VENUS FLAGSHIP MISSION PLANETARY DECADAL STUDY

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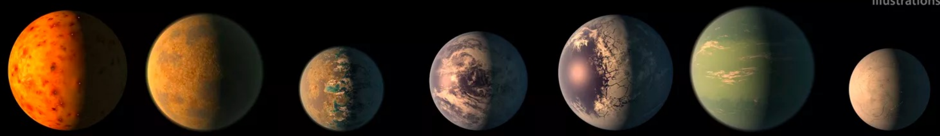
AND THE VENUS FLAGSHIP MISSION STUDY TEAM

Planetary and Astrobiology Decadal Survey Steering Group
May 27, 2021

Our neighborhood 4 billion years ago
3 habitable planets?

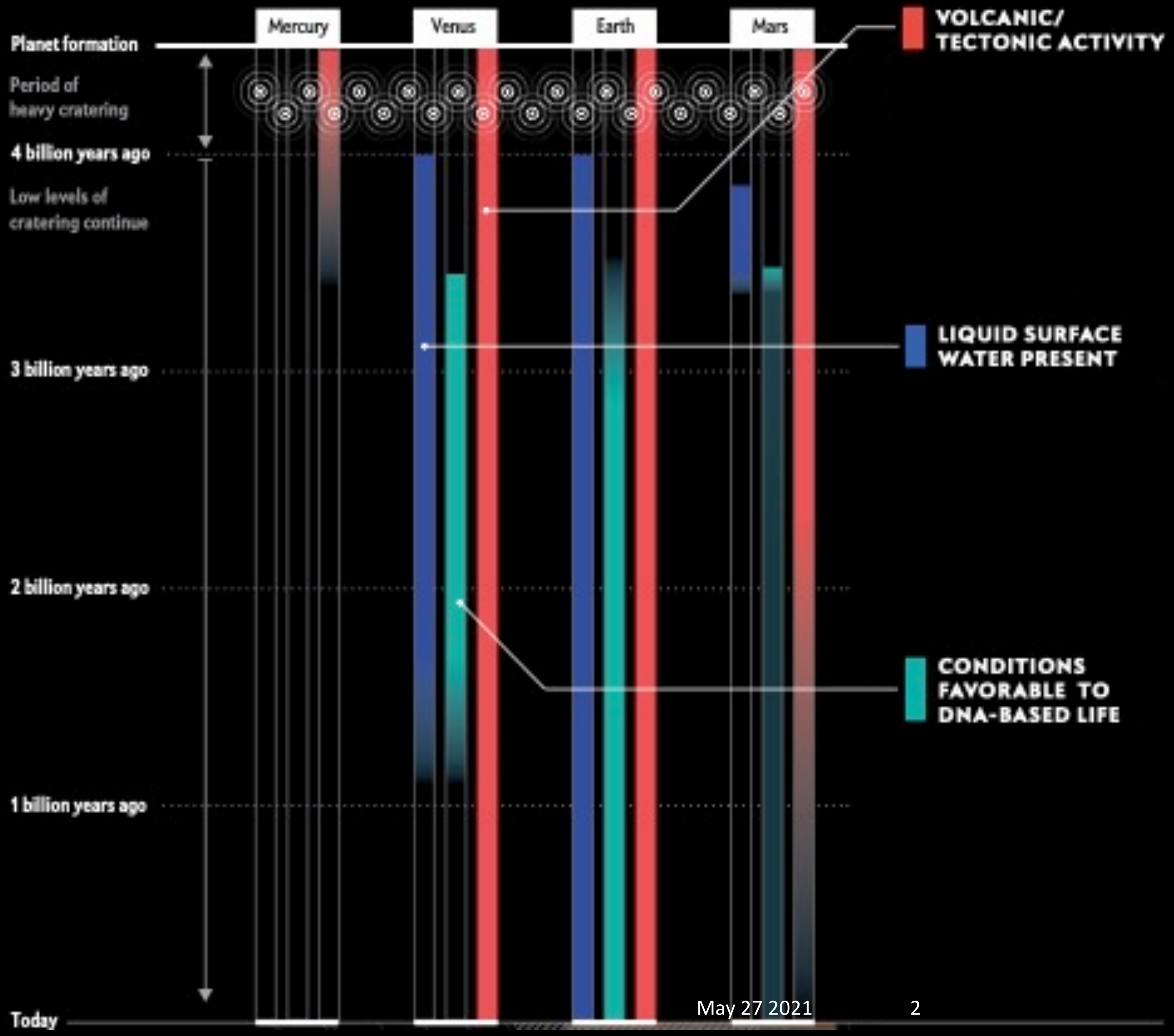
Illustrations



TRAPPIST-1 System	b	c	d	e	f	g	h
Orbital Period (days)	1.51 days	2.42 days	4.05 days	6.10 days	9.21 days	12.35 days	~20 days
Distance to Star (Astronomical Units (AU))	0.011 AU	0.015 AU	0.021 AU	0.028 AU	0.037 AU	0.045 AU	~0.06 AU
Planet Radius (relative to Earth)	1.09 R_{earth}	1.06 R_{earth}	0.77 R_{earth}	0.92 R_{earth}	1.04 R_{earth}	1.13 R_{earth}	0.76 R_{earth}
Planet Mass (relative to Earth)	0.85 M_{earth}	1.38 M_{earth}	0.41 M_{earth}	0.62 M_{earth}	0.68 M_{earth}	1.34 $_{earth}$	–

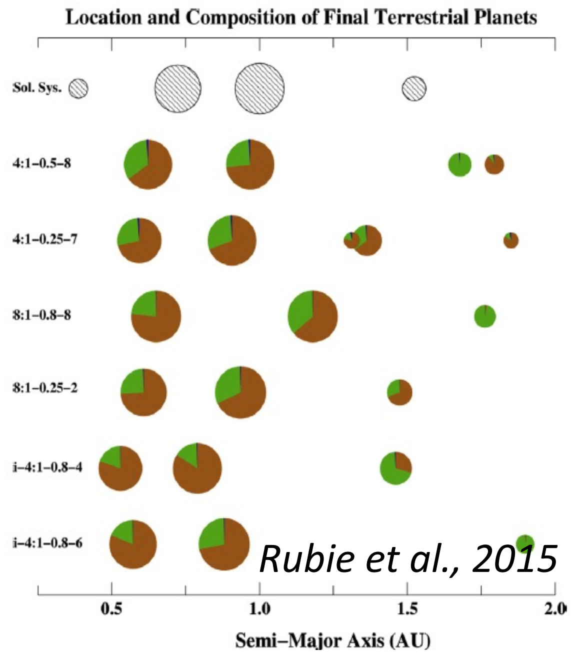
Solar System (Rocky Planets)	Mercury	Venus	Earth	Mars
Orbital Period (days)	87.97 days	224.70 days	365.26 days	686.98 days
Distance to Star (Astronomical Units (AU))	0.387 AU	0.723 AU	1.000 AU	1.524 AU
Planet Radius (relative to Earth)	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}	0.53 R_{earth}
Planet Mass (relative to Earth)	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}	0.11 M_{earth}

S. Kane:
"Venus is the only exoplanet we will ever touch"

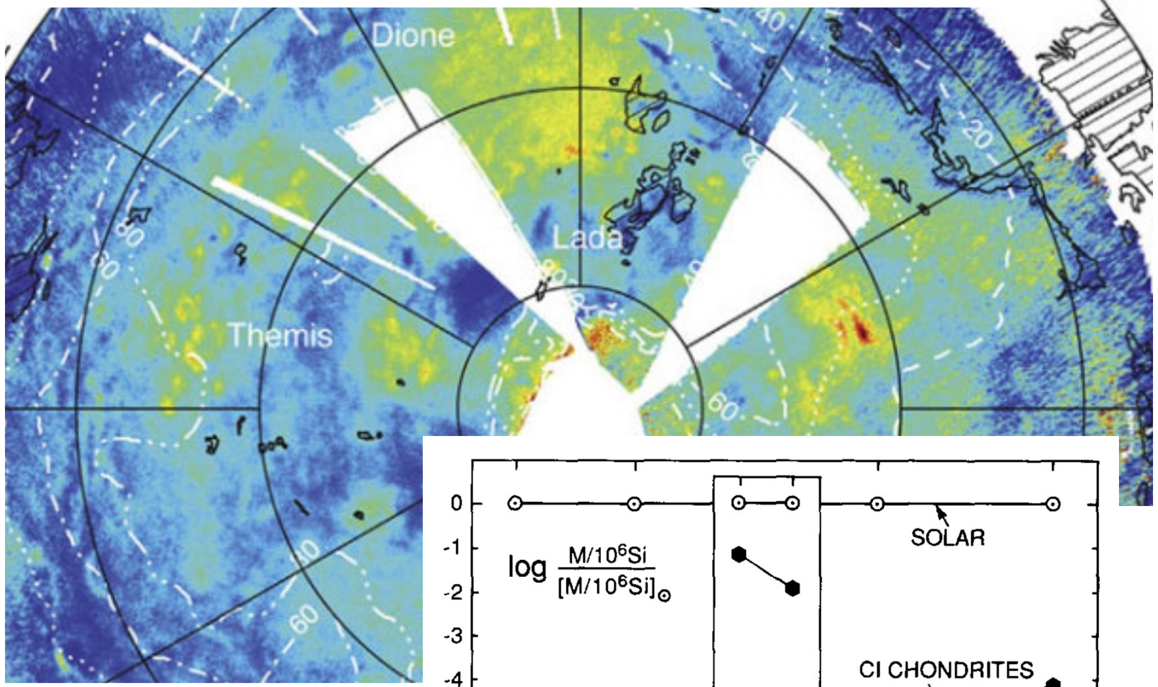


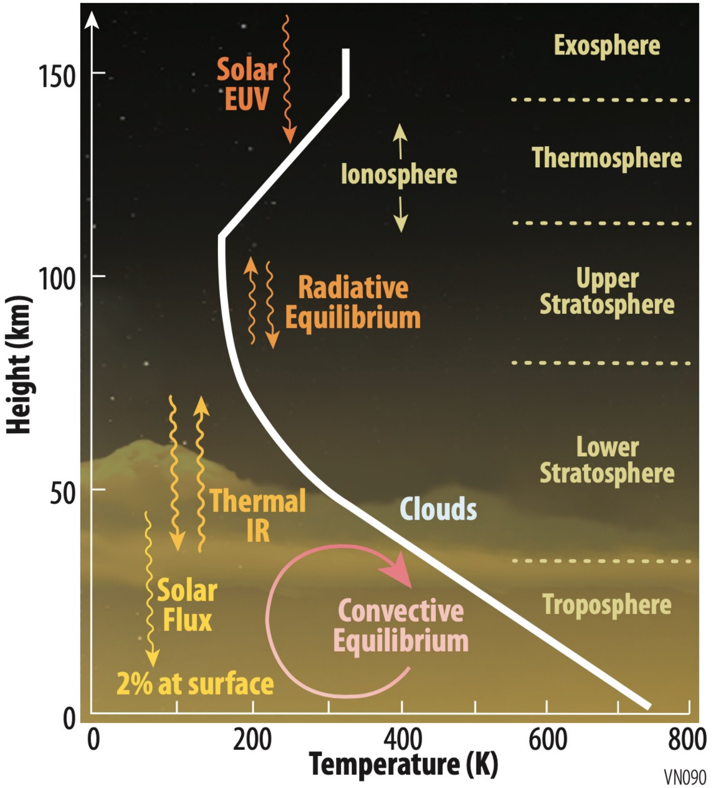
Graphic by Tiffany Farrant-Gonzalez, Dyar et al. Sci. Am. Feb 2019

WHAT WE DON'T KNOW ABOUT THE CLOSEST EARTH SIZE PLANET COULD FILL A BOOK….OR A FIELD.



