An experiment to investigate Venus's deep atmosphere

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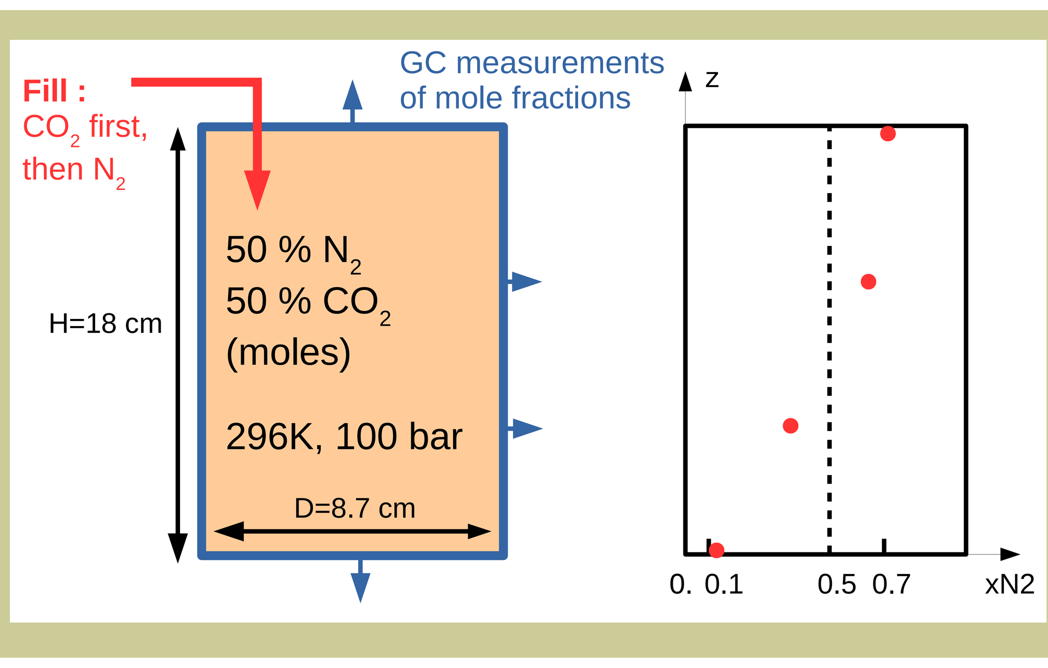
Sébastien Lebonnois (LMD/IPSL, CNRS, France), **Gérald Schubert** (UCLA, USA), **Josette Bellan** (JPL, USA), **Tibor Kremic, Leah Nakley, Kyle Phillips** (NASA GRC, USA), **Thomas Navarro** (UCLA, USA)

Context The characteristics of the Venus atmosphere closest to the ground are still unknown to a large degree. The only reliable temperature profile measured below 12 km altitude was obtained in 1985 by the VeGa-2 lander [1,2]. This profile, obtained during the ~1h descent, is highly unstable in the lowest 7 km. This would imply that the near-constant vertical gradient is steeper than the adiabat – a characteristic that may be explained by a variation of the abundance of nitrogen from 3.5% at 7 km altitude to 0 at the surface [3] (see Fig.1).

Motivation The physics of the composition gradient is difficult to understand in the absence of more information. However, considering the observations in a recent experiment (Hendry et al., 2013 [4], see Fig. 2), we conjectured that this gradient could result from gravity effects inducing a density-driven separation of nitrogen and carbon dioxide.

Figure 2 : The Hendry et al. (2013) experiment [4].
The experiment vessel was 18 cm tall, and was filled with CO_2 and N_2 at pressures ranging from 100 to 310 bar, at room temperature (296K). CO_2 was introduced first, then N_2, to reach a molar mix of 50%/50%. The gas was let to rest for « several hours » then the composition was measured with a Gas Chromatograph at four different locations in the vessel (top, bottom, and two intermediate points).
At 296K, 100 bar, the composition was reported to be stable, with 70% N_2 at the top and 90% CO_2 at the bottom.
The authors claim that this gradient is stable and due to a density-driven separation of the two gases.



