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Citation for published version (APA):

Greaves, J. S., Petkowski, J. J., Richards, A. M. S., Sousa-Silva, C., Seager, S., & Clements, D. L. (2022). *Recovery of Phosphine in Venus' Atmosphere from SOFIA Observations*.

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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 PH₃ abundance is ~1 part-per billion (ppb).
- Six recoveries/limits show lower PH₃ between the clouds and mesosphere, which would require an unknown re-formation process or extra source.
- Recoveries and upper limits can instead be reconciled by PH₃ 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 PH₃. We noticed that spectral artefacts arose mainly from inessential calibration-load signals. By-passing these signals allows simpler post-processing, and 6.5 σ detection of 1 ppb of PH₃ 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 6.5 σ -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 PH₃ (e.g. volcanic, disequilibrium 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 PH₃ 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 PH₃ 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 PH₃ 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 PH₃ over altitudes of 75-110 km, with a 1.5 σ hint of PH₃ 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

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

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 .

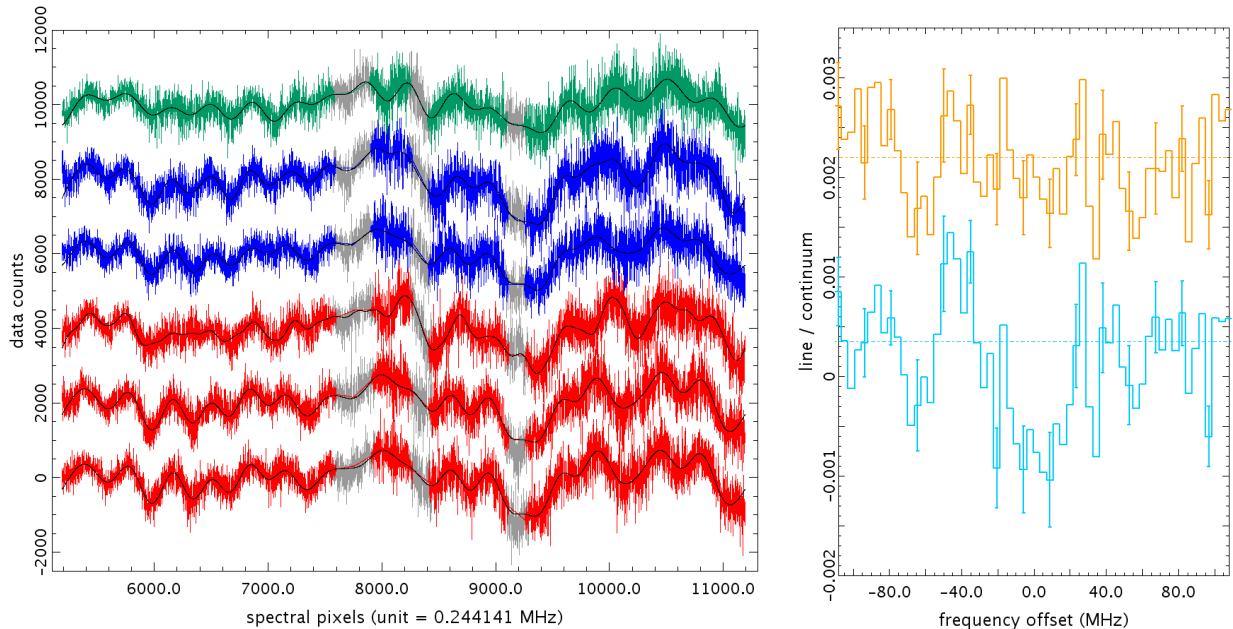
Remaining lower-level ripples in the J=4-3 spectra could then be removed by a one-stage Fourier process, rather than the iterative Lomb-Scargle periodogram used by C22, or traditional polynomial fitting (less useful for spectra with many ripples). Here, a forwards Fourier transform identifies peaks in 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 $1/\text{noise}^2$ 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 $6-8\sigma$ 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).