Rubie et al., 2015



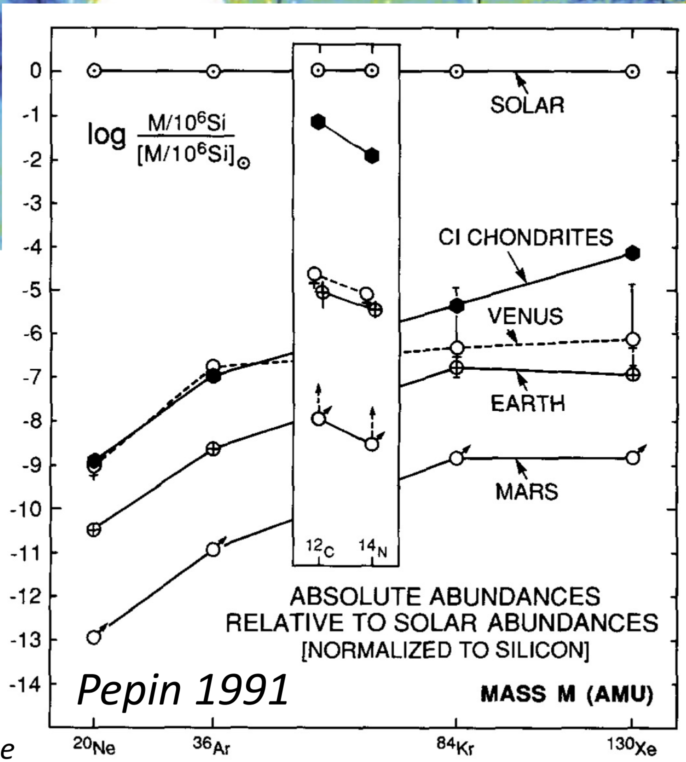


Deuterium on Venus: Observations From Earth

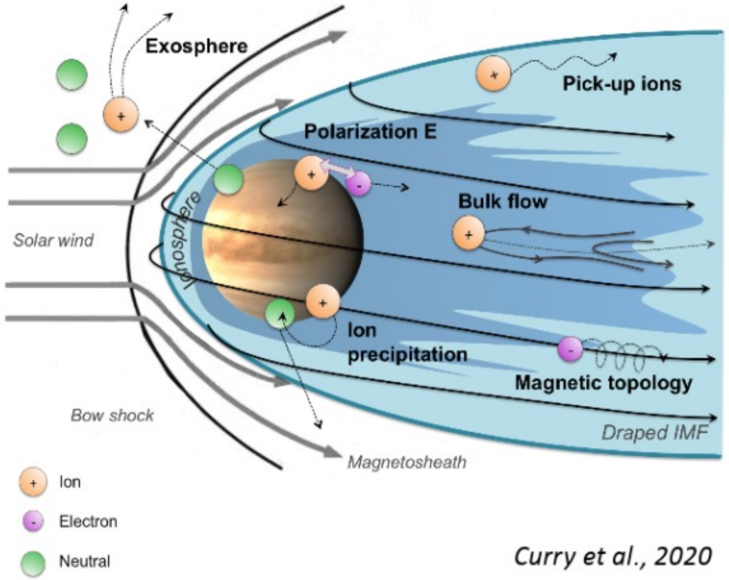
Catherine de Bergh, Bruno Bézard, Tobias Owen, David Crisp, Jean-Pierre Maillard, Barry L. Lutz

Absorption lines of HDO and H_2O have been detected in a 0.23–wave number resolution spectrum of the dark side of Venus in the interval 2.34 to 2.43 micrometers, where the atmosphere is sounded in the altitude range from 32 to 42 kilometers (8 to 3 bars). The resulting value of the deuterium-to-hydrogen ratio (D/H) is 120 ± 40 times the telluric ratio, providing unequivocal confirmation of in situ Pioneer Venus mass spectrometer measurements that were in apparent conflict with an upper limit set from International Ultraviolet Explorer spectra. The 100-fold enrichment of the D/H ratio on Venus compared to Earth is thus a fundamental constraint on models for its atmospheric evolution.

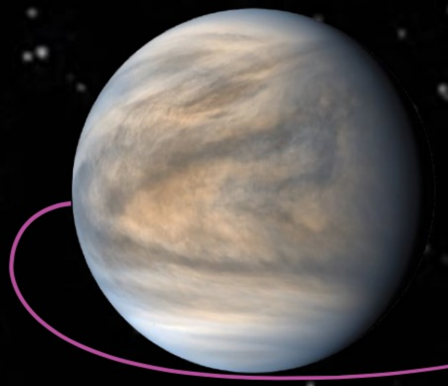
1991, *Science*



Pepin 1991



Curry et al., 2020



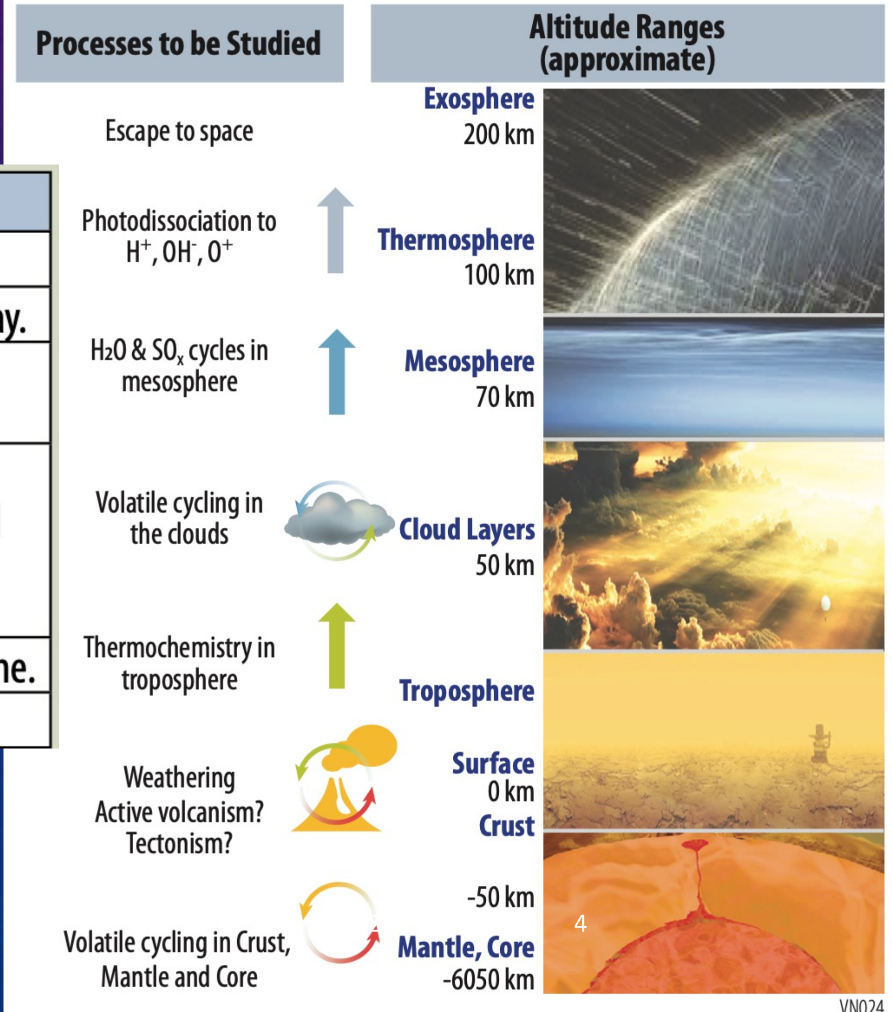
FACT SHEET

Venus Flagship Mission Study

A MISSION TO EXPLORE THE HABITABILITY OF VENUS

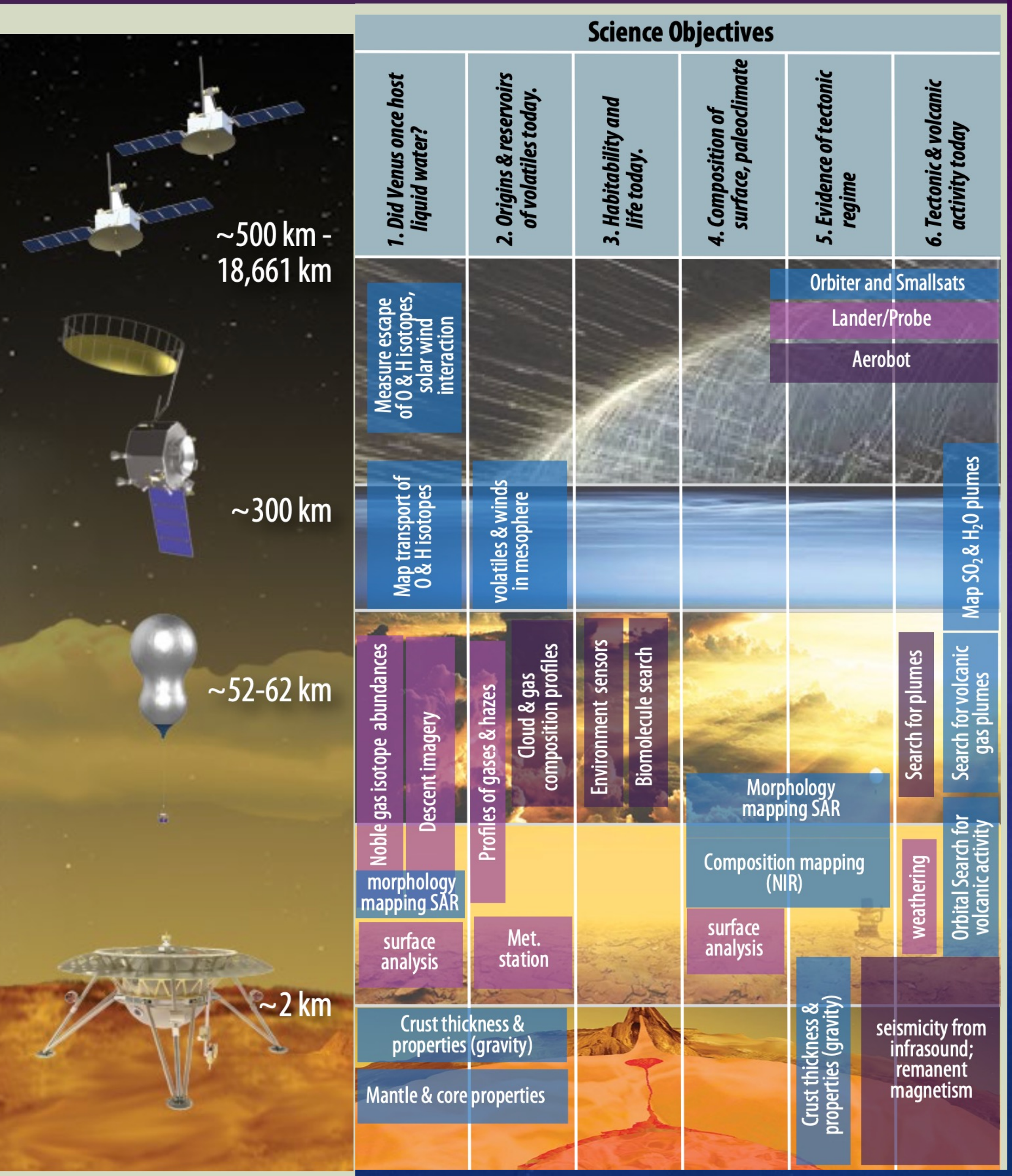
PI: Martha Gilmore, *Wesleyan University*; D-PI: Patricia Beauchamp, *Jet Propulsion Laboratory, California Institute of Technology*

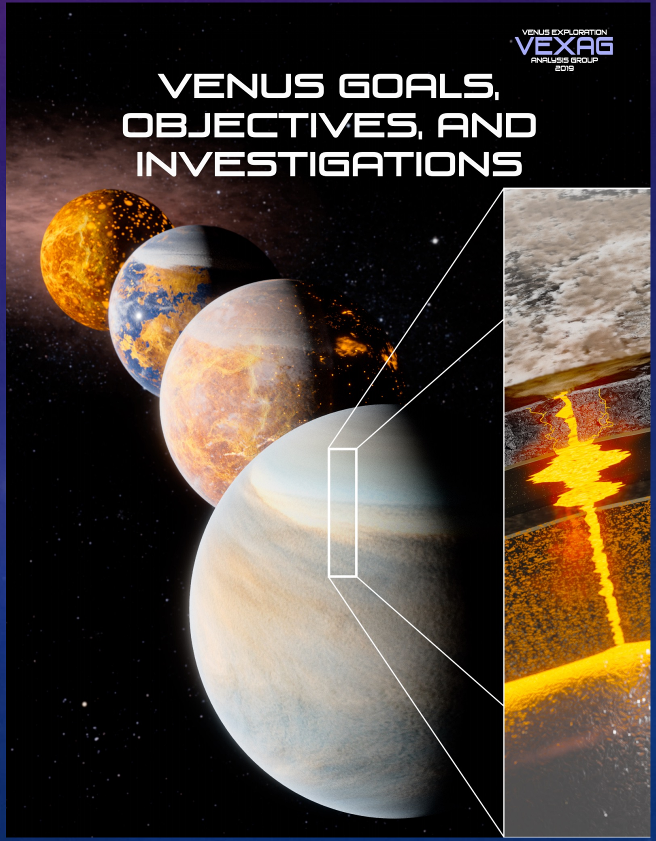
Science Goals	Science Objectives
Understand the history of volatiles and liquid water on Venus and determine if Venus has ever been habitable.	Determine if Venus once hosted liquid water at the surface.
	Identify and characterize the origins and reservoirs of Venus's volatiles today.
	Place constraints on whether there are habitable environments on Venus today and search for organic materials and biosignatures.
Understand the composition and climatological history of the surface of Venus and the present-day couplings between the surface and atmosphere.	Constrain the composition of the surface and chemical markers of past and present climate.
Understand the geologic history of Venus and whether Venus is active today.	Determine if Venus shows evidence of a current or past plate tectonic regime.
	Determine whether Venus is tectonically and volcanically active today.



