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LETTER TO THE EDITOR

Re-analysis of the 267 GHz ALMA observations of Venus

No statistically significant detection of phosphine*

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ABSTRACT

Context. ALMA observations of Venus at 267 GHz that show the apparent presence of phosphine (PH_3) in its atmosphere have been presented in the literature. Phosphine currently has no evident production routes on the planet's surface or in its atmosphere.
Aims. The aim of this work is to assess the statistical reliability of the line detection via independent re-analysis of the ALMA data.
Methods. The ALMA data were reduced the same way as in the published study, following the provided scripts. First, the spectral analysis presented in the study was reproduced and assessed. Subsequently, the spectrum, including its dependence on selected ALMA baselines, was statistically evaluated.
Results. We find that the 12th-order polynomial fit to the spectral passband utilised in the published study leads to spurious results. Following their recipe, five other $>10\sigma$ lines can be produced in absorption or emission within 60 km s^{-1} from the PH_3 1−0 transition frequency by suppressing the surrounding noise. Our independent analysis shows a feature near the PH_3 frequency at a $\sim 2\sigma$ level, below the common threshold for statistical significance. Since the spectral data have a non-Gaussian distribution, we consider a feature at such level as statistically unreliable, which cannot be linked to a false positive probability.
Conclusions. We find that the published 267 GHz ALMA data provide no statistical evidence for phosphine in the atmosphere of Venus.

Key words. planets and satellites: individual: Venus

1. Introduction

Atacama Large Millimeter Array (ALMA) observations of Venus at 267 GHz that show the apparent presence of phosphine (PH_3) in its atmosphere at ∼20 parts-per-billion (Greaves et al. 2020; hereafter GRB20) have recently been presented. Since phosphorus is expected to be in oxidised forms, phosphine has no easily explained production routes on the planet's surface or in its atmosphere at this level (Bains et al. 2020). At the same time, PH_3 is identified as a potential biomarker gas (Sousa-Silva et al. 2020), and an aerial biosphere of Venusian microbes (Seager et al. 2020) has been proposed as the possible source. The required biomass is potentially just a fraction of that of the Earth's aerial biosphere (Lingam & Loeb 2020). Furthermore, the Venusian life may have an Earth origin (Siraj & Loeb 2020). A balloon mission is proposed to search in situ for these life forms (Hein et al. 2020), which could be launched as soon as 2022−2023. In the meantime, Encrenaz et al. (2020) have provided a stringent upper limit on the PH_3 abundance of <5 ppb from observations in the thermal infrared, which, in the absence of variability, is in conflict with the results presented by GRB20.

The aim of this work is to assess the statistical reliability of the PH_3 $J = 1{-}0$ line detection by independently re-analysing the ALMA data. In Sect. 2, the processing and calibration of the ALMA data are described, which was performed in a similar way as by GRB20. In Sect. 3, the procedure that led to the $\sim 15\sigma$ detection of PH_3 by GRB20 is reproduced and is shown to give spurious results. In Sect. 4, an independent analysis of the ALMA spectrum is presented and discussed. Short conclusions follow in Sect. 5.

2. Processing and calibration of ALMA data

The ALMA data processing and calibration are briefly discussed here, but the reader should consult GRB20 for more details. The aim was to perform the processing and calibration in the same way as in the original study, making use of the (updated) scripts provided by GRB20. This study only concentrates on the high-resolution narrow-band data centred on PH_3.

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[*] Since the publication of GRB20, the authors alerted us about an update in the ALMA data processing script and made the new script available. In parallel, the data available in the ALMA Science Archive are undergoing (so-called QA3) reprocessing to include the same correction. The resulting reprocessed data no longer contain the strong ripples that GRB20 report and that we also find, for example as manifested in the non-Gaussian noise distribution. In these reprocessed data, we do not find a clear absorption feature that can be attributed to PH_3, although further exploration of these data is necessary to analyse this in more detail.