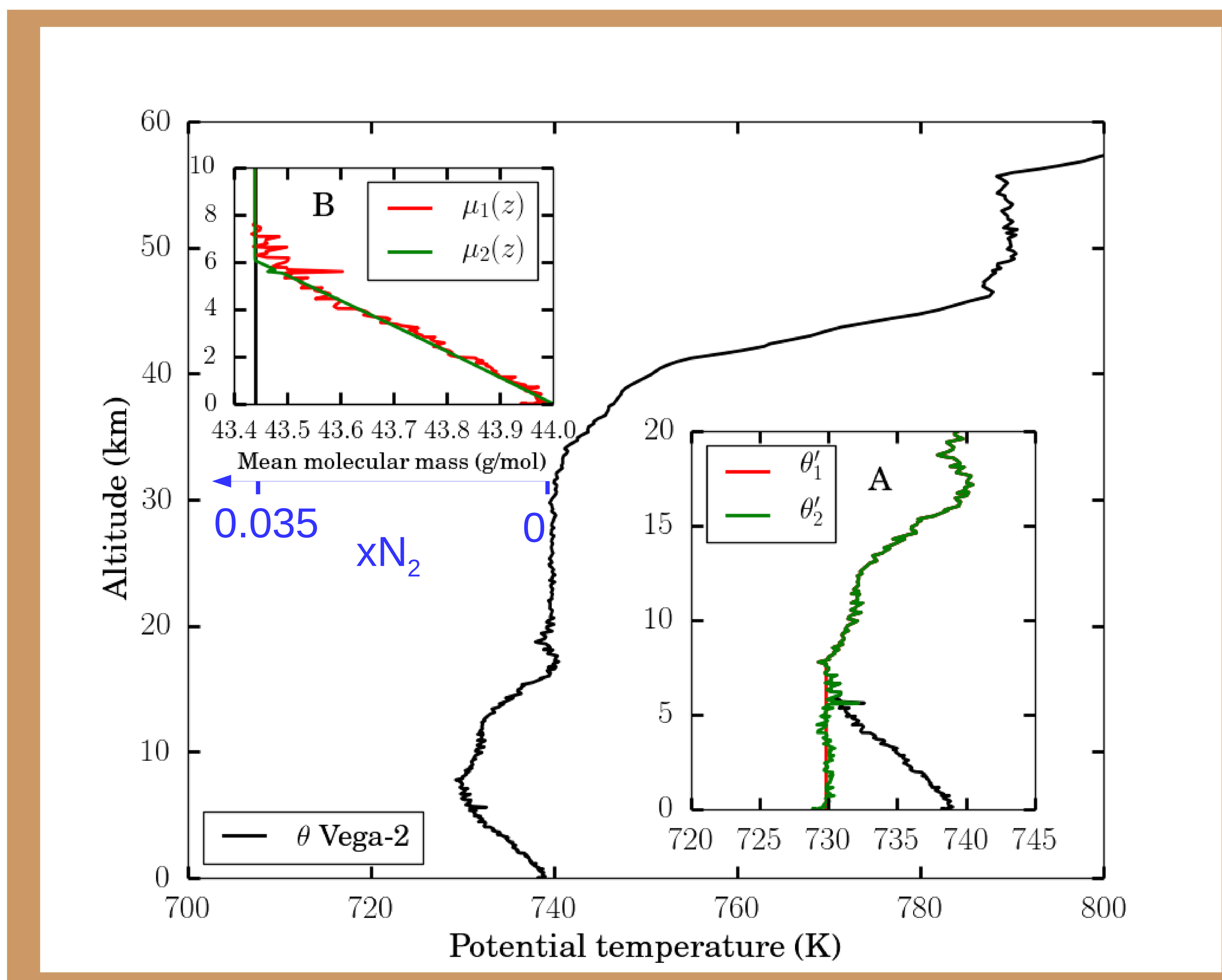


Figure 1 : The potential temperature profile measured by the VeGa-2 probe is highly unstable in the lowest 7 kilometers (black). A neutral profile can be obtained (A, red/green) if the mean molecular mass varies with height (B, red/green). This corresponds to a vertical gradient in the mole fraction of N_2 [3].

GEER experiment To investigate the behavior of the CO_2-N_2 mixture under conditions ranging from the Hendry et al. (2013) experiment [4] to the near-surface atmosphere of Venus, we designed an experiment that was conducted at the Glenn Extreme Environment Rig (GEER) [5], at NASA Glenn Research Center in Cleveland in August 2018 (Figs. 3 and 4).
This experiment was funded by the NASA Solar System Workings Program.

Figure 3 : The GEER chamber [5].
(top) Front end, with the three sampling lines.
(bottom) Inside, with the thermal heaters and the test vessel for our experiment.