EXPLORING AN EARTH-SIZED PLANET REQUIRES DIRECT SYNERGISTIC EXPLORATION OF INTERRELATED SYSTEMS OVER SPACE AND TIME

MISSION ASSETS





- Objectives of VFM align with and have substantial input from the Venus community.
- Ambitious in scope, flexible and modular to address the broad science goals of the Venus community.

VENUS FLAGSHIP MISSION CONCEPT SCIENCE TEAM

Study Team

Science Team

Sushil Atreya, University of Michigan
Patricia Beauchamp, JPL-Caltech
Penelope Boston, NASA ARC
Mark Bullock, Science & Technology Corp.
Shannon Curry, U.C. Berkeley
Martha Gilmore, Wesleyan University
Robbie Herrick, University of Alaska
Jennifer Jackson, Caltech
Stephen Kane, U.C. Riverside
Alison Santos, NASA GRC
David Stevenson, Caltech
Colin Wilson, Oxford University
Robert Lillis, U.C. Berkeley (Collaborator)
Janet Luhmann, U.C. Berkeley (Collaborator)
Joshua Knicely, University of Alaska (Student)

Main Technical Team at GSFC

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Art Jacques
Andrew Jones
Richard Lynch
Paul Mason
Ryo Nakamura
Tony Nicoletti
Eric Queen
Glenn Rakow
Rafael Rincon
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GSFC MDL Team

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Sara Riall
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Frank Kirchman
John Panek
Patrick Coronado
Mark Underdown
Mike Xapsos
Luis Gallo
James Sturm
Jennifer Bracken

Mission Design at GSFC, Richard Lynch, Lead, M. Amato; Adriana Ocampo, NASA HQ liaison
Host of generous domestic and international colleagues, collaboration between several GSFC, JPL, GRC and Ames sharing science, instrument and engineering expertise – THANK YOU!

Erica Aguirre, Abby Allwood, Chi Ao, Shahid Aslam, Sami Asmar, Kevin Baines, Charles Baker, Don Banfield, Bruce Bills, Dave Blake, Jeremy Brossier, Paul Byrne, Gordon Chin, Sam Clegg, Glynn Collinson, Jim Cutts, Doris Daou, Darby Dyar, Larry Esposito, Sabrina Feldman, Justin Filiberto, Stephanie Getty, Jim Greenwood, Jeff Hall, Paul Hartogh, Chris Heirwegh, Joern Helbert, Scott Hensley, Laurie Higa, Gary Hunter, Noam Izenberg, Jacob Izraelevitz, Andrew Johnson, Kandis-Lea Jessup, Attila Komjathy, Tibor Kremic, Siddharth Krishnamoorthy, Sebastian Lebonnois, Yang Liu, Earl Maize, Darby Makel, Larry Matthies, Suman Muppidi, Dragan Nikolic, Adriana Ocampo, Joe O'Rourke, Bob Pappalardo, Brian Paczkowski, Richard Quinn, Ann Parsons, Michael Pauken, Jason Rabinovitch, Bruce Milam, Miguel San Martin, Dave Senske, Rainee Simons, Suzanne Smrekar, Christophe Sotin, Eric Sunada, Melissa Trainer, Allan Treiman, Ethiraj Venkatapathy, Panagiotis Vergados, Larry Wade, Michael Way, Chris Webster, Thomas Widemann.[1]

Science/Engineering Team meetings 2-4x/week, 2.5 days at GSFC Feb, 2 week Design run virtually in April

J. Brossier, Wesleyan U., H. Ghannadian, GSFC

Key elements of Design

Launch 2031. **Synergistic measurements** between multiple assets:

- **Orbiter and 2 SmallSats** support in situ assets prior to science campaign
- **Lander** – 7 hour lifetime on tessera terrain after 1 hour of measurements on descent
- **Aerobot** – 60+ days, variable altitude between 52 and 62 km altitude
- **Long-lived lander (LLISSE)** – 60+ days

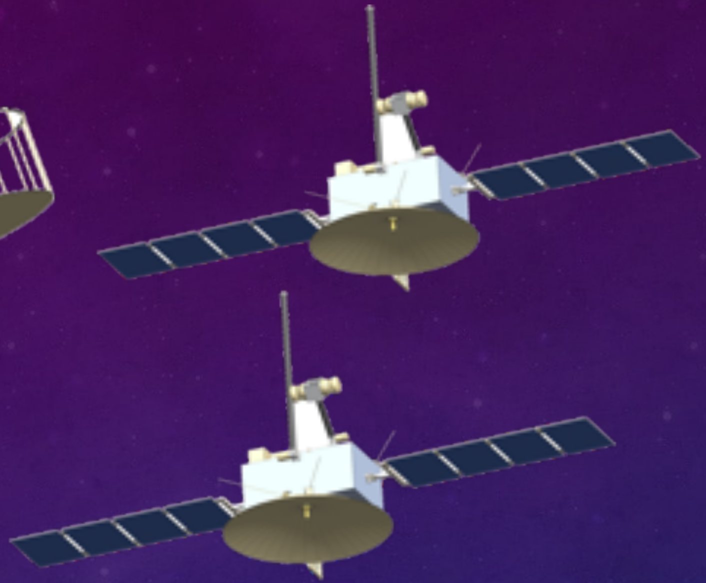
- Assumed no prior Venus missions, but flexible to accommodate them.

- The overall mission concept was derived from the three major science goals and two cost-driven requirements that were derived early in the study: 1) launch all elements on a single rocket and 2) limit the g-load for Venus entry to ≤ 50g in order to maximize the use state-of-the-art instruments that had high heritage or were assessed to have high technology levels. Both of these requirements were accomplished.

VFM PLATFORMS

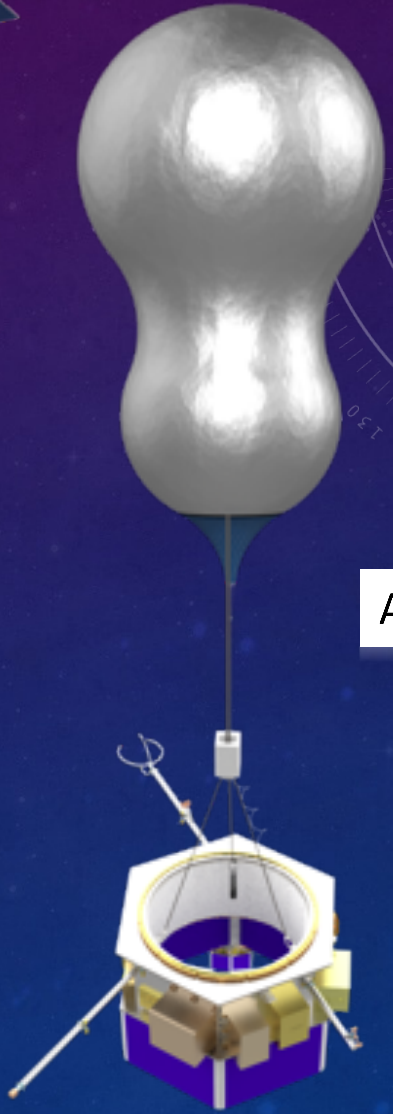
Falcon 9 Heavy Expendable w/ 5 m Fairing