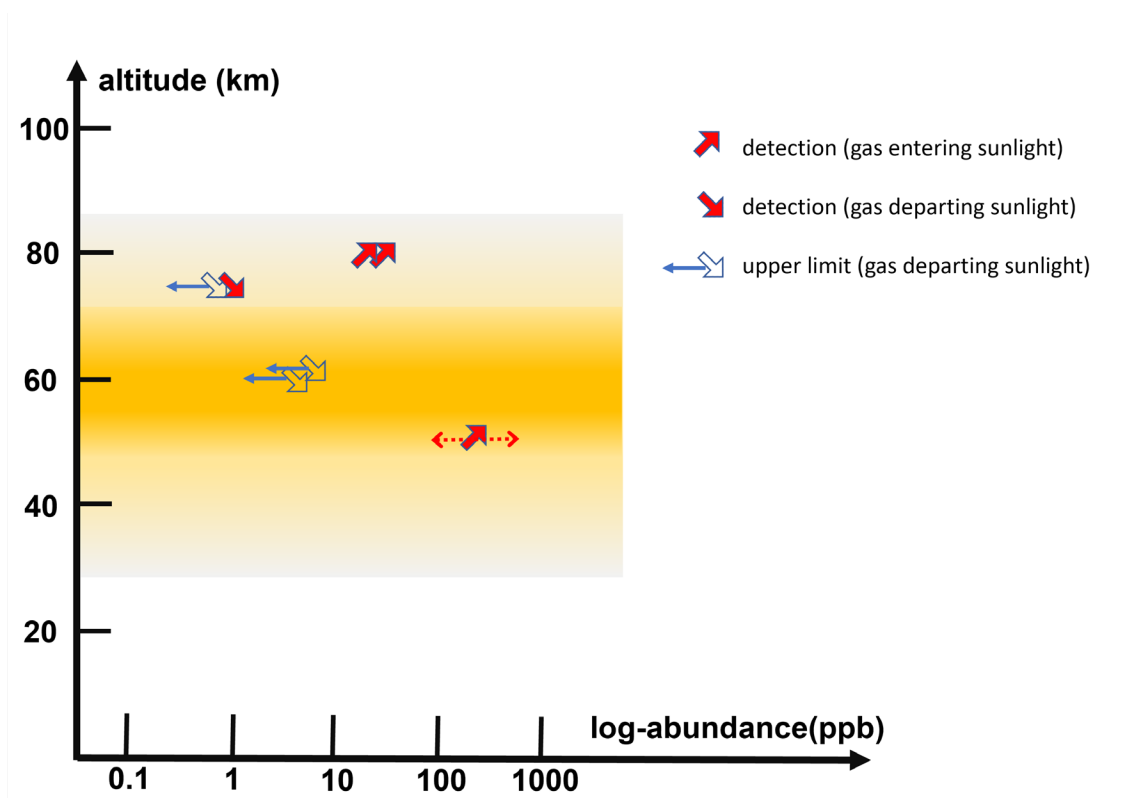
4 Discussion

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 PH₃.

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. PH₃ 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. However, 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 survey¹ 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 disequilibrium, 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.

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

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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Supporting Information for

Recovery of Phosphine in Venus' Atmosphere from SOFIA Observations

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Contents of this file

Text S1

Introduction

Text S1 contains the shell script used to process the *SOFIA/GREAT* data. Comment lines describe the methods used and include a link to download the software, which is supported by the East Asian Observatory. The script was run in a Linux environment. To run the script, copy the text into a file such as phosphine.sh and then run the command
>> source phosphine.sh.