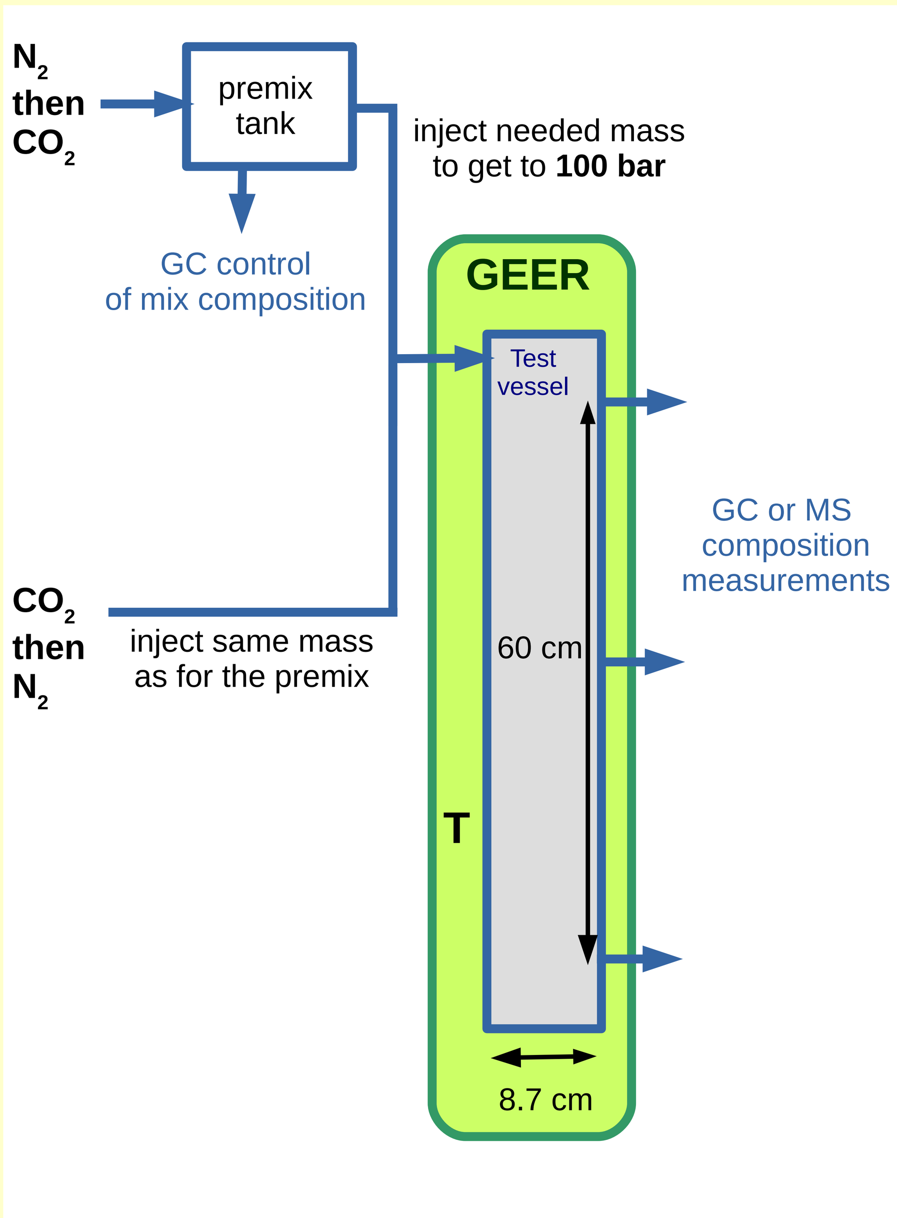


Figure 4 : Experiment set-up.

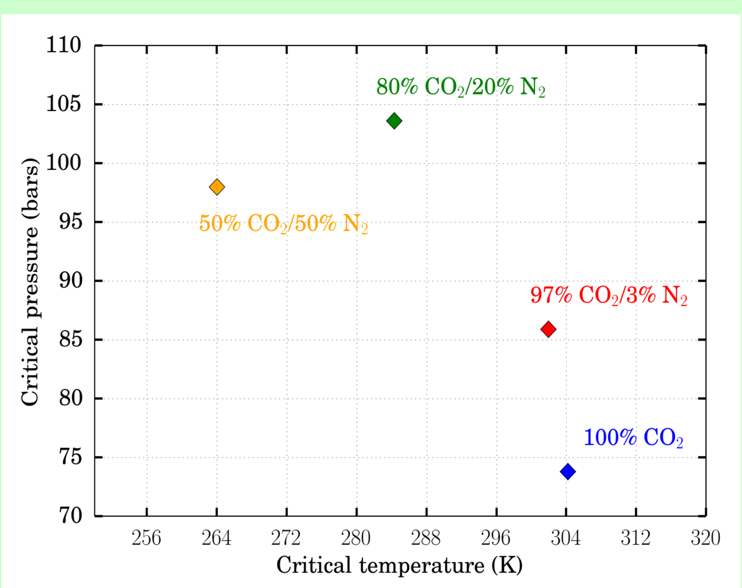


Figure 5: Critical points for the various mix used.