Orbiter and carrier spacecraft

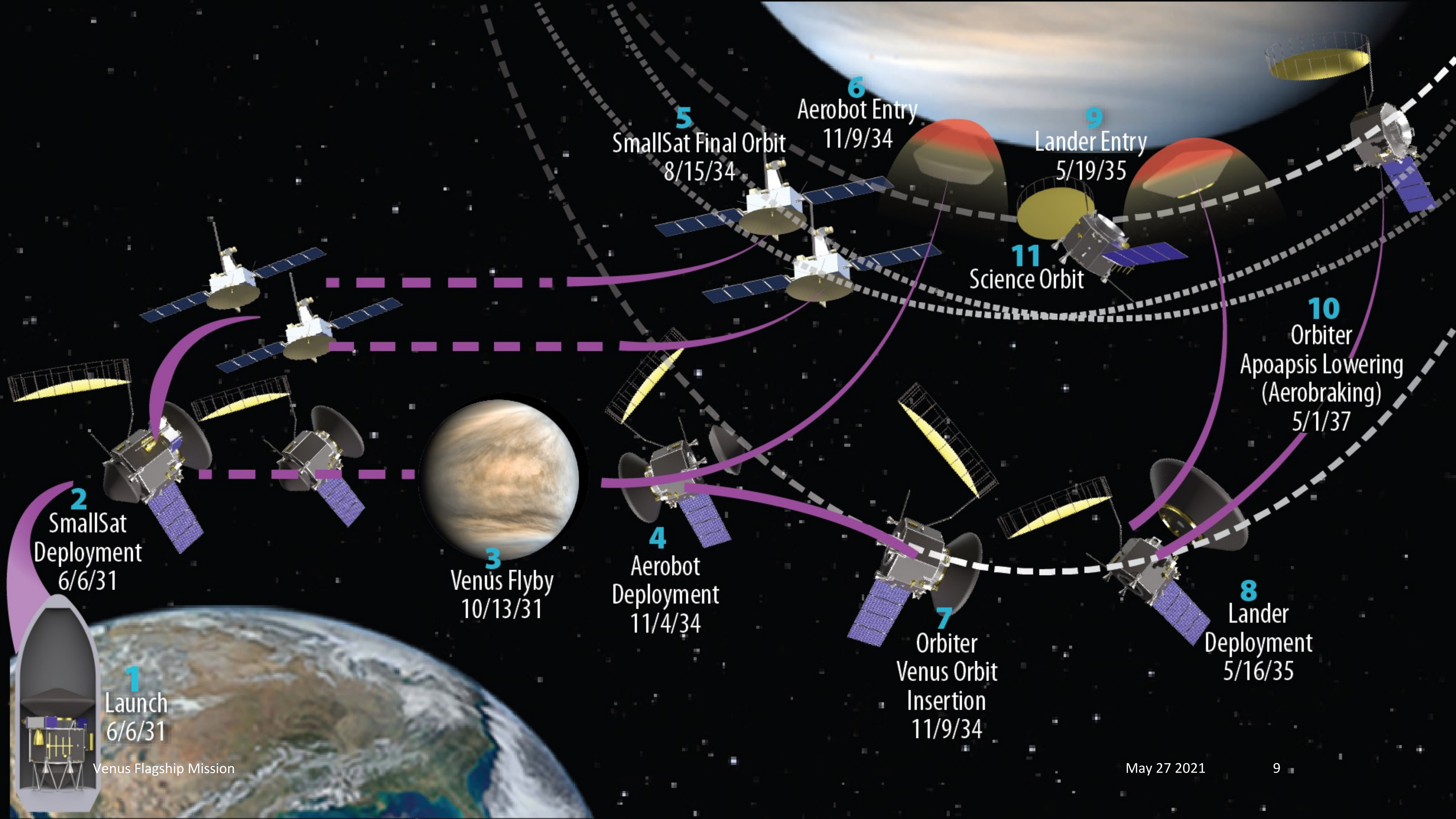


Two SmallSat orbiters

Lander/Descent Probe and LLISSE

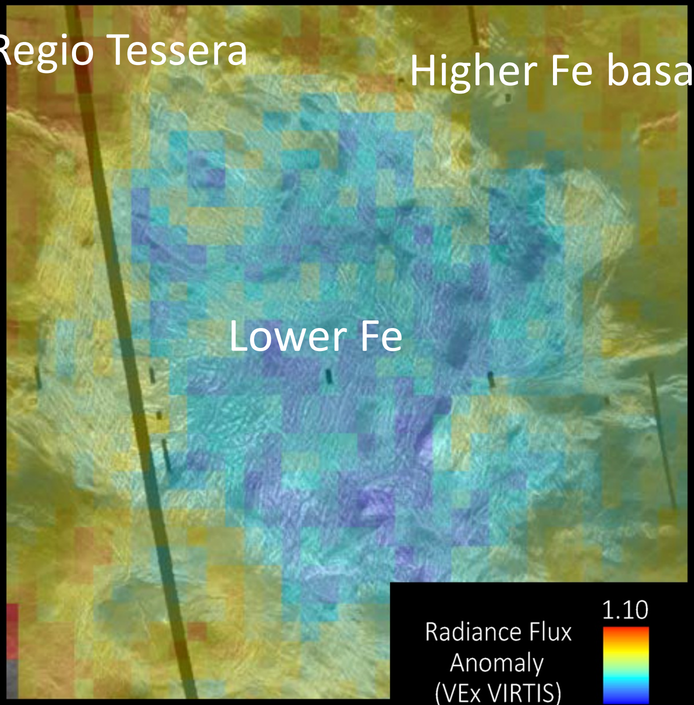


Aerobot

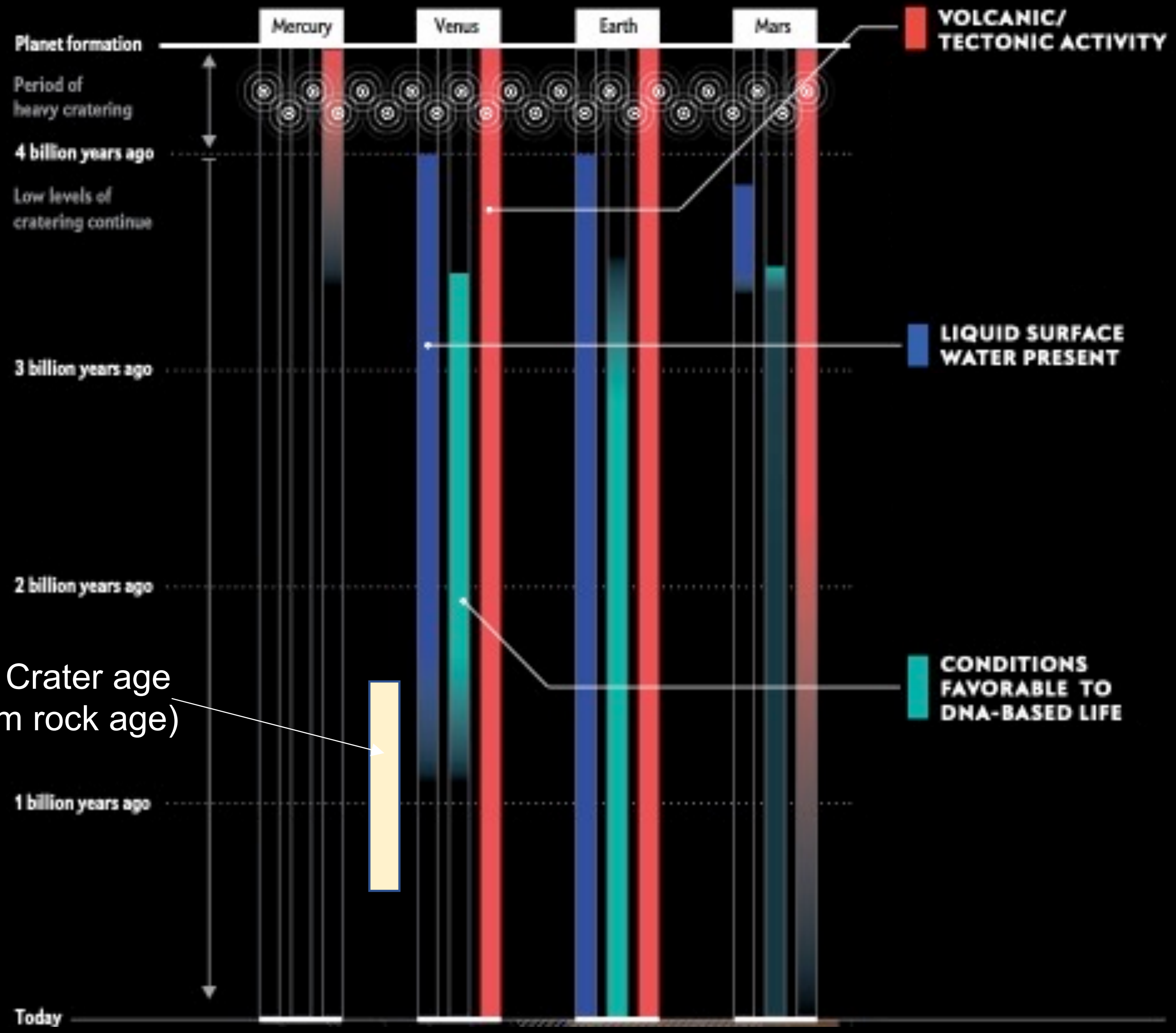


1
Launch
6/6/31
2
SmallSat
Deployment
6/6/31
3
Venus Flyby
10/13/31
4
Aerobot
Deployment
11/4/34
5
SmallSat Final Orbit
8/15/34
6
Aerobot Entry
11/9/34
7
Orbiter
Venus Orbit
Insertion
11/9/34
8
Lander
Deployment
5/16/35
9
Lander Entry
5/19/35
10
Orbiter
Apoapsis Lowering
(Aerobraking)
5/1/37
11
Science Orbit

Our neighborhood 4 billion years ago
3 habitable planets?

