently. The upper limits were derived from the mean of the 12 retrieved VMR vertical profiles. This method was developed to examine the weak signature of HDO in the upper atmosphere towards the hygropause but has effectively been used to study hydrogen chloride (HCl) (Olsen et al. 2021b), the first novel trace gas discovered by ACS MIR (Korablev et al. 2021). Vertical profiles of temperature and pressure are independently measured by simultaneous observations with ACS NIR, which observes a CO$_2$ band at 1.38$\mu$m (7250 cm$^{-1}$). Spectral fitting is done with the Jet Propulsion Laboratory’s Gas Fitting software suite (GFT or GGG) (Sen et al. 1996, Irion et al. 2002, Wunch et al. 2011).

Vertical profiles of a fitted gas’s VMR were retrieved by inverting the matrices of line-of-sight optical paths through the atmospheric layers with the matrices of estimated number densities derived from the spectral fits at each altitude. Two fitting windows covering the strongest features in order 143 were used (2394.95–2401.53 cm$^{-1}$ and 2401.52–2405.84 cm$^{-1}$; see Fig. 1). Uncertainties were computed from the Jacobian matrix of partial derivatives. Additional details about spectral fitting and VMR retrievals can be found in Olsen et al. (2020), Olsen et al. (2021a), and Korablev et al. (2021), and details about the analysis method used here can be found in Olsen et al. (2021b).

Figure 3 shows an example of the ACS MIR data and helps to illustrate the PH$_3$ analysis technique. For one occultation, at a tangent height near 13 km, each row extracted from order 143 in the detector frame has been normalized and is shown. Also shown is the mean spectrum, with greatly reduced instrument noise (the root mean square of fitting residuals is reduced from $\sim$ 0.0014 to 0.0008). The observed absorption lines are due to CO$_2$, and two best-fit lines are shown, for which PH$_3$ abundances were fixed in order to illustrate where PH$_3$ features would be found. We note that the noise to the left, near 2396 cm$^{-1}$, is larger than elsewhere. This is because it is near the edge of the detector frame and has a lower signal strength. We also note that there appears to be a systematic error fitting the CO$_2$ lines from left to right; this is due to the normalization of the spectra, which can safely remove the impact of aerosols under normal circumstances but should not be performed in this region due to the CO$_2$ continuum near the CO$_2$ $\nu_3$ band. Normalization was not used when computing detection limits; it is only used in Fig.[3] to facilitate the comparison of the spectra and to illustrate the line locations of PH$_3$ absorption features, the impact that 10 ppbv of PH$_3$ would have, and the noise level of ACS MIR spectra.

To determine whether PH$_3$ was detected, we considered the set of 12 retrieved VMR vertical profiles. We computed the weighted mean, using the uncertainty ($\sigma$) of each retrieval as weights ($1/\sigma^2$), and computed the standard error of the weighted mean. Figure 3 shows the VMR vertical profile retrieval uncertainties for the 12 sets of solar occultation spectra from which those shown in Fig.[3] were taken. Also shown are the retrieval uncertainties derived using the mean spectra, which are lower than those of the individual spectra due to the reduced noise, but still greater than the standard error of the weighted mean, which is the uncertainty of the mean retrieved VMR vertical profile.

If the retrieved VMR was greater than three or five times the standard error, we considered it to be a possible detection. We would then verify it by examining the ensemble of spectra and mean spectra at each altitude. However, no candidate detections were found.

In the absence of any detection, we interpreted the vertical profile of the standard error of the weighted mean as an upper limit to the detection. These 1$\sigma$ upper limits are shown in Fig.[4] for the entire ACS MIR dataset recorded thus far using secondary grating position 9. Each profile is coloured by the density of observations, derived using a Gaussian kernel density estimation for the entire dataset. The density is low below 10 km due to differences in the lowest observable tangent height. That is, only a fraction of the occultations are clearly able to probe the lowest layers of the atmosphere due to aerosol extinction (dust is present during most of the observation period). Above 50 km, the differences are related to the total number density, which varies with the latitude and time of observation.

4. Discussion and conclusions

The highest density of derived upper limits occurs near 30 km and at a detection limit of $\sim$ 0.6 ppbv. The lowest values are < 0.2 ppbv and are reached at altitudes between 10 and 35 km. These are comparable to the reported upper limits in Korablev et al. (2019) for CH$_4$ of 0.15 ppbv. While several ACS MIR observations led to CH$_4$ detection limits of the order of tens of pptv, we must note that the $R$-branch CH$_4$ lines available are stronger than the PH$_3$ lines in Fig.[3] (e.g. compare to Fig.[2]) and they are more towards the centre of their diffraction orders, which leads to a higher signal-to-noise ratio. Furthermore, potential CH$_4$ lines are not subject to the strong absorption of the CO$_2$ $\nu_3$ continuum, which effectively reduces the line depth relative to the noise. We also note that, relative to the Venusian observations of 20 ppbv, the line strengths of PH$_3$ in the ACS MIR spectral range ($\sim$ 1.5 $\times$ 10$^{-19}$) are much larger than that
of the single line claimed in Venus’s atmosphere ($1.27 \times 10^{-22}$) (Greaves et al. 2020c).

Had PH$_3$ been detected at Mars, a biological origin would not be certain. The Martian environment is not anoxic, unlike the environments proposed by Sousa-Silva et al. (2020), and biogenic (or other) PH$_3$ may be removed by rapid oxidation by the hydroxyl radical (OH), itself a by-product of water vapour photolysis.

While ACS MIR observations have not detected any sulphur species indicative of a geological source of methane, they have detected hydrogen chloride, which may have a magmatic or volcanic origin (Korablev et al. 2021). However, ACS MIR has also not detected any signatures of methane in the atmosphere of Mars (Montmessin et al. 2021). Phosphorus is found on the surface of Mars (e.g. Gellert et al. 2004; Rieder et al. 2004), and phosphate has been identified in Martian meteorites (e.g. McCubbin & Nekvasil 2008; Agee et al. 2013). Though not favoured, there are abiotic processes that may release PH$_3$ gas from the surface (Glindemann et al. 2004, 2005b), and volcanic processes have even been proposed to explain its presence on Venus (Truong & Linné 2020).

Thus, while PH$_3$ has been proposed as a possible biomarker for anoxic exoplanetary environments, it is not observed in the atmosphere of Mars, where the biomarker CH$_4$ had previously been reported (although we note that these reports remain controversial and have not been corroborated by the ExoMars TGO). Due to the highly oxidative state of the Martian atmosphere, however, its presence was perhaps unexpected. An upper limit of 0.2–0.6 ppbv is set for the atmosphere of Mars between 10 and 45 km.

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