Aerobots to Explore Venusian Clouds

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Introduction

- Aerobots are robotic balloon-based aerial vehicles that:
  - Use buoyancy to fly (and not aerodynamic lift)
  - Autonomously exert some control over the vehicle trajectory and/or altitude
  - Such a vehicle could extensively explore the Venusian clouds, including the habitability zone for long periods of time (weeks, months)
- An altitude-controlled only version was the preferred option identified in the 2018 NASA study of Venus aerial platforms
  - There are many different altitude-controlled aerobot concepts developed for Earth that could be adapted to work for Venus
  - But which one is “best”?
- JPL performed a study in 2019 that tried to answer this question
  - Results are summarized in this presentation
  - More details in AIAA 2019-3194

Air Ballast Balloon (Google Loon)

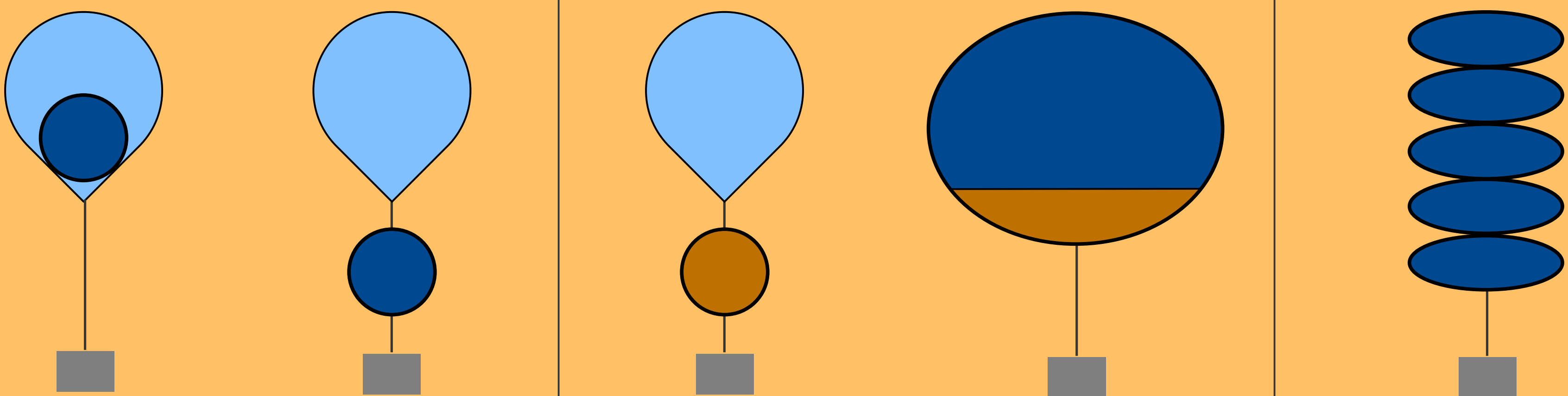
Mechanical Compression Balloon
(Thin Red Line Aerospace)

Venus Aerobot Science

- As a long duration *in situ* observation platform, a Venus cloud aerobot can address multiple key scientific mysteries:
  - Planetary origins through noble gas and isotope ratio measurements.
  - Superrotation mechanism through measurements of solar energy deposition and IR fluxes.
  - Cloud particle (aerosol) chemistry and trace gas chemistry, including issues of potential habitability (see companion paper by Kevin Baines et al.) and the search for the unknown absorber.
  - Atmospheric structure via wind tracking, pressure, and temperature measurements
- In addition to these atmospheric science objectives, a number of geophysical objectives may be achievable including
  - Detecting Venus seismic activity with infrasound measurements
  - Probing surface conductivity profiles with electromagnetic sounding
  - Searching for evidence of an early magnetic field by mapping remnant magnetism
  - Characterizing possible subduction zones with aerial gravity field measurements
- This rich science return could be further enhanced by adding one or more small drop probes (deployed from the entry vehicle or aerobot) that can obtain data from the clouds to the surface.
  - The data obtained can include atmospheric structure, gas composition and descent imaging of the surface from < 15 km altitudes.