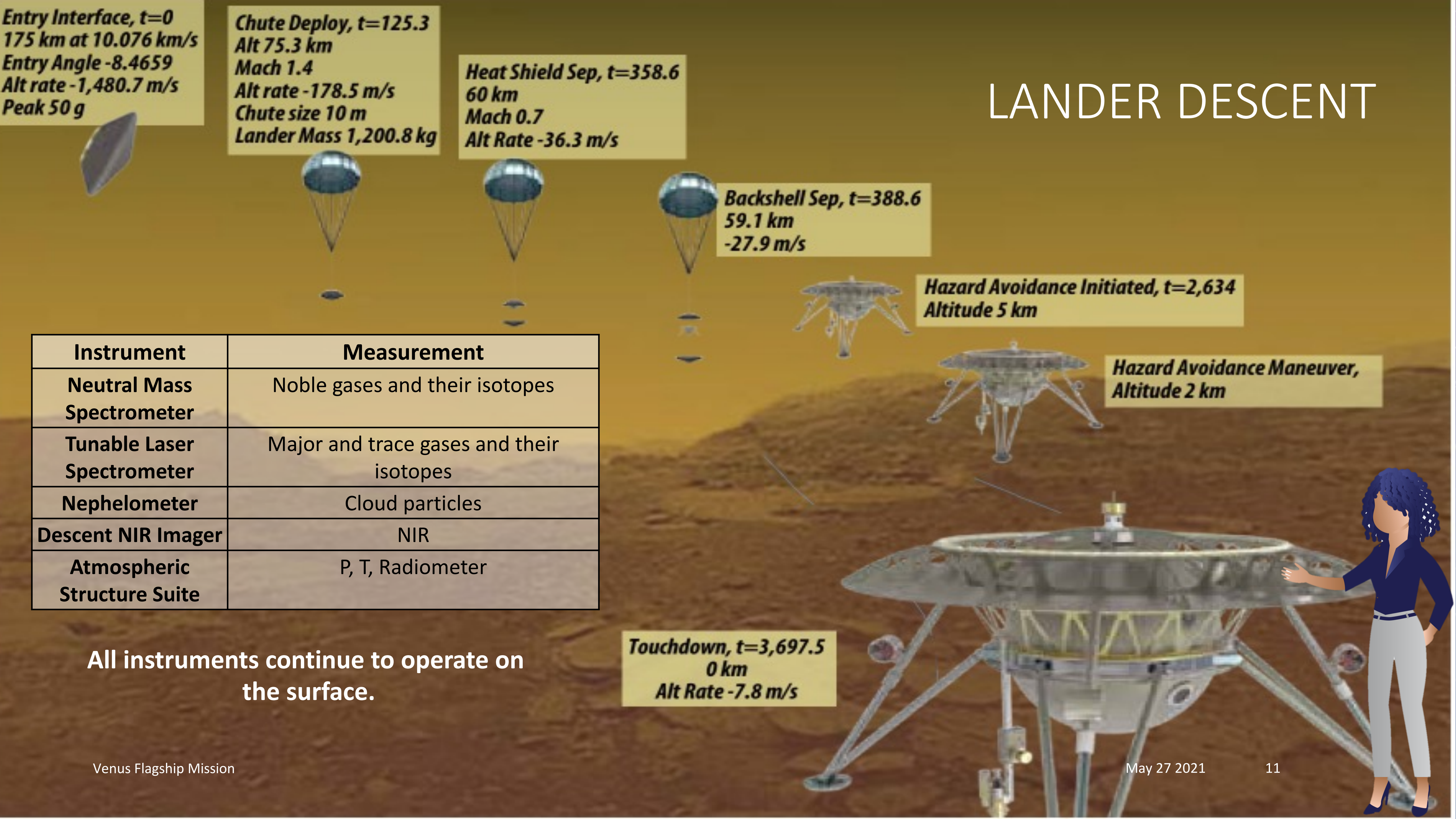


Gilmore et al., 2015



Graphic by Tiffany Farrant-Gonzalez, Dyar et al. Sci. Am. Feb 2019

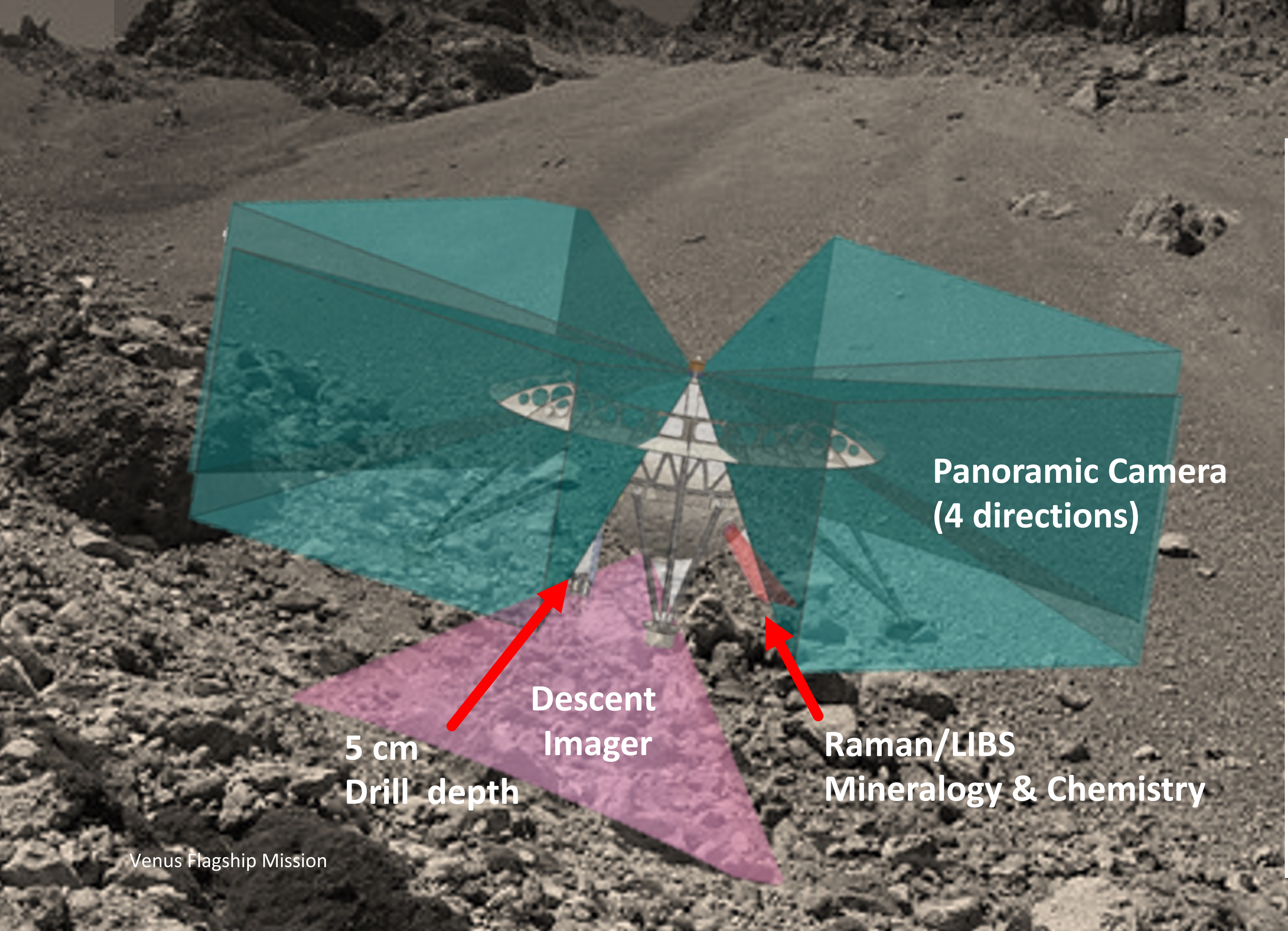
LANDER DESCENT

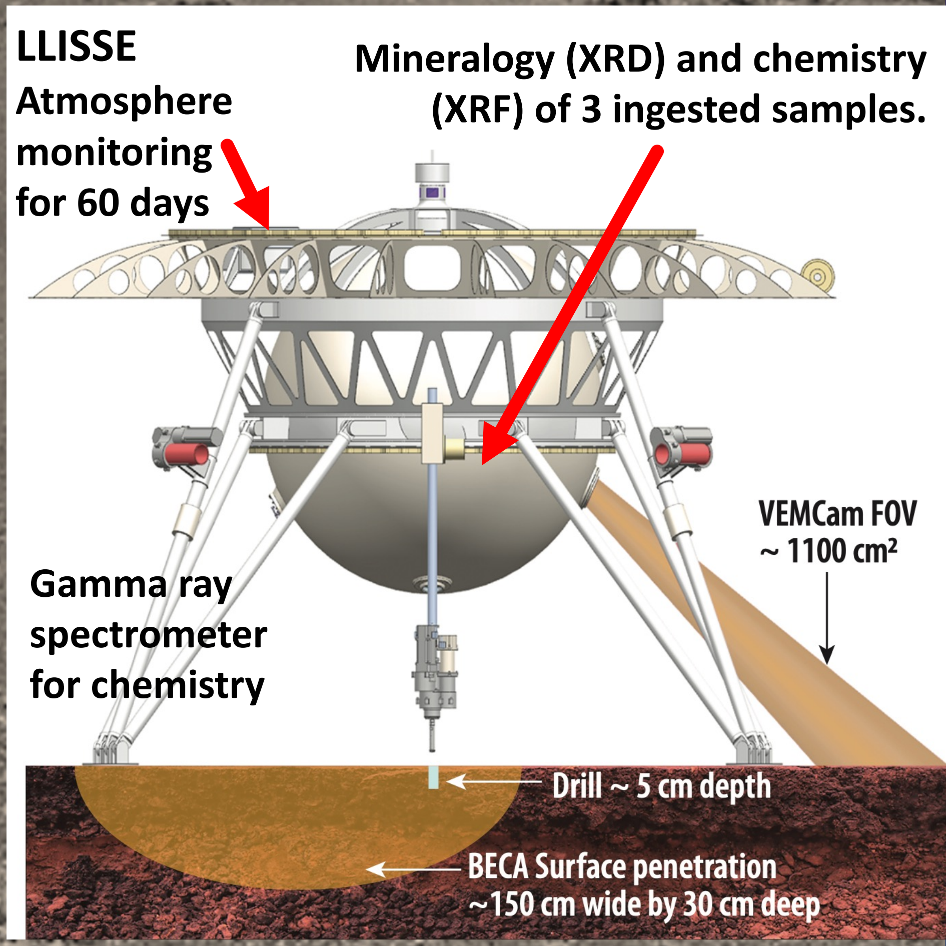


Instrument	Measurement
Neutral Mass Spectrometer	Noble gases and their isotopes
Tunable Laser Spectrometer	Major and trace gases and their isotopes
Nephelometer	Cloud particles
Descent NIR Imager	NIR
Atmospheric Structure Suite	P, T, Radiometer

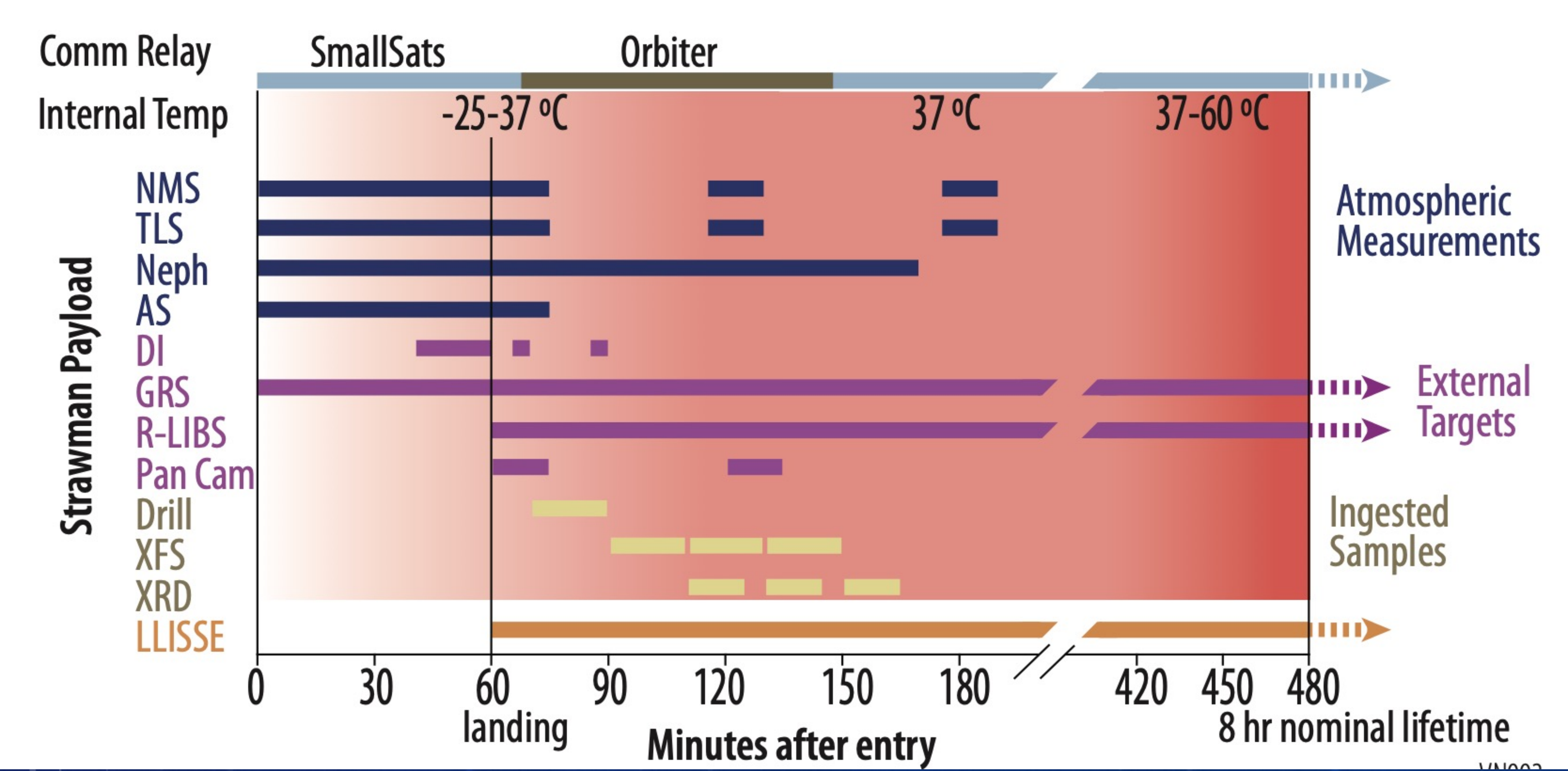
All instruments continue to operate on the surface.