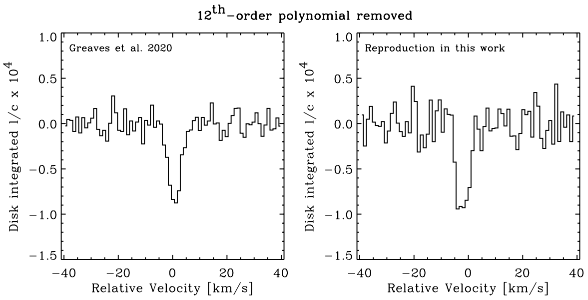

Fig. 1. Reproduction of the ALMA line spectrum as presented by Greaves et al. (2020), with the original and the reproduction in the *left-* and *right-hand panels*, respectively. This is after a 12th-order polynomial is removed from the spectral baseline. The reproduced spectrum is artificially scaled down by a factor of 12.8/16.1 to account for the different continuum brightnesses used in the studies. In the reproduction, the line feature shows a small velocity offset and the spectral baseline is somewhat noisy, but the overall S/N of the two features is similar.

The raw data from ALMA project 2018.A.00023.S were retrieved from the ALMA Science Archive. The python script Supplementary Software 2 and 3 from GRB20 was used for the initial calibration to produce the ALMA data cubes. The script selects data from baselines >33 m; this is the range chosen by GRB20 to maximise the signal-to-noise (S/N) of the proposed PH_3 1−0 signal, and it also forms the main focus of the analysis presented here. The 33 m cutoff is near the second minimum of the visibility amplitudes of the Venus disk at this frequency. These procedures were subsequently altered to process the data for different baseline selections, including all baselines as well as baselines >20 m and >50 m, which correspond to the first and third minimum of the visibility amplitudes, respectively. Verify that your intended meaning has not been changed. Supplementary Software 4 was used to image the data cubes[1]. Following GRB20, the Venus rest-frame frequency of the PH_3 1−0 transition was adopted to be 266.9445 GHz (Müller 2013). The spectral data were binned to velocity steps of 1.10 km s^{-1}.

3. Reproduction of the phosphine results

At the time of observations, the angular diameter of Venus was 15.36″ (GRB20). Since for the >33 m baseline selection the spectral line data from the limb of the planet still show strong ripples, data from within one major axis of the synthesised beam (<1.16″) of the planet limb were excluded from analysis. The continuum-subtracted line data were summed over the planet disk and divided by the summed continuum data to make the continuum-normalised line-spectrum (l:c).

To further mitigate the effects of the instrumental ripples and obtain the flattest spectral baseline, GRB20 fitted a 12th-order polynomial over a restricted passband of ±40 km s^{-1} around the PH_3 transition, interpolating across $|v| < 5$ km s^{-1}. The central region needs to be masked out, otherwise any line will also be removed. This procedure was reproduced here. The disk-integrated spectrum obtained by GRB20 is shown in the left-hand panel of Fig. 1 and our reproduction is shown in the right-hand panel. Since in this study the continuum level of Venus is found at 12.8 Jy beam^{-1} but is reported as 16.1 Jy beam^{-1} in GRB20, the reproduced spectrum is artificially scaled down by a factor of 12.8/16.1. The two spectra appear similar, although the line feature is slightly off-centre in the reproduction. In addition, the reproduced signal is stronger, but the spectrum is also noisier. The S/N is estimated to be ~18 by measuring the peak and standard deviation of the spectrum after applying a boxcar smoothing over seven velocity steps. This is very similar (15σ) to that presented by GRB20.