Text S1.

```
#!/bin/bash
alias echo "echo > /dev/null"

# command set to generate stacked PH3 J=4-3 spectrum
# from SOFIA/GREAT observations of Nov 2021 - uses Level 1 data
# leading digits of observation numbers are omitted in file-naming

# Level 1 archival ON and OFF spectra were pre-processed, as follows
# for example: in /2021-11-13_GR_F791/r1/040402_..._4G2_PX00_S.fits
# there are 16 files, 8 ON and 8 OFF Venus, identifiable in the headers
# the file formats were first converted to NDF, using e.g.:
# fits2ndf 040402_001_4G2_PX00_S.fits 040402_001_4G2_PX00_S.sdf
# then to make e.g. the ON average, list the 8 filenames within in="...", in this command:
# makemos method=mean weights=! in="..." out=402-ON
# to make a cut of only the central 6000 channels, around the PH3 lines, e.g:
# ndfcopy 402-ON'(5191:11191)' out=402-ON-cut
# (channels are +0.244141 MHz and centre channel is 8191)
# then to find/subtract a smooth trend of background signals, for example:
# mfitrend fitype=poly order=4 subtract=false 402-ON-cut out=402-ON-base
# mfitrend fitype=poly order=4 subtract=true 402-ON-cut out=402-ON-resid
# necessary output files: 402-ON-cut, 402-ON-base, 402-OFF-base, 402-OFF-resid (for example)

# start packages (download at https://starlink.eao.hawaii.edu/starlink)
kappa
ccdpack

# OBS 040091

# set PH3 line regions temporarily to bad values
chpix in=91-ON-cut out=temp1 section=""7600:7740"" newval=""Bad""
chpix in=temp1 out=temp2 section=""7768:7908"" newval=""Bad""
chpix in=temp2 out=temp3 section=""8273:8413"" newval=""Bad""
chpix in=temp3 out=91blank section=""9117:9257"" newval=""Bad""

# find + show the residual of (ON - OFF x pa) where pa is scaling factor <- USER CHECK (on standard deviation)
maths exp=""ia-(pa*ib+ic)" ia=91blank ib=91-OFF-resid ic=91-ON-base out=91diff pa=1.056780 | stats 91diff | grep dev
```

```

# apply the scaling factor and make residual spectrum (ON-OFF*)
maths exp="ia-(pa*ib+ic)" ia=91-ON-cut ib=91-OFF-resid ic=91-ON-base pa=1.056780 out=91diffnoblanks

# make linear interpolations across each line component
mfittrend subtract=false order=1 ranges=""7570,7770"" in=91diff out=temp
ndfcopy temp'(7570:7770)' 91inter1
mfittrend subtract=false order=1 ranges=""7738,7938"" in=91diff out=temp
ndfcopy temp'(7738:7938)' 91inter2
mfittrend subtract=false order=1 ranges=""8243,8443"" in=91diff out=temp
ndfcopy temp'(8243:8443)' 91inter3
mfittrend subtract=false order=1 ranges=""9087,9287"" in=91diff out=temp
ndfcopy temp'(9087:9287)' 91inter4

# re-combine so the interpolated sections over-write the bad values
makemos method=median weights=! in=""91diff,91inter1,91inter2,91inter3,91inter4"" out=91interpolated

# run the Fourier transform step
# the output is a model spectral baseline
# the Hermitian is cut to retain values above/below 1000 counts <- USER CHOICE
# 1000 counts is approx. 3 sigma in the Hermitian for all the observations
# the cut is implemented with thresholds 0.001 in (1/spectrum)
# new values in (1/spectrum) are arbitrary high values (-> ~zero in spectrum)
fourier in=91interpolated hermout=91herm
maths exp=1/ia ia=91herm out=inv
thresh inv out=thr thrlo=-1e-3 newlo=-1e8 thrhi=1e-3 newhi=1e8
maths exp="1/ia" ia=thr out=inv2
fourier inverse=true hermin=inv2 out=91mod

# subtract the model baseline
# then make the line/continuum spectrum
sub 91diffnoblanks 91mod out=91-adjFT-4G2
maths exp="ia/(ib-ic)" ia=91-adjFT-4G2 ib=91-ON-base ic=91-OFF-base out=91div

# OBS 040093

# all the same steps are repeated
chpix in=93-ON-cut out=temp1 section=""7600:7740"" newval=""Bad""
chpix in=temp1 out=temp2 section=""7768:7908"" newval=""Bad""
chpix in=temp2 out=temp3 section=""8273:8413"" newval=""Bad""
chpix in=temp3 out=93blank section=""9117:9257"" newval=""Bad""

# find + show the residual of (ON - OFF x pa) where pa is scaling factor <- USER CHECK
maths exp="ia-(pa*ib+ic)" ia=93blank ib=93-OFF-resid ic=93-ON-base out=93diff pa=1.056202 | stats 93diff | grep dev

maths exp="ia-(pa*ib+ic)" ia=93-ON-cut ib=93-OFF-resid ic=93-ON-base pa=1.056202 out=93diffnoblanks

mfittrend subtract=false order=1 ranges=""7570,7770"" in=93diff out=temp
ndfcopy temp'(7570:7770)' 93inter1
mfittrend subtract=false order=1 ranges=""7738,7938"" in=93diff out=temp
ndfcopy temp'(7738:7938)' 93inter2
mfittrend subtract=false order=1 ranges=""8243,8443"" in=93diff out=temp
ndfcopy temp'(8243:8443)' 93inter3
mfittrend subtract=false order=1 ranges=""9087,9287"" in=93diff out=temp
ndfcopy temp'(9087:9287)' 93inter4

makemos method=median weights=! in=""93diff,93inter1,93inter2,93inter3,93inter4"" out=93interpolated

fourier in=93interpolated hermout=93herm
maths exp=1/ia ia=93herm out=inv