Balloon Types Analyzed

Pumped Helium (PH)	Air Ballast (AB)	Mechanical Compression (MC)



Helium pressurized balloon **inside** of helium unpressurized balloon [1]	Helium pressurized balloon **outside** of helium unpressurized balloon	Air pressurized balloon **outside** helium unpressurized balloon [2]	Single pressurized balloon with **internal membrane** separating helium and air [3]	**Stack of connected** pressurized helium balloons [4]

Change buoyancy by pumping He between balloons	**Change weight** by pumping air into balloon	**Change volume** by squeezing

All of these balloon types use gas pressurization to actively control altitude, but with key differences:

- A large volume of pressurized gas is more altitude-stable (i.e. a sky-anchor)
- Pressurized balloon envelope material is necessarily heavier (to be stronger)
- Venus gas is corrosive, so Teflon must be added to inside of envelopes if atmosphere is also pumped to internal volumes

- Unpressurized Helium
- Pressurized Helium
- Unpressurized Atmosphere
- Pressurized Atmosphere

[1] Voss et al 2005 [2] World View 2019 [3] Loon LLC 2019 [4] de Jong 2017

Study Approach

- Assess “best vehicle” on the basis of three key metrics:
  - Mass
  - Energy consumption to change altitude
  - Achievable altitude range
- Point designs were developed for each of the five balloon types according to a common mission scenario:
  - 100 kg carried under the balloon
    - Corresponds to ~20 kg science instrument mass
  - 52 to 60 km controllable altitude range (+60°C to -10°C)
    - Lower than 52km adds a difficult thermal problem for instruments
    - Higher than 60km requires larger balloons in the thinner atmosphere
  - Design margins to tolerate solar heating and vertical winds
- Simplifying assumptions were made that enable computations to be quick, and cross-checks were made for errors and to ensure fair comparisons.
- Preparatory work on the fundamental thermodynamics of these balloons discovered simple scaling laws for the gas pressurization as a function of altitude (see AIAA 2019-3194).
  - These scaling laws were used to develop and error-check the point designs.

General Aerobot Behavior

- The aerobot will be carried by the high speed zonal winds and circumnavigate the planet every 5-6 days.
- Gas is compressed (pumped) or the balloon is squeezed (via a pole to pole tether) to make the aerobot decrease in altitude.
  - This requires energy, generally assumed to come from onboard solar cells.
  - Each amount of pumping or volume change will correspond to a new equilibrium altitude. The aerobot will move to this new altitude and stabilize.
- Decompression of gas or increasing the balloon volume will reverse the process and move the aerobot to a higher altitude.
  - This typically requires negligible energy since a valve can be opened to vent gas, or a brake released to allow unspooling of the tether.
- Design margin is required at the minimum and maximum altitudes to ensure that the balloon does not move to an unsafe altitude.
  - Too low results in excessively high temperatures
  - Too high results in excessive pressurization and possible bursting
- Practically speaking, design margin takes the form of:
  - Always have enough pressurized gas to vent to arrest downwards motion
  - Sufficiently strong balloon material to tolerate pressurization from upwards motion.

Venus Mid-Altitude Analysis (Nighttime)

Altitude effects:

- Both internal and external pressures change with altitude
- Simple relations describe the superpressure assuming inside and outside gas temperatures are equal (no solar heating).

