Recovery of Phosphine in Venus' Atmosphere from SOFIA Observations

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Key Points:

- We recover Venusian phosphine in *SOFIA* spectra by reducing contaminating signals; the PH_3 abundance is ~1 part-per billion (ppb).
- Six recoveries/limits show lower PH_3 between the clouds and mesophere, which would require an unknown re-formation process or extra source.
- Recoveries and upper limits can instead be reconciled by PH_3 photolysis, as high/low abundances correspond to Venusian mornings/evenings.

Abstract

Searches for phosphine in Venus' atmosphere have sparked a debate. Cordiner et al. 2022 analyse spectra from the Stratospheric Observatory For Infrared Astronomy (SOFIA) and infer <0.8 ppb of PH_3. We noticed that spectral artefacts arose mainly from inessential calibration-load signals. By-passing these signals allows simpler post-processing, and 6.5σ detection of 1 ppb of PH_3 at ~75 km altitude (just above the clouds). Compiling six phosphine results would suggest the abundance inverts: decreasing above the clouds but rising again in the mesosphere from some unexplained source. However, no such extra source is needed if phosphine is undergoing destruction by sunlight (photolysis), as it does on Earth. Low values/limits were found where the viewed part of the super-rotating Venusian atmosphere had passed through sunlight, while the high values are from views moving into sunlight. We suggest Venusian phosphine is indeed present, and so merits further work on models of its origins.

Plain Language Summary

Cordiner et al. find no phosphine in Venus' atmosphere, using the airborne SOFIA telescope. By-passing some instrumental effects, we extract a detection with 6.5σ-confidence from the same data. We can resolve the tension between detections and deep lower- limits by noticing that the former are from 'mornings' in Venus' atmosphere and the latter from 'evenings'. Sunlight destroys phosphine in Earth's atmosphere, so similarly on Venus, we might expect lower abundances in data taken when the part of the atmosphere observed has passed through sunlight. If the six available datasets can be reconciled in this way, further modelling of possible sources of PH_3 (e.g. volcanic, disequilbrium chemistry, extant life) seems worthwhile.

1 Introduction

Phosphine, if present in Venus' atmosphere, would be unexpected on an oxidised planet. Greaves et al. (2021) searched for PH_3 absorption at 1 mm wavelength, testing the concept that this molecule may be a biosignature when seen in anoxic environments. The unexpected detection-candidates from *JCMT* and *ALMA* have stimulated much community work on robust spectral processing, and on other methods to detect PH_3 at Venus, mostly proving negative except for an in-situ mass-spectrometry recovery (Mogul, Limaye, Way, et al., 2021). Particularly deep (above-cloud) limits have been set by infrared spectroscopy (Encrenaz et al., 2020; Trompet et al., 2021).

Cordiner et al. (2022), hereafter C22, present null results in a search for PH_3 using the *GREAT* instrument on *SOFIA*. Their observations are of the rotational transitions J=4-3 and 2-1 (around 1 and 0.5 THz), uniquely accessible to this airborne telescope, and complementary to the J=1-0 data (0.27 THz) from JCMT and ALMA. They derive from the J=4-3 data a planet-averaged upper limit of 0.8 ppb of PH_3 over altitudes of 75-110 km, with a 1.5σ hint of PH_3 at ~2.3 ppb in the J=2-1 data. These values are difficult to reconcile with ~20 ppb levels from the J=1-0 data, without invoking strong temporal-variations or steep gradients over the slightly different altitudes these lines trace.

2 Materials and Methods

C22 note the existence in the *GREAT* spectra of quasi-periodic fringe patterns, due to standing waves between optical elements and frequency-dependent gain factors used in calibration. Their calibration to antenna temperatures T_A follows the standard method of dividing the power difference of on- and off-Venus spectra by the power difference of hot and cold calibration-load signals, and then multiplying by the temperature difference of the hot and cold loads. We noticed that much of the fringing is introduced because the standing waves differ when observing the sky and the calibration loads. However, calibration to T_A is not essential in measuring the line-to-continuum ratios, *l/c*, from which abundances derive. In the case of the PH_3 J=4-3 line components (seen by the "4G2 pixel"), an alternative is

$$l/c = (On - Off^*)/(On - Off) \qquad [1]$$

where *On* and *Off* are the spectra on Venus and on adjacent blank sky, and *Off** is a scaled-up version of *Off* – it represents what *GREAT* would see for a line-less patch of sky with the brightness of Venus. *On – Off** was generated by modifying *Off* by a scaling-number and adjusting this value until residuals in the difference were minimised. Smooth fits to *On* and *Off* were used in the denominator to further minimise noise. This method worked well for PH_3 J=4-3, but failed for the PH_3 J=2-1 line-pair ("4G1 pixel") because ripples differed between *On* and *Off*.