```

```

thresh inv out=thr thrlo=-1e-3 newlo=-1e8 thrhi=1e-3 newhi=1e8
maths exp="1/ia" ia=thr out=inv2
fourier inverse=true hermin=inv2 out=93mod

sub 93diffnoblanks 93mod out=93-adjFT-4G2
maths exp="ia/(ib-ic)" ia=93-adjFT-4G2 ib=93-ON-base ic=93-OFF-base out=93div

# OBS 040095

# all the same steps are repeated
chpix in=95-ON-cut out=temp1 section=""7600:7740"" newval=""Bad""
chpix in=temp1 out=temp2 section=""7768:7908"" newval=""Bad""
chpix in=temp2 out=temp3 section=""8273:8413"" newval=""Bad""
chpix in=temp3 out=95blank section=""9117:9257"" newval=""Bad""

# find + show the residual of (ON - OFF x pa) where pa is scaling factor <- USER CHECK
maths exp="ia-(pa*ib+ic)" ia=95blank ib=95-OFF-resid ic=95-ON-base out=95diff pa=1.055950 | stats 95diff | grep dev

maths exp="ia-(pa*ib+ic)" ia=95-ON-cut ib=95-OFF-resid ic=95-ON-base pa=1.055950 out=95diffnoblanks

mfittrend subtract=false order=1 ranges=""7570,7770"" in=95diff out=temp
ndfcopy temp'(7570:7770)' 95inter1
mfittrend subtract=false order=1 ranges=""7738,7938"" in=95diff out=temp
ndfcopy temp'(7738:7938)' 95inter2
mfittrend subtract=false order=1 ranges=""8243,8443"" in=95diff out=temp
ndfcopy temp'(8243:8443)' 95inter3
mfittrend subtract=false order=1 ranges=""9087,9287"" in=95diff out=temp
ndfcopy temp'(9087:9287)' 95inter4

makemos method=median weights=! in=""95diff,95inter1,95inter2,95inter3,95inter4"" out=95interpolated

fourier in=95interpolated hermout=95herm
maths exp=1/ia ia=95herm out=inv
thresh inv out=thr thrlo=-1e-3 newlo=-1e8 thrhi=1e-3 newhi=1e8
maths exp="1/ia" ia=thr out=inv2
fourier inverse=true hermin=inv2 out=95mod

sub 95diffnoblanks 95mod out=95-adjFT-4G2
maths exp="ia/(ib-ic)" ia=95-adjFT-4G2 ib=95-ON-base ic=95-OFF-base out=95div

# OBS 040220

# all the same steps are repeated
chpix in=220-ON-cut out=temp1 section=""7595:7735"" newval=""Bad""
chpix in=temp1 out=temp2 section=""7763:7903"" newval=""Bad""
chpix in=temp2 out=temp3 section=""8268:8408"" newval=""Bad""
chpix in=temp3 out=220blank section=""9112:9252"" newval=""Bad""

# find + show the residual of (ON - OFF x pa) where pa is scaling factor <- USER CHECK
maths exp="ia-(pa*ib+ic)" ia=220blank ib=220-OFF-resid ic=220-ON-base out=220diff pa=1.043051 | stats 220diff | grep dev

maths exp="ia-(pa*ib+ic)" ia=220-ON-cut ib=220-OFF-resid ic=220-ON-base pa=1.043051 out=220diffnoblanks

mfittrend subtract=false order=1 ranges=""7565,7765"" in=220diff out=temp
ndfcopy temp'(7565:7765)' 220inter1
mfittrend subtract=false order=1 ranges=""7733,7933"" in=220diff out=temp
ndfcopy temp'(7733:7933)' 220inter2
mfittrend subtract=false order=1 ranges=""8238,8438"" in=220diff out=temp
ndfcopy temp'(8238:8438)' 220inter3