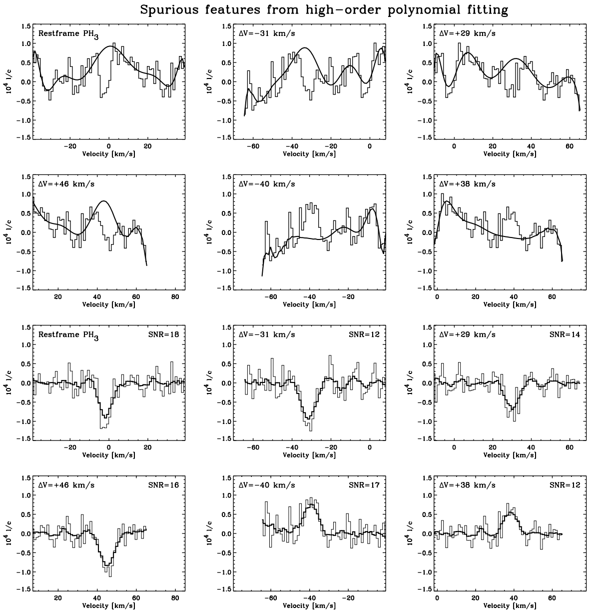

Fig. 2. *Top two rows*: parts of the final ALMA spectrum centred on the transition frequency of PH_3 1−0 (*top left*) and five other features, with superimposed the 12th-order polynomials fitted to the local data. *Bottom two rows*: same with these polynomials removed. We find that now all these features appear at S/Ns above 10 within 60 km s^{-1} of PH_3. It shows that the procedure followed by GRB20 is incorrect, and results in spurious, high S/N lines.

In general, removal of a 12th-order polynomial over a small spectral range in this way has the effect of removing noise structures and instrumental effects. This can lead to severe overestimations of the significance of spectral features as well as artificial results. To demonstrate this, a search by eye for other features over the observed spectral range of $|v| < 60$ km s^{-1} was performed and they were subsequently treated with the same procedure. The result is shown in Fig. 2. It leads to at least five other lines with an $S/N > 10$, three in absorption and two in emission. The S/N is estimated in the same way as for the feature near the phosphine transition. No plausible assignments to the rest frequencies of these features were found. It shows that the procedure followed by GRB20 is incorrect and results in a spurious, high S/N line.

4. Independent analysis

To independently assess the possible significance of a PH_3 1−0 line in the ALMA data, the disk-averaged l:c spectrum, as shown in the left-hand panel of Fig. 3, was fitted with a third-order polynomial to remove the low-frequency curvature of the spectral baseline. This polynomial is removed from the spectrum, as shown in the right-hand panel of Fig. 3, resulting in a standard deviation of 3.5×10^{-5}. The central dip, identified by GRB20 as the PH_3 1−0 line, has an S/N of ~2. Without the polynomial fitting, the S/N is ~1. In astronomy, features at such a low S/N are generally not deemed statistically significant. Furthermore, as is

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[1] Imaging was performed as in GRB20, with mask "circle[[121 pix, 96 pix],50 pix]" and the multiscale clean method (niter 1000000; cycleniter 20000).

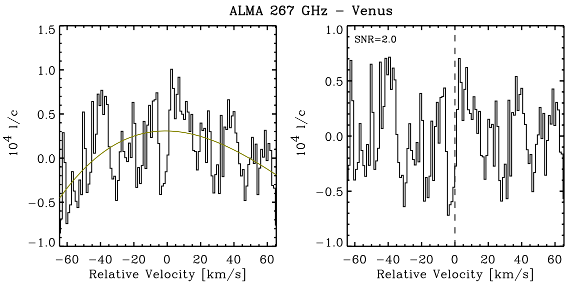

Fig. 3. Resulting spectrum from the data analysis presented in this work, before and after the removal of a third-order polynomial in the *left* and *right panel* respectively. A feature near the PH_3 1−0 transition is seen at a signal-to-noise of ~2, below the common threshold of statistical significance.

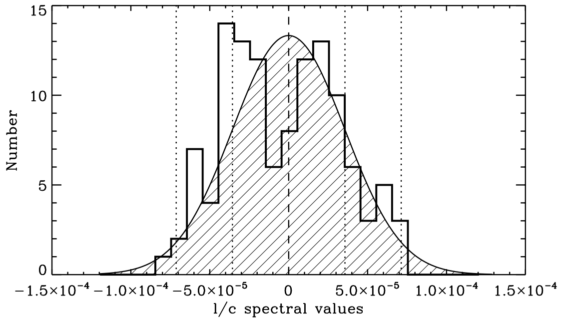

Fig. 4. Distribution of the spectral data points of the ALMA 267 GHz observations shown in Fig. 3 (histogram) with the expected Gaussian distribution for the measured standard deviation of the data overplotted. The vertical dotted lines indicate 1 and 2σ limits. The data are clearly non-Gaussian, showing a bimodal distribution that would be expected for a spectrum dominated by systematics such as instrumental ripples. This means that low S/N signals cannot be reliably linked to a false positive probability.