REDUNDANT MINERALOGY AND GEOCHEMISTRY OF MULTIPLE SAMPLES OVER 7 HOURS

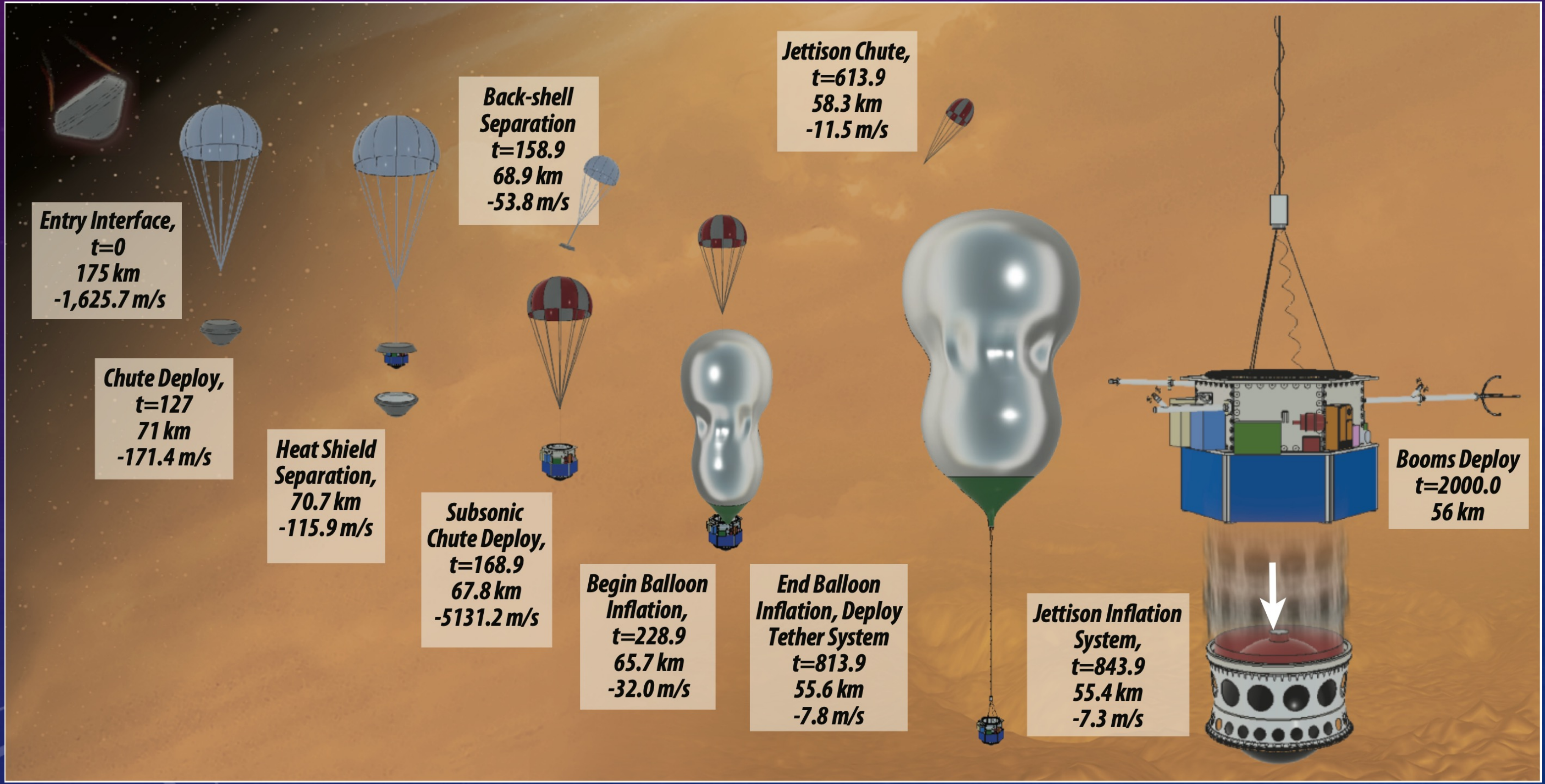


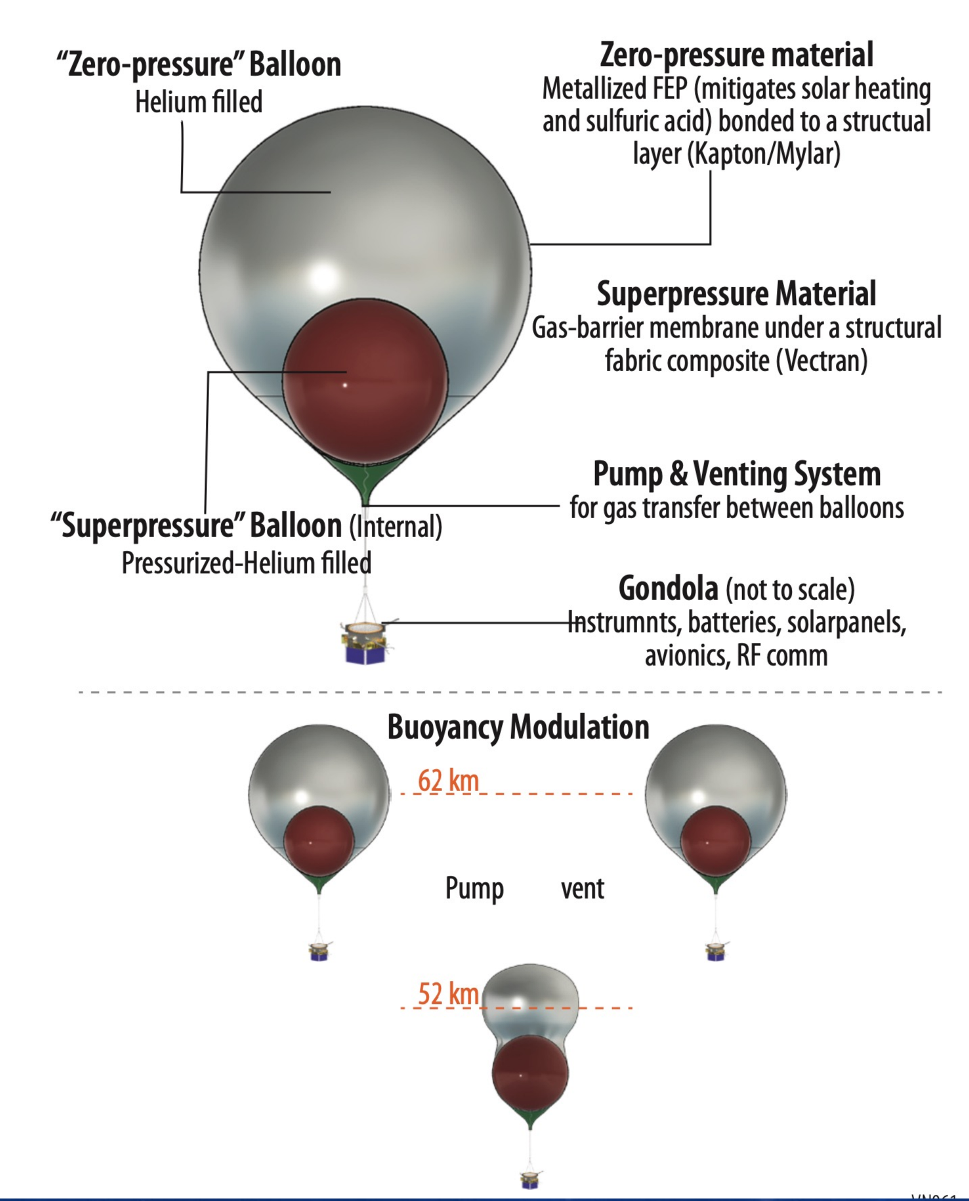


VFM LANDER OPERATIONS



ENTRY, DESCENT AND FLOAT

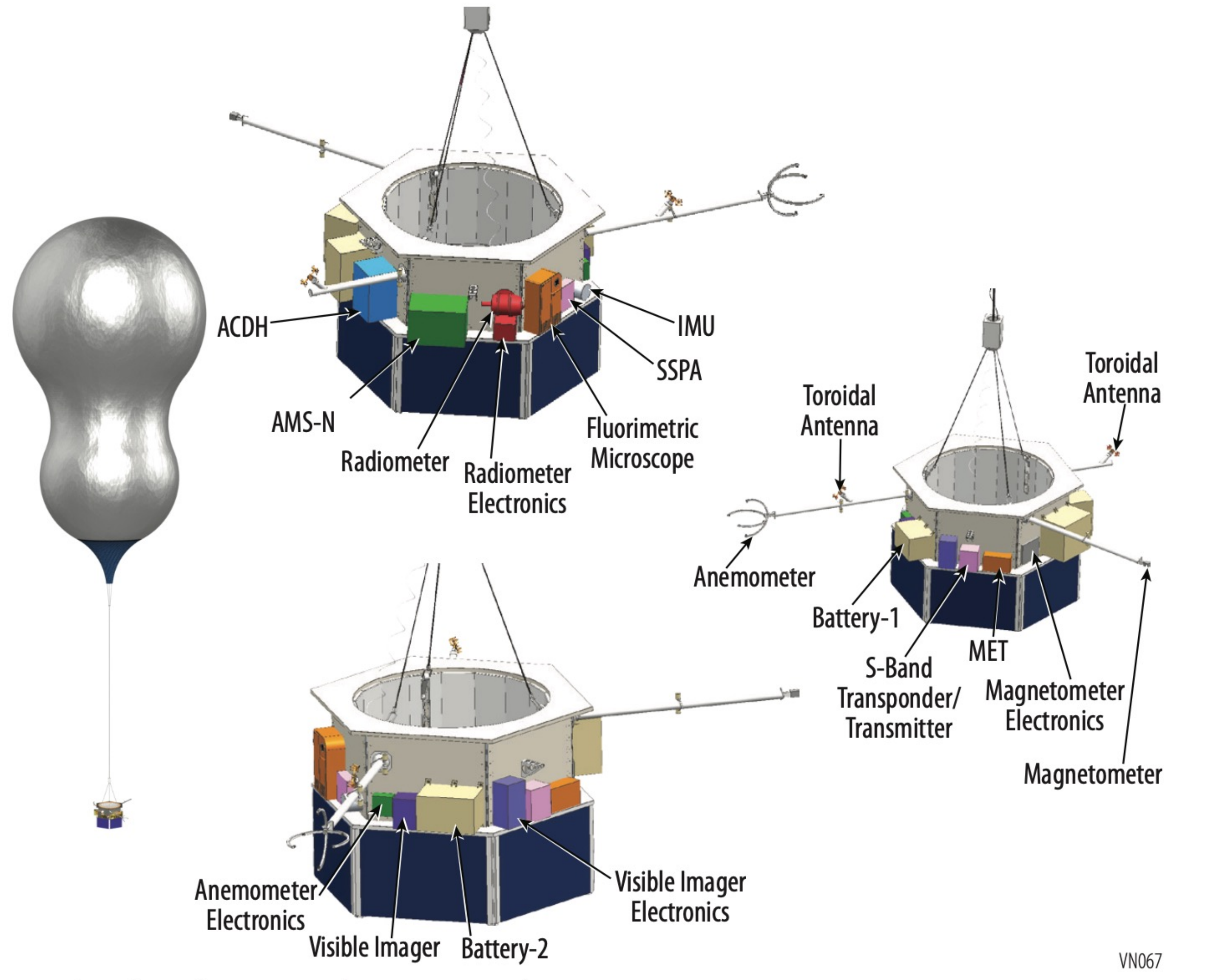




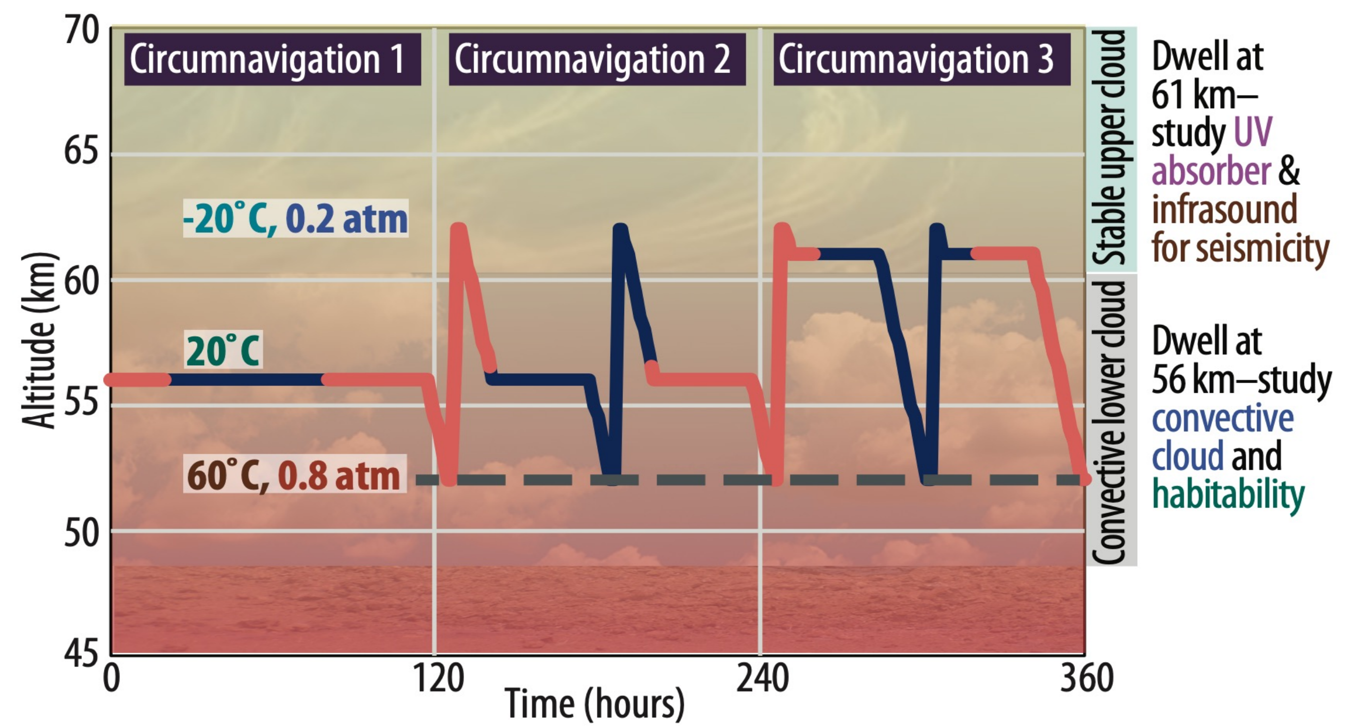
AEROBOT PAYLOAD

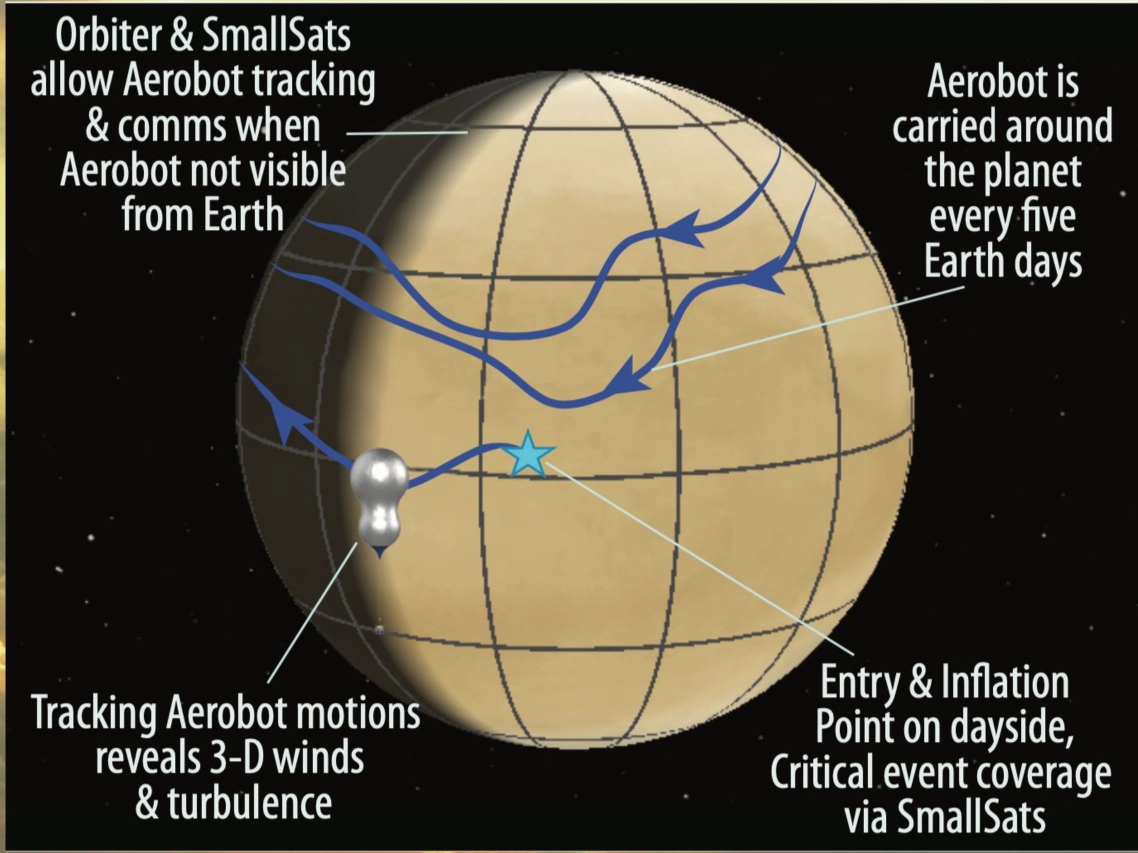
Science goals:

- **Chemistry**: Measure composition and microphysics of cloud particles, including search for biomolecules.
- **Meteorology**: Measure cloud-level dynamics & radiances & role in volatile transport.
- **Surface science**: Measure seismicity by infrasound; search for remanent magnetism.



AEROBOT FLIGHT PLAN



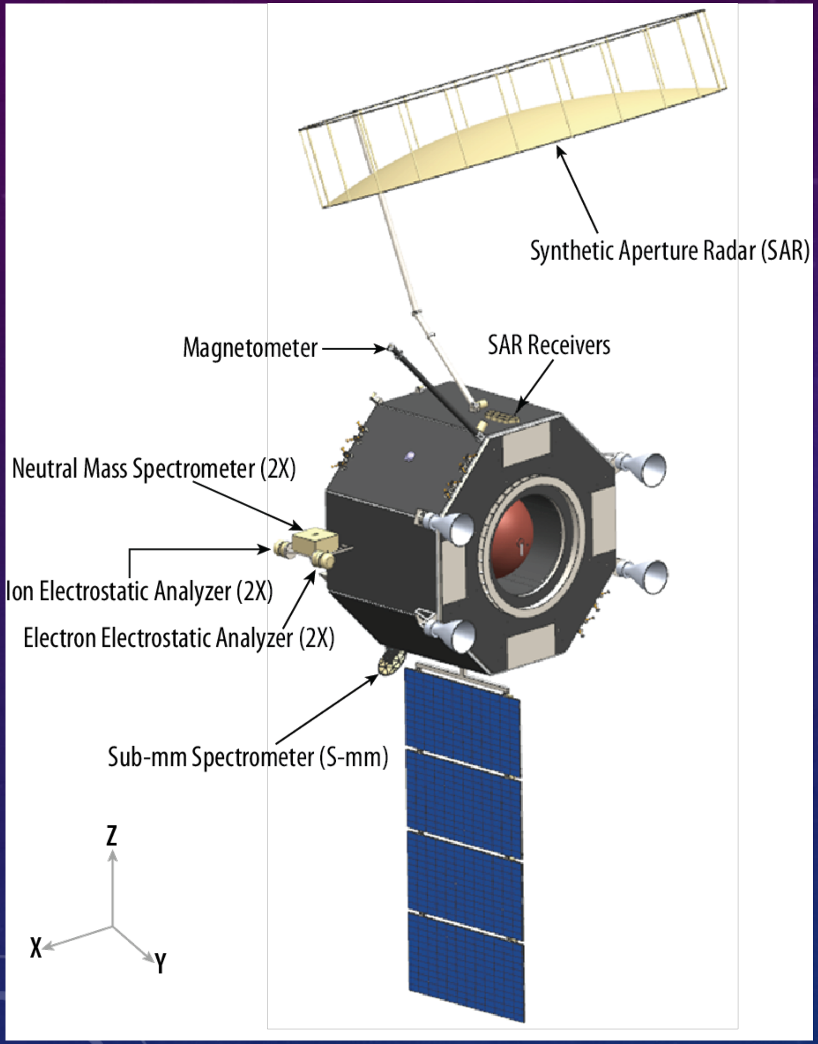


Later circumnavigations: obtain **vertical profiles at all times of day and night**. Choose dwell altitude to study different cloud layers.