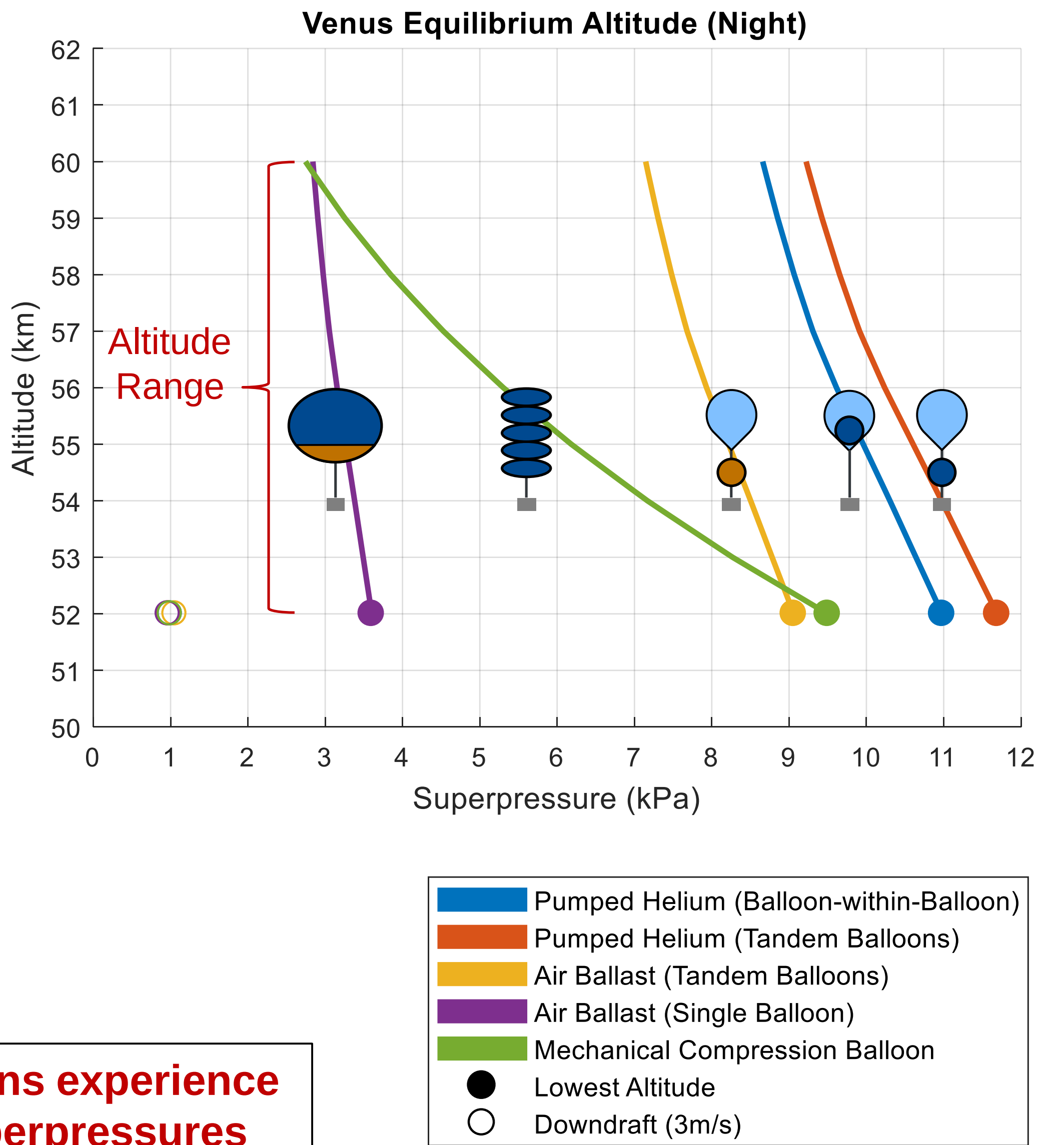
Mechanical Compression:

$$\Delta P(z) \propto P_{\mathrm{atm}}(z)$$

Pumped Helium or Air Ballast:

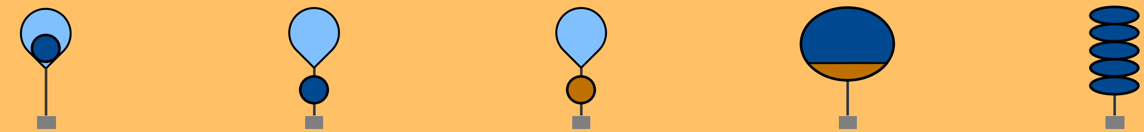
$$\Delta P(z) \propto T_{\mathrm{atm}}(z)$$

- Pressure varies more than temperature
- Constant of proportionality depends on gas volumes



Mechanical compression balloons experience a wider range of nighttime superpressures

Venus Aerobot Mass and Power Metrics



	PH (balloon in balloon)	PH (two balloon)	AB (two balloon)	AB (one balloon)	MC (one balloon)
Converged Design					
ZP balloon areal density (g/m^2)	120	120	120	120	N/A
SP balloon areal density (g/m^2)	170	270	330	285	270
Zero-P (ZP) balloon diameter	10.6	10.4	12.6	N/A	N/A
Superpressure (SP) balloon diameter	5.30	5.2	6.93	11.8	10.5
Total Envelope mass	89.5	99.4	171.0	235.4	145.9
Minimum superpressure (Pa)	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**
Total Helium mass	20.6	21.6	29.9	38.9	26.8
Performance					
Total aerobot mass (w/o helium)	**189.5**	**199.4**	**271.0**	**335.4**	**245.9**
Maximum superpressure (Pa)	**32,800**	**36,300**	**31,300**	**8,700**	**10,800**
Maximum perturbed altitude (km)	**62.0**	**62.1**	**61.8**	**60.3**	**60.3**
Daylight energy for max to min altitude (J)	**1,270,000**	**1,264,000**	**2,843,000**	**6,282,000**	**2,660,000**