To vary the experimental conditions from the Hendry et al. (2013) experiment to Venusian conditions, the following tests were done :

P (bar)	100	100	100	100	100	100
T (K)	296	310	310	310	500	735
% CO_2	50	50	80	97	97	97
% N_2	50	50	20	3	3	3

Each experiment was done first with a well-mixed batch of gas, then, using the same masses of each gas, for a mix done by inserting first CO_2, then N_2, as was done in the Hendry et al. (2013) experiment.

Results

(1) For the well-mixed batch of gas, the composition was measured at all three ports **during roughly 15 hours** in each configuration.
The results are always the same: **the composition is identical at all three ports, and stable. No density-driven separation is observed**.

(2) To understand the Hendry et al. experiment, the same protocol was used: introducing CO_2 first, then N_2. To reproduce the same mix of gas, the same masses were used for each gas. In these cases, the first samples indicated nearly 100% CO_2 at the bottom port and nearly 100% N_2 at the top port. **The composition evolved very slowly over time at each port, with time scales of the order of 10 days.** The composition was measured over at least 24 hours, over 3 days for the first and last tests, with continous (but slow) composition variations.
This may explain the results of the Hendry et al. experiment. It was not a stable situation, but rather a slowly evolving mix.
A full analysis of the experiment results will be done in the coming months.

Pressure evolution (non-ideal behavior)
At 296K and 310K, inserting the gases one after the other results in a peculiar behavior. When filled with exactly the same mass of each component as for the well-mixed batch, the pressure after filling is not 100 bar, but significantly less (80 bar for the 50%/50% mix), and the pressure rises slowly with time. This behavior is explained by the fact that CO_2 (even with a small amount of N_2) is close to the critical point, and, therefore, the density in the bottom of the vessel is significantly greater than for an ideal gas. The non-homogeneous system has to balance nearly-pure N_2 at the top and nearly-pure CO_2 at the bottom. The resulting pressure is much less than for the well-mixed gas. As mixing occurs, the amount of N_2 in the CO_2 at the bottom of the tank increases and the density of the mix changes, resulting in a continous increase in pressure.
This behavior is not observed at the higher temperatures of the current experiment.

Diffusion timescales
In the vessel, diffusion may occur through small-scale turbulence during the initial fill, but may be dominated by molecular diffusion after resting for a while.
The molecular diffusion coefficient for the binary mix CO_2/N_2 is :
D = 0.16 cm²/s @ 1 bar, 293K => D ~ 1.6 10^{-3} cm²/s @ 100 bar, 296K
Time scale for molecular diffusion in the test vessel (L~60 cm) :
$\tau \sim L^2/D \sim 2\ 10^6$ s ~ 26 days (τ ~ 7 days @ 100 bar, 735K)

Conclusions - Perspectives

This experiment clearly showed that there is no peculiar density-driven separation in the CO_2 / N_2 mixture occuring at 100 bar. When these two gases are well-mixed, they stay well-mixed over the time scales used in this experiment. However, it also showed that when CO_2 and N_2 are stratified, it may be difficult to mix them.
How to explain the gradient in composition suggested by the VeGa-2 temperature profile in the 7-kilometer layer above the surface of Venus, then ?
Could there be unexpected sources or sinks of CO_2 and/or N_2 near the surface of Venus ? This question needs to be thoroughly investigated.
We also emphasize that additional in-situ data from the near-surface layer of the Venusian atmosphere is crucial ! We will not be able to understand the processes occuring near and at the surface of Venus without a new mission to investigate this harsh but surprising environment.

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References [1] Linkin et al., *Sov. Astron. Lett.* 12, 40-42, 1986 ; [2] Lorenz et al., *Icarus* 305, 277-283, 2018 ; [3] Lebonnois & Schubert, *Nature Geosci.* 10, 473-477, 2017 ; [4] Hendry et al., *J. of CO_2 Utilization* 3-4, 37-43, 2013 ; [5] Kremic et al., *IEEE Aerospace*, 2014 (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140013390.pdf)