shown in Fig. 4, the noise distribution in these data is highly non-Gaussian, as expected for data dominated by systematic ripples. In the absence of other noise factors, systematic effects like sinusoidal and sawtooth ripples can result in extremities at 1.5−2 times the standard deviation in the data. This implies that any features at such levels have no statistical meaning because they cannot be reliably linked to a false positive probability.

As described in Sect. 2, the ALMA data were also calibrated, processed, and reduced using different selections on baseline length. The final disk-integrated l:c spectra are shown in Fig. 5 for, from top to bottom, all data and for baselines >20 m, >33 m (as used for the main analysis), and >50 m. These baseline limits correspond to the first, second, and third minima in the visibility amplitudes of the Venus disk for these observations. In this way, the influence of the adopted baseline limits on the central feature in the spectrum are also assessed. The spectra based on all data and on a >20 m cutoff show a dip near zero velocity, but at a level that is smaller than several other features in the spectra ($S/N \leq 1$). The spectrum based on a >50 m cutoff does not show a central feature. Only the spectrum based on the >33 m cutoff exhibits a dip at an S/N of ~2, implying that the chosen >33 m ALMA baseline limit has maximised any potential PH_3 signal.

The time dependence of the ALMA spectrum is also investigated by dividing the data into a first and second half. As expected, the spectra based on half of the data are noisier and provide no evidence for a high-S/N PH_3 signal. In addition, the data from Venus's disk was angularly divided into four quadrants, NE, NW, SW, and SE. These spectra are even noisier and show no candidate features for phosphine.

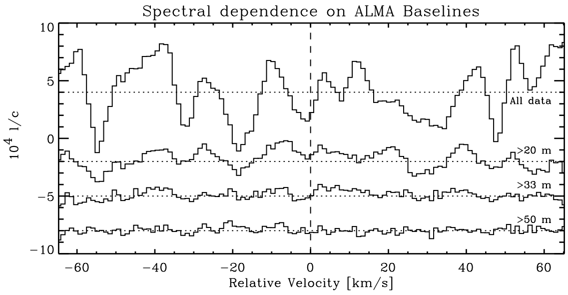

Fig. 5. Resulting spectrum for different ALMA baseline selections, vertically offset for clarity, with, *from top to bottom*: all data and >20 m, >33 m, and >50 m baselines. These limits correspond to minima in the visibility amplitudes. Only the spectrum based on the >33 m limit exhibits a central dip at an S/N of ~2, implying that this chosen limit has maximised any potential PH_3 signal.

5. Conclusions

We find that the 267 GHz ALMA observations presented by GRB20 provide no statistical evidence for phosphine in the atmosphere of Venus. The reported 15σ detection of PH_3 1−0 is caused by a high-order polynomial fit that suppresses the noise features in the surrounding spectrum. The same procedure creates a handful of other $>10\sigma$ lines without plausible spectroscopic assignments, both in emission and absorption, in the direct vicinity of the phosphine 1−0 transition. Low-order spectral baseline fitting shows a feature near the expected wavelength at a signal-to-noise of only ~2. While this already in itself is not enough to claim a statistical detection, the noise on the ALMA spectrum is highly non-Gaussian, making any link to a false positive probability unreliable.

GRB20 provide several arguments to support the validity of their identification of the PH_3 feature, including comparison to the JCMT data and a test at offset frequencies. Our analysis, however, shows that at least a handful of spurious features can be obtained using their method, and we therefore conclude that the presented analysis does not provide a solid basis to infer the presence of PH_3 in the atmosphere of Venus.

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