Table Coloring

Lowest Value	Over 25% higher	Over 50% higher	Over 100% higher

Pumped Helium is lightest and uses least energy.
Air Ballast is the heaviest and uses the most energy.
Mechanical Compression is in the middle of mass and energy.

Venus Point Designs: 52 to 62 km

- We also looked at the case where the balloon was re-designed for a slightly expanded altitude range, 52 to 62 km (+60°C to -19°C).
  - That is, adding 2 km to the maximum altitude.
- Generally speaking, the balloons must increase in size (and mass) to accommodate the helium expansion needed for the lower pressure experienced at 62 km vs 60 km.
- We found that the two air ballast balloon concepts could not be re-designed to reach this altitude with the given assumptions.
  - The already large and massive balloons needed to just reach 60 km became so much larger and heavier that no design solution existed.
- The other concepts were feasible with modest increases in balloon mass and energy consumption.
  - The pumped helium balloons remained lighter than mechanical compression balloon and still required less energy to change altitude.

Other Observations

- We recommend pumped helium or mechanical compression balloon options because:
  - Favorable mass and energy metrics
  - They don't require ingestion of sulfuric acid aerosols into the balloon
  - Able to reach 62 km, unlike the air ballast options
- It is not yet known how much the altitude range for these balloons can be expanded beyond 52 to 62 km.
  - The temperature is ~60°C at 52 km → likely the maximum allowable with existing spacecraft avionics and science instruments without a complex cooling system.
- The carry mass can be easily scaled lower and higher than the 100 kg assumed in this study.
- The current study did not examine aerobot dynamics but generally assumed slow altitude changes (<1 m/s)
  - Such slow altitude changes align with the desire to minimize solar cell, pump and motor sizes.
- **Altitude control enables sampling of different altitudes, no longer moving with the mean flow, sample acquisition, and can sample the same altitude twice without sampling the same volume of gas (due to wind speed variability)**

Conclusions

- On the basis of this study we recommend either a pumped helium or mechanical compression balloon to serve as the basis for a long-lived Venus aerobot exploring the cloud habitability zone.
- Preliminary point designs provide approximate starting points for sizing (mass, energy, altitude).
  - These designs can be scaled as needed, but quantitative trades have not yet been done to provide other design points.
- Although Earth examples exist for these kinds of balloons, no prototypes have yet been fabricated and tested using Venus compatible materials.
  - Such prototype development would seem to be a logical next step to take to enable future mission use.
- There is a need for advanced simulation tools that can delve into the details of balloon dynamics and thermodynamics and thereby evaluate the simplifying assumptions made in the 2019 JPL study.
  - Such a tool is under development at JPL as described in AIAA 2019-3194.

Summary Table

System Concept	Achievable Sampling Altitude	Anticipated T range in Sampling Altitude	Sampling Speed	Vertical Stability (relative to Venus local time)	Anticipated wind speed in sampling altitude	Latitude stability (relative to Venus Local time)	Science Lifetime (days)	Science Payload Fraction
Pumped Helium	52-62 km at least	-20 °C to + 60 °C (for 52 to 62 km)	< 1 m/s (maybe up to 3 m/s if needed)	Probably ±1 km	< 2 m/s vehicle relative winds, 60+ m/s ground relative	No stability, will move with meridional winds	unknown, probably > 1 month	~20% of carried mass
Mechanical Compression	52-62 km at least	-20 °C to + 60 °C (for 52 to 62 km)	< 1 m/s (maybe up to 5 m/s if needed)	Probably ±1 km	< 2 m/s vehicle relative winds, 60+ m/s ground relative	No stability, will move with meridional winds	unknown, probably > 1 month	~20% of carried mass