```

```

mfittrend subtract=false order=1 ranges=""9082,9282"" in=220diff out=temp
ndfcopy temp'(9082:9282)' 220inter4

makemos method=median weights=! in=""220diff,220inter1,220inter2,220inter3,220inter4"" out=220interpolated

fourier in=220interpolated hermout=220herm
maths exp=1/ia ia=220herm out=inv
thresh inv out=thr thrlo=-1e-3 newlo=-1e8 thrhi=1e-3 newhi=1e8
maths exp=""1/ia"" ia=thr out=inv2
fourier inverse=true hermin=inv2 out=220mod

sub 220diffnoblanks 220mod out=220-adjFT-4G2
maths exp=""ia/(ib-ic)"" ia=220-adjFT-4G2 ib=220-ON-base ic=220-OFF-base out=220div

# OBS 040235

# all the same steps are repeated
chpix in=235-ON-cut out=temp1 section=""7595:7735"" newval=""Bad""
chpix in=temp1 out=temp2 section=""7763:7903"" newval=""Bad""
chpix in=temp2 out=temp3 section=""8268:8408"" newval=""Bad""
chpix in=temp3 out=235blank section=""9112:9252"" newval=""Bad""

# find + show the residual of (ON - OFF x pa) where pa is scaling factor <- USER CHECK
maths exp=""ia-(pa*ib+ic)"" ia=235blank ib=235-OFF-resid ic=235-ON-base out=235diff pa=1.049978 | stats 235diff | grep dev

maths exp=""ia-(pa*ib+ic)"" ia=235-ON-cut ib=235-OFF-resid ic=235-ON-base pa=1.049978 out=235diffnoblanks

mfittrend subtract=false order=1 ranges=""7565,7765"" in=235diff out=temp
ndfcopy temp'(7565:7765)' 235inter1
mfittrend subtract=false order=1 ranges=""7733,7933"" in=235diff out=temp
ndfcopy temp'(7733:7933)' 235inter2
mfittrend subtract=false order=1 ranges=""8238,8438"" in=235diff out=temp
ndfcopy temp'(8238:8438)' 235inter3
mfittrend subtract=false order=1 ranges=""9082,9282"" in=235diff out=temp
ndfcopy temp'(9082:9282)' 235inter4

makemos method=median weights=! in=""235diff,235inter1,235inter2,235inter3,235inter4"" out=235interpolated

fourier in=235interpolated hermout=235herm
maths exp=1/ia ia=235herm out=inv
thresh inv out=thr thrlo=-1e-3 newlo=-1e8 thrhi=1e-3 newhi=1e8
maths exp=""1/ia"" ia=thr out=inv2
fourier inverse=true hermin=inv2 out=235mod

sub 235diffnoblanks 235mod out=235-adjFT-4G2
maths exp=""ia/(ib-ic)"" ia=235-adjFT-4G2 ib=235-ON-base ic=235-OFF-base out=235div

# OBS 040402

# all the same steps are repeated
chpix in=402-ON-cut out=temp1 section=""7584:7724"" newval=""Bad""
chpix in=temp1 out=temp2 section=""7752:7892"" newval=""Bad""
chpix in=temp2 out=temp3 section=""8257:8397"" newval=""Bad""
chpix in=temp3 out=402blank section=""9101:9241"" newval=""Bad""

# find + show the residual of (ON - OFF x pa) where pa is scaling factor <- USER CHECK
maths exp=""ia-(pa*ib+ic)"" ia=402blank ib=402-OFF-resid ic=402-ON-base out=402diff pa=1.031155 | stats 402diff | grep dev