First circumnavigation: dwell at ~20°C to complete initial chemical characterization including noble gases.

12 Navigations over 60 day lifetime

VFM ORBITER



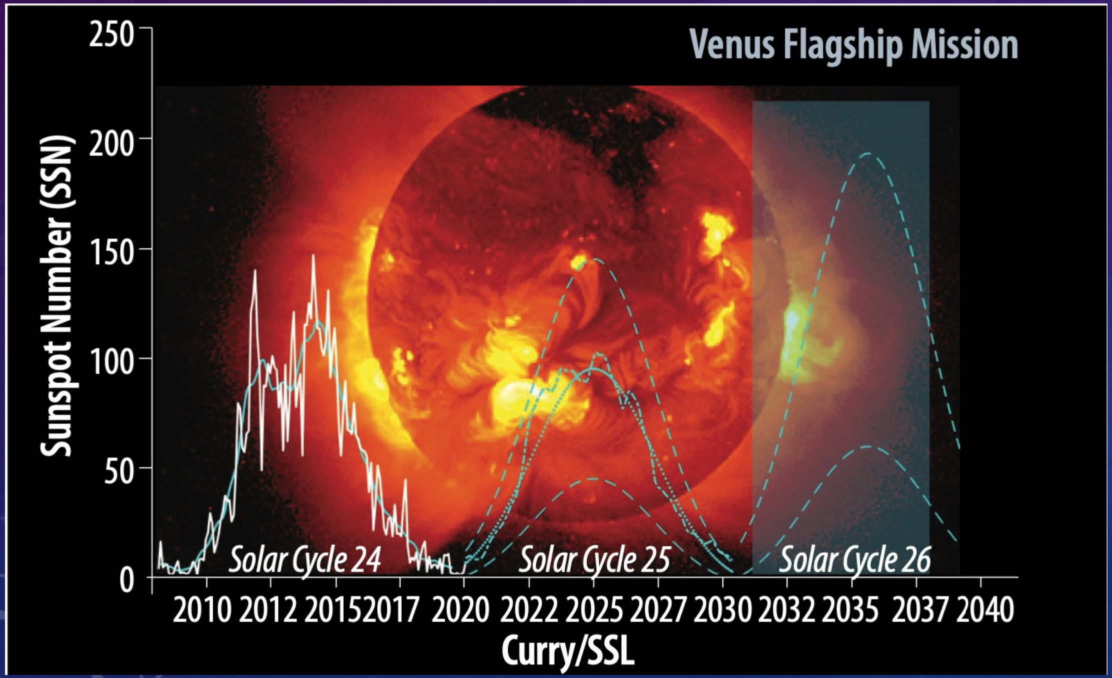
Science: Morphology and composition of Venus surface, gravity field, particles and fields, upper atmosphere composition.

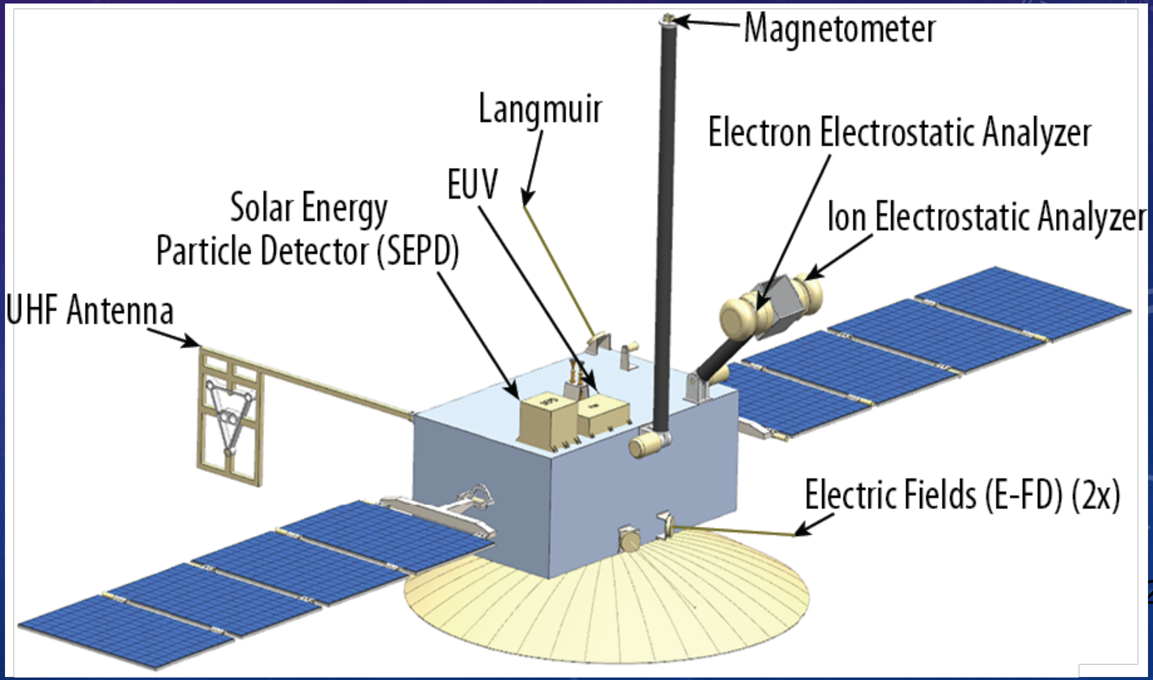
- After lander release aerobrake to circular mapping orbit.
- Provides critical comm for aerobot and lander
- Targeted SAR images of ~5% of the surface to accomplish science objectives. Specifics of mapping campaign will consider status of Venus missions currently in consideration in Discovery and by ESA.

TWO SMALLSATS

Science: Understand evolution of Venus atmosphere and magnetosphere via measurements of the interaction the with solar wind.