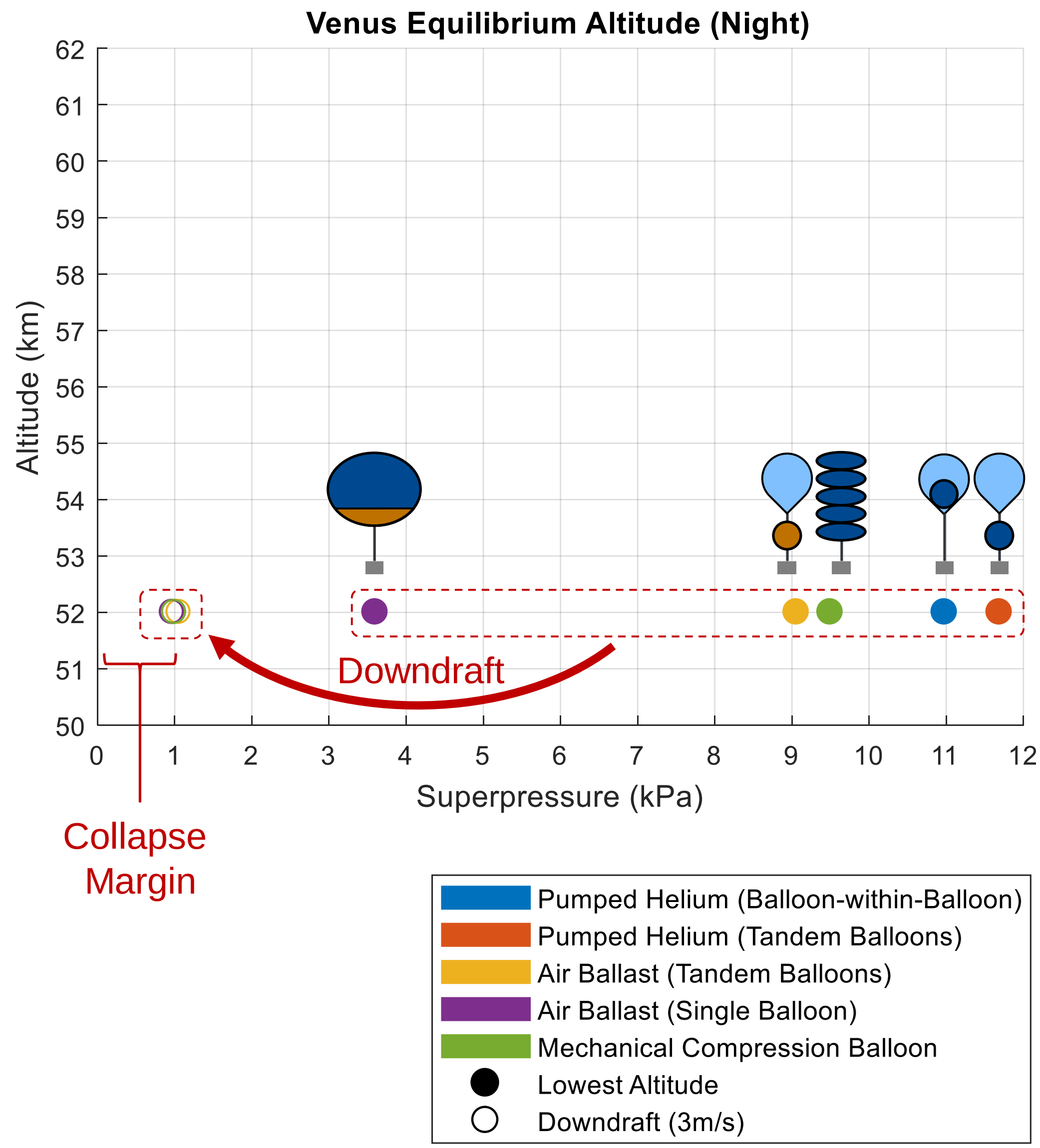
Venus Low Altitude Analysis (Nighttime)

Downdraft effects:

- Aerobot will enter dangerously high temperatures if motion not arrested.
- Model: Balloons vent pressure as quickly as needed to maintain altitude, but only to 1kPa to keep some operational margin.

Results

- Defining margin of 1kPa narrows design space to one solution per balloon type
- Single Air Ballast Balloon needs the smallest excess superpressure as it has a large restorative volume
- Other concepts must have significantly higher margin to provide the required amount of vented gas.