```

```
maths exp="ia-(pa*ib+ic)" ia=402-ON-cut ib=402-OFF-resid ic=402-ON-base pa=1.031155 out=402diffnoblanks
```

```
mfittrend subtract=false order=1 ranges=""7554,7754"" in=402diff out=temp  
ndfcopy temp'(7554:7754)' 402inter1  
mfittrend subtract=false order=1 ranges=""7722,7922"" in=402diff out=temp  
ndfcopy temp'(7722:7922)' 402inter2  
mfittrend subtract=false order=1 ranges=""8227,8427"" in=402diff out=temp  
ndfcopy temp'(8227:8427)' 402inter3  
mfittrend subtract=false order=1 ranges=""9071,9271"" in=402diff out=temp  
ndfcopy temp'(9071:9271)' 402inter4
```

```
makemos method=median weights=! in=""402diff,402inter1,402inter2,402inter3,402inter4"" out=402interpolated
```

```
fourier in=402interpolated hermout=402herm  
maths exp=1/ia ia=402herm out=inv  
thresh inv out=thr thrlo=-1e-3 newlo=-1e8 thrhi=1e-3 newhi=1e8  
maths exp="1/ia" ia=thr out=inv2  
fourier inverse=true hermin=inv2 out=402mod
```

```
sub 402diffnoblanks 402mod out=402-adjFT-4G2  
maths exp="ia/(ib-ic)" ia=402-adjFT-4G2 ib=402-ON-base ic=402-OFF-base out=402div
```

```
# now slide the spectra in channel number to correct to Venus velocity frame  
# original frame set was LSR and velocities were given by VFRAME  
# use settings from Level 1 headers, noting VFRAME + LSR did not put PH3 at band-centre
```

```
# use if prior runs gave similar names for outputs  
rm slid*
```

```
# slide files with per-flight corrections  
slide in=91div out=slid91 abs=-8343  
slide in=93div out=slid93 abs=-8343  
slide in=95div out=slid95 abs=-8343  
slide in=220div out=slid220 abs=-8338  
slide in=235div out=slid235 abs=-8338  
slide in=402div out=slid402 abs=-8327
```

```
# co-add the spectra using weights derived from their standard deviations  
# unresolved command-line syntax problem <- INPUT WEIGHTS INTERACTIVELY  
# file order (numerical) is 220, 235, 402, 91, 93, 95  
# respective inputs for weights: 0.6 (value already within the command) then input 0.6, 0.3, 1, 1, 1  
makemos weights=0.6 method=mean usevar=false genvar=true in="slid*" out=aligned
```

```
# alternative command to co-add with equal weights  
# makemos weights=! method=mean usevar=false genvar=true in="slid*" out=aligned
```

```
# make a smaller section (for visual inspection)  
ndfcopy in=aligned'(-3052:2764)' out=aligned-trunc
```

```
# copy the sections with the 4 (resolved) PH3 components to new files  
# the file names refer to frequency offset from the 1067.00003 GHz component  
ndfcopy aligned-trunc'(-1123:-223)' out=Comp-164  
ndfcopy aligned-trunc'(-955:-55)' out=Comp-123  
ndfcopy aligned-trunc'(-450:450)' out=Comp0  
ndfcopy aligned-trunc'(394:1294)' out=Comp+206
```

```
# slide the 4 components to align in Venus-frame centred on 1067.00003 GHz component
slide Comp-164 out=Comp-164-onzero abs=673
slide Comp-123 out=Comp-123-onzero abs=505
slide Comp0 out=Comp-0-onzero abs=0
slide Comp+206 out=Comp+206-onzero abs=-844
```

```
# in the first two sections, set to bad the duplicates of the nearby adjacent component
# for the other sections, just blank one channel, to maintain filename uniformity
chpix in=Comp-164-onzero out=Comp-164-onzero-chpix section=""68:268"" newval=""Bad""
chpix in=Comp-123-onzero out=Comp-123-onzero-chpix section=""-268:-68"" newval=""Bad""
chpix in=Comp-0-onzero out=Comp-0-onzero-chpix section=""-500:-499"" newval=""Bad""
chpix in=Comp+206-onzero out=Comp+206-onzero-chpix section=""499:500"" newval=""Bad""
```

```
# co-add the 4 components + write to output file <- USER CHOICE
makemos weights=! method=mean usevar=false genvar=true in=""*onzero-chpix.sdf"
```