Remaining lower-level ripples in the J=4-3 spectra could then be removed by a one-stage Fourier process, rather than the iterative Lomb-Scargle periodogram used by C22, or traditional polynomial fitting (less useful for spectra with many ripples). Here, a forwards Fourier transform identifies peaks in period-space; a 3-sigma cut was applied; and features above this cut were inverse-Fourier-transformed to create a model for a family of spectral sinusoids. Subtracting these models yielded six flatter spectra, from three *SOFIA* flights. In final steps: shifts of ~35 MHz were applied to align one PH_3- component at Venus' velocity (correcting from LSR velocity-frame in data-headers to topocentric-frame, and then for Venus-Earth motion); the six spectra were co-added using 1/noise^2 weighting factors (0.3-1); and the sections covering four J=4-3 components (of equal intrinsic strength within ~15%) were aligned and averaged to improve signal-to-noise.

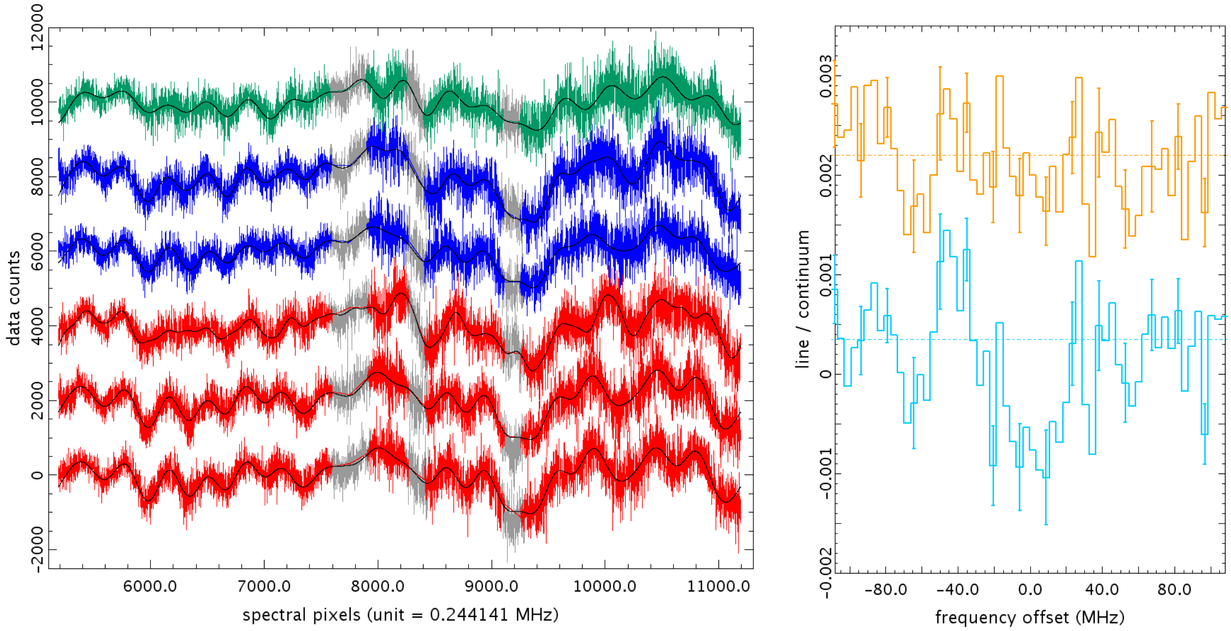
The script used to make our final PH_3 J=4-3 spectrum is provided as Supplementary Text 1. The script can be adapted for robustness checking, and we show one example of identical processing run over spectral channel numbers that are lower by 2000, as a "fake line" test. Further tests could also explore how the Fourier transform 'bridges' over regions where lines are expected – this bridging was necessary to prevent spectral features being fitted as part of the fringing pattern (also noted by C22). We bridged with a linear interpolation, and maximised widths of the line-sections while still maintaining separation of the closest line-pair.

3 Results

Figure 1 shows the six *SOFIA/GREAT* observations after the Eq. [1] step and with the Fourier-based model baseline superposed; also shown is the final spectrum of PH_3 J=4-3 after averaging the 6 observations and then the 4 line-components. A phosphine absorption feature is present, and it has no counterpart in the "fake line" test. There are a few residuals, e.g. the small positive feature at -40 MHz, and some narrow spikes that may result from our Fourier implementation; all of these have low significance.