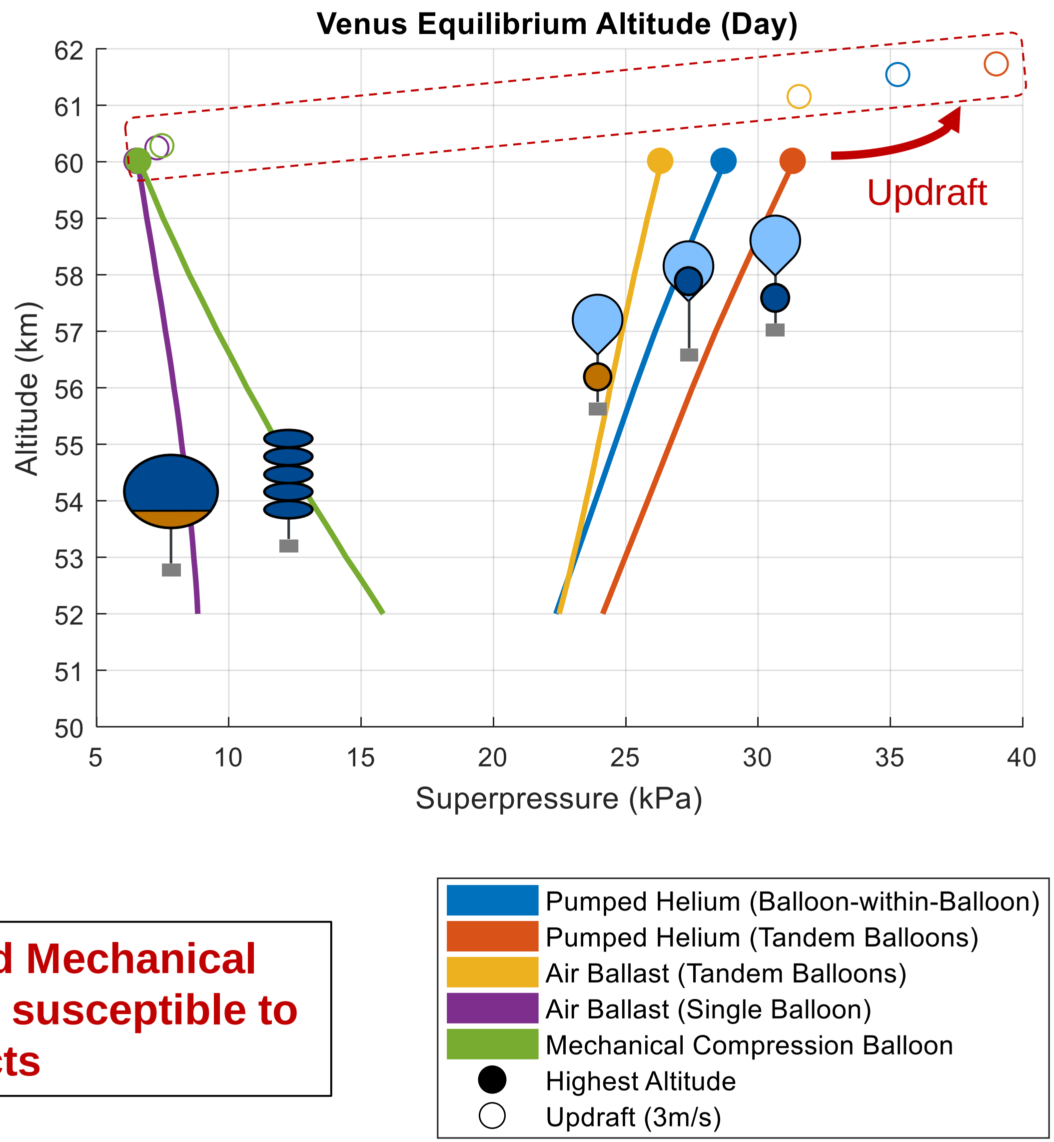
Venus Solar Flux Analysis

Solar Heating:

- Rough linear temperature model
  - Add 20°C + 2°C/km
- Small volumes of gas pressurize more given the same temperature change, can dominate the simple scaling laws noted previously.
- Increases in superpressure by ~3x, especially at high altitudes.

Balloon Implications:

- Smaller superpressurized volumes (the tandem balloon concepts) have large daytime superpressures
- Updrafts affect the tandem balloons more as well



Single-balloon Air Ballast and Mechanical Compression balloons are less susceptible to solar heating effects