- Sophisticated instrument compliment
- Elliptical orbits with periapses in both Northern and Southern hemispheres during solar cycle 26



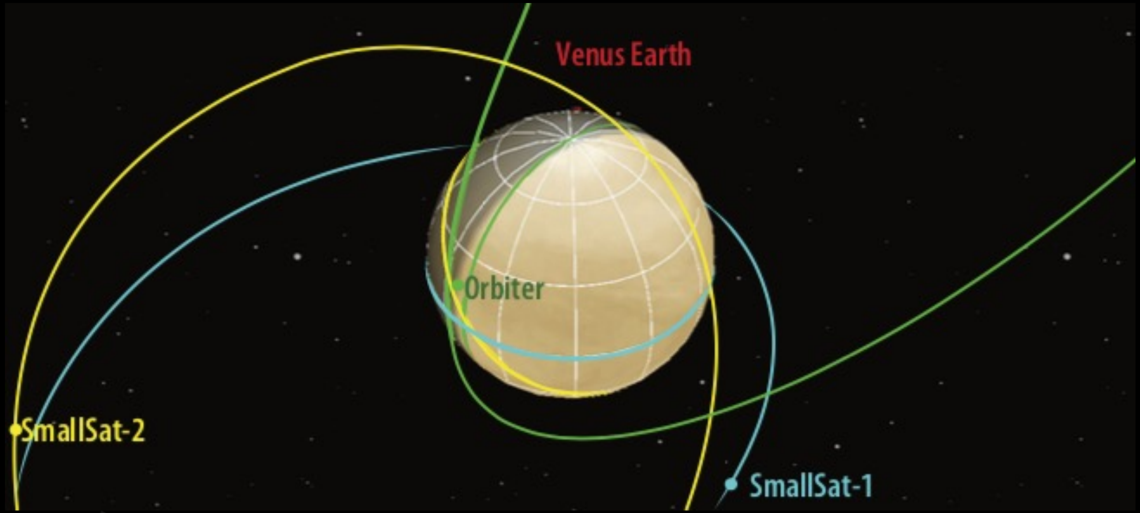


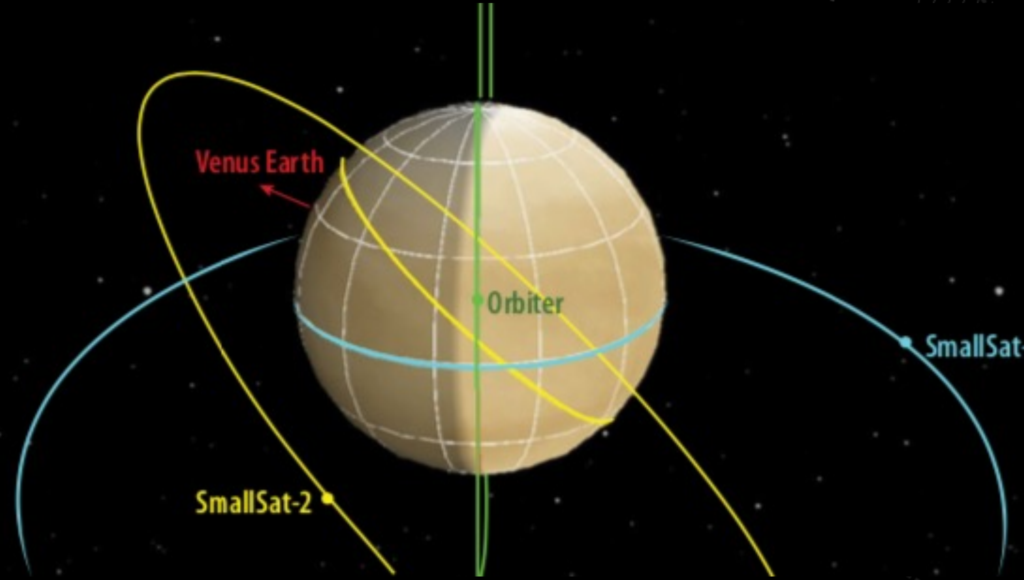
2020

THREE ORBITERS AT VENUS

Orbit Parameters (Venus Inertial Frame)	Orbiter Elliptical	Orbiter Circular	SmallSat 1	SmallSat 2
Apoapsis (km)	116,108.4	300	18,661	18,661
Periapsis (km)	300	300	500	500
Eccentricity	0.945	0	0.578	0.578
Inclination (°)	90	90	22.5	65
Orbital Period	5 days	1.55 hours	6 hours	6 hours
RAAN (°)	334.4	334.4	251.0	339.9
Argument of Periapsis (°)	188.6	188.6	86.7	359.5

- All three measure particles and fields at different locations/times.
- *Critically* aid in tracking, comm and data return of in situ elements





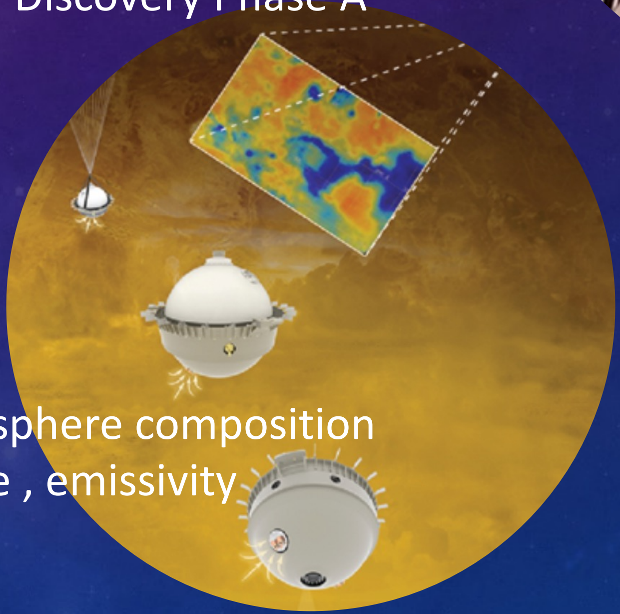
A FLAGSHIP COMPLEMENTS OTHER VENUS MISSIONS

- **VERITAS** would be pathfinder for VFM lander site selection and hi-res SAR targets. ***Possible VFM descope: SAR/NIR emissivity/gravity.***
- **DAVINCI+** would inform VFM descent profile at another location. VFM does unique surface atmospheric science. ***Possible VFM descope: None***
- **EnVision** at Venus concurrently with VFM could provide the SAR and NIR emissivity to support VFM objectives. ***Possible VFM descope: SAR/NIR emissivity/gravity.***
- **VENERA-D** lander will visit the plains

VERITAS - launch 2026
Discovery Phase A

Global SAR, topography, emissivity, gravity

DAVINCI+ - launch 2026
Discovery Phase A

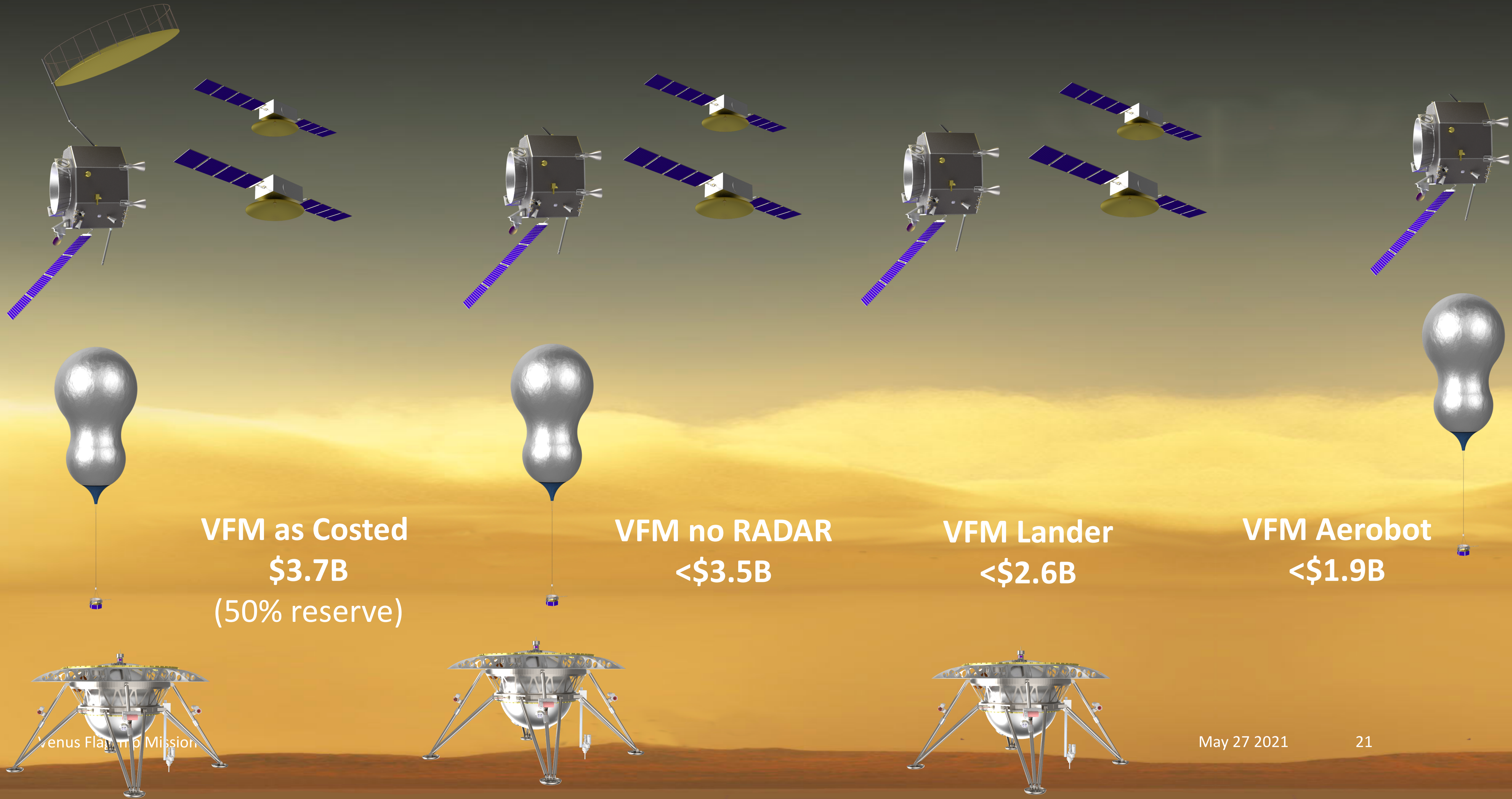


Atmosphere composition profile , emissivity

EnVision - launch 2032
ESA M5 candidate

SAR, topography, emissivity, gravity

Potential VFM Configurations - Descope options eliminate only instrumentation or asset and are thus upper limits



VFM as Costed
$3.7B
(50% reserve)

VFM no RADAR
<$3.5B

VFM Lander
<$2.6B

VFM Aerobot
<$1.9B

VENUS EXPLORATION IS A DECADAL PRIORITY

Visions and Voyages Science Goals for the Inner Planets:

- Understand the origin and diversity of terrestrial planets.
- Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life.
- Understand the processes that control climate on Earth-like planets.

VENUS EXPLORATION VEXAG ANALYSIS GROUP

- Goal #1. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-sized (exo)planets.
- Goal #2. Understand atmospheric composition and dynamics on Venus.
- Goal #3. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.

NASA Science SOLAR SYSTEM EXPLORATION

How did life begin and evolve on Earth?
How did the solar system evolve?
How did the sun's family originate?
What are the characteristics of the Solar System?

NASA EXOPLANET EXPLORATION Planets Beyond Our Solar System

How do we find habitable planets?

NASA HELIOPHYSICS

How do Earth, the planets, and the heliosphere interact?


MARS MISSIONS
OPERATIONAL 2001–2017
FUTURE 2018–2030
Mars Odyssey (2001)
Mars Express (ESA) (2003)
Mars Reconnaissance Orbiter (2005)
MAVEN (2013)
Mars Orbiter Mission (ISRO) (2013)
Trace Gas Orbiter (ESA/RSA) (2016)
HOPE (UAE)
MMX (JAXA)
Mars Orbiter (China)
Mars Lander & Rover (China)
Opportunity Rover (2003)
Curiosity Rover (2011)
InSight
Mars 2020 Rover (NASA)
ExoMars Rover (ESA/RSA)
Mars Sample Return (China)
Follow the Water
Explore Habitability
Seek Signs of Life
Prepare for Future Human Explorers

VENUS EXPLORATION PROGRAM

UNDERSTANDING THE HABITABILITY OF EARTH-SIZED PLANETS