Figure 1. The process of extracting the PH_3 J=4-3 detection from the SOFIA/GREAT data is illustrated. Left panel, the 6 SOFIA/GREAT spectra (histograms), processed as described in the text. Colours distinguish spectra from different SOFIA flights, with straight-line segments showing the interpolated sections where PH_3 J=4-3 line-components lie, original data are shown in grey. The overlaid black curves are the Fourier-derived models for the spectral baselines.

Right panel, the result from averaging the baseline-subtracted spectra and then the line-components sections (light blue histogram, shown with representative 1σ error bars). The upper (orange) spectrum in the right panel shows the null result of the blind test described in the text.



This candidate detection of PH_3 J=4-3 has 6.5σ confidence, when integrated over a span of ±20 MHz. The centroid of the feature is within -0.3 ±0.9 km/s of Venus' velocity, strongly suggesting that this is a real Venus-associated feature, not a processing artefact. The line-depth in *l/c* is ≈-0.001, which in the models of C22 corresponds to ~1 ppb of PH_3. Thus our result does not markedly conflict from the upper limit of 0.8 ppb obtained by C22 for the J=4-3 transition, but benefits from data processing that bypasses some of the fringing problems.

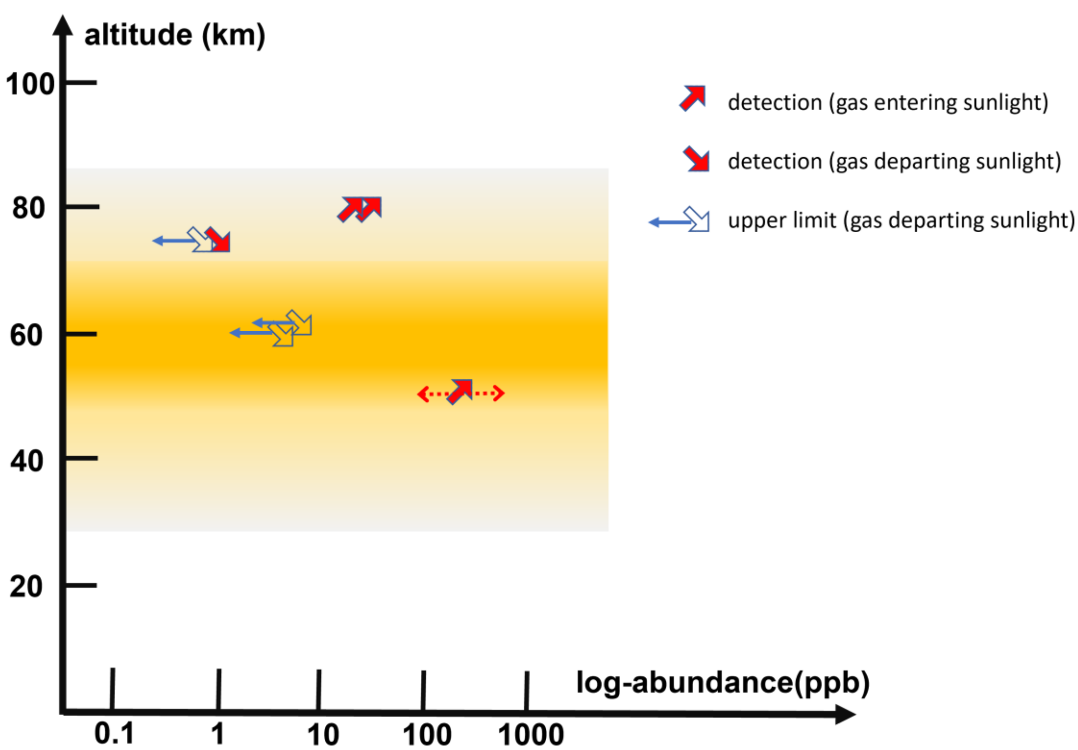
The J=4-3 line (Figure 1) spans a pressure-broadened width ~50 MHz, which in the model of C22 (their Figure 4) corresponds to an altitude ~75 km. The 6-8σ features found for PH_3 J=1-0 (Greaves et al., 2022) spanned only ~15 MHz, consistent with the finding of C22 (their Figure S4) that ~80 km is the best-sampled altitude for this line-frequency (and predicted short lifetime of PH_3 above ~80 km, (Bains, Petkowski, Seager, et al., 2021)). These altitudes are uncertain because the pressure-broadening coefficient has not been experimentally verified. We also note that all these observations are limited by the spectral span that can be recovered. Here, any absorption wider than ~200 MHz leads to blended PH_3 J=4-3 components, which we do not recover, and so we lose any phosphine signatures below ~70 km (roughly the cloud-top level).

4 Discussion

Debates continue about the best methods to acquire and process deep GHz/THz spectra of Venus. These observations are very challenging in dynamic range, as Venus is so bright, revealing "ripples" in spectral baselines that are not evident in more typical telescope usage. Depending on preferred approaches, different authors argue for between zero and three detections (so far) of rotational transitions of PH_3.

We can compare results from the data discussed here with the outcomes of other searches for phosphine at Venus, and assess whether this results in a plausible altitude profile of the molecule (Figure 2). The trend found by connecting the results from six searches for phosphine appears as an upwards decline that then reverses, i.e. PH_3 is depleted somewhere between ~50 km and ~80 km. This is hard to explain in the absence of a chemical route to reform the molecules, or a new mesospheric source. The contrast between the claimed detections (>10 ppb) and the upper limits (<1-10 ppb) has led to doubts over the presence of phosphine. Howevcr, we noticed that this divide is also between observations made when the ‘morning’ versus the ‘evening’ sides of Venus’ atmosphere were targeted – and this is relevant in gas-mixing processes (e.g. (Lefèvre et al., 2022)). The deep limits (and our ~1 ppb recovery) are all for observations where the gas observed on Venus has travelled through sunlight and is descending towards the night-side of the planet. The detections above 10 ppb are all for gas that is rising into the sun. Hence photolysis – similar to the observed destruction of terrestrial phosphine by sunlight (Sousa-Silva et al., 2020) – could explain the split between high and low phosphine abundances on Venus.

Figure 2. The trend of phosphine abundances by altitude is sketched. Shading indicates cloud (orange) and haze (grey) layers of Venus’ atmosphere. Superposed symbols indicate candidate detections plus best upper limits for phosphine abundances. Rising arrows indicate observations made where the super-rotating atmosphere was rising into sunlight and falling arrows indicate observations made where the atmosphere was descending towards the nightside (see key). Abundances are, from top: ~20, 25 ppb from J=1-0 data (via Greaves et al., 2022) *and following the contribution-plots in C22); 1 ppb / < 0.8 ppb from J=4-3 data (this work, C22); < 7 ppb at 62 km from 4 µm spectra (*(Trompet et al., 2021) – *low-latitude data, corresponding best to whole-planet points); < 5ppb at 60 km from 10 µm spectra* (Encrenaz et al., 2020)*; mid-to-high ppb at 51 km from Pioneer-Venus in-situ sampling* (Mogul, Limaye, Way, et al., 2021).



5 Conclusions

The question regarding phosphine in Venus' atmosphere is likely to be debated for some time. A further JCMT survey[1] is ongoing, producing open-source data that should yield more definitive answers. The most direct answer could come from new in-situ sampling, potentially with an instrument on-board the *DAVINCI* descent probe.

The origins of any phosphine present are also debated, and most scenarios are hard to test for lack of some contextual data. For example, it seems only extreme volcanic activity could make ~ppb-level phosphine (Bains et al., 2022) but vulcanism on Venus is not well understood. In some new avenues, (Ferus et al., 2022) discuss abiotic routes to phosphine involving redox disequlibrium, while others (Bains, Petkowski, Rimmer, et al., 2021; Mogul, Limaye, Lee, et al., 2021) explore phototrophic life, with conditions inside Venusian aerosols potentially within bounds for water activity and acidity. We conclude that establishing an improved PH_3 altitude-profile is worthwhile to test these new models of origins.

Acknowledgments

This work is based in part on observations made with the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA). SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NNA17BF53C, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 2002 to the University of Stuttgart. We gratefully acknowledge staff at the SOFIA Science Center for their advice and assistance with the Level 1 data, GREAT staff for discussion of the instrumental issues, and the team led by M. Cordiner for their acquisition of the data.

Open Research

The SOFIA Level 1 data are available under the project id 75_0059_1 through the public data archive at https://irsa.ipac.caltech.edu/applications/sofia. The custom software to generate the data shown in here in the figures is supplied as Supplementary Text 1. The script requires the UK-Starlink software environment, via https://starlink.eao.hawaii.edu/starlink/2021ADownload. The Starlink software (Currie et al., 2014) is currently supported by the East Asian Observatory.

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[1] https://www.eaobservatory.org/jcmt/science/large-programs/jcmt-venus-monitoring-phosphine-and-other-molecules-in-venuss-atmosphere/

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