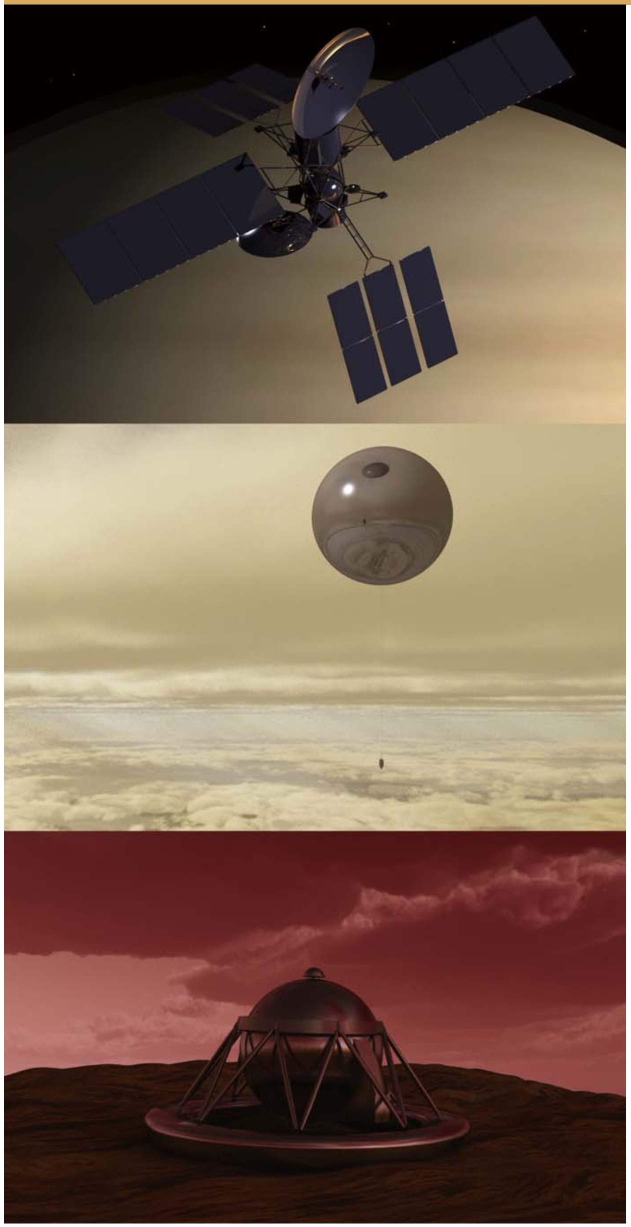

Venus Seismology Study: Short Course

Part II: Exploring Venus with Landers, Orbiters and Balloons

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Outline

1. Venus Environmental Challenges
2. A Brief History of Robotic Exploration of Venus
3. Characteristics of Venus Orbiters, Balloons and Landers
4. Plans and Possibilities for new Venus Missions

1. Venus Environment Challenges

Basic Characteristics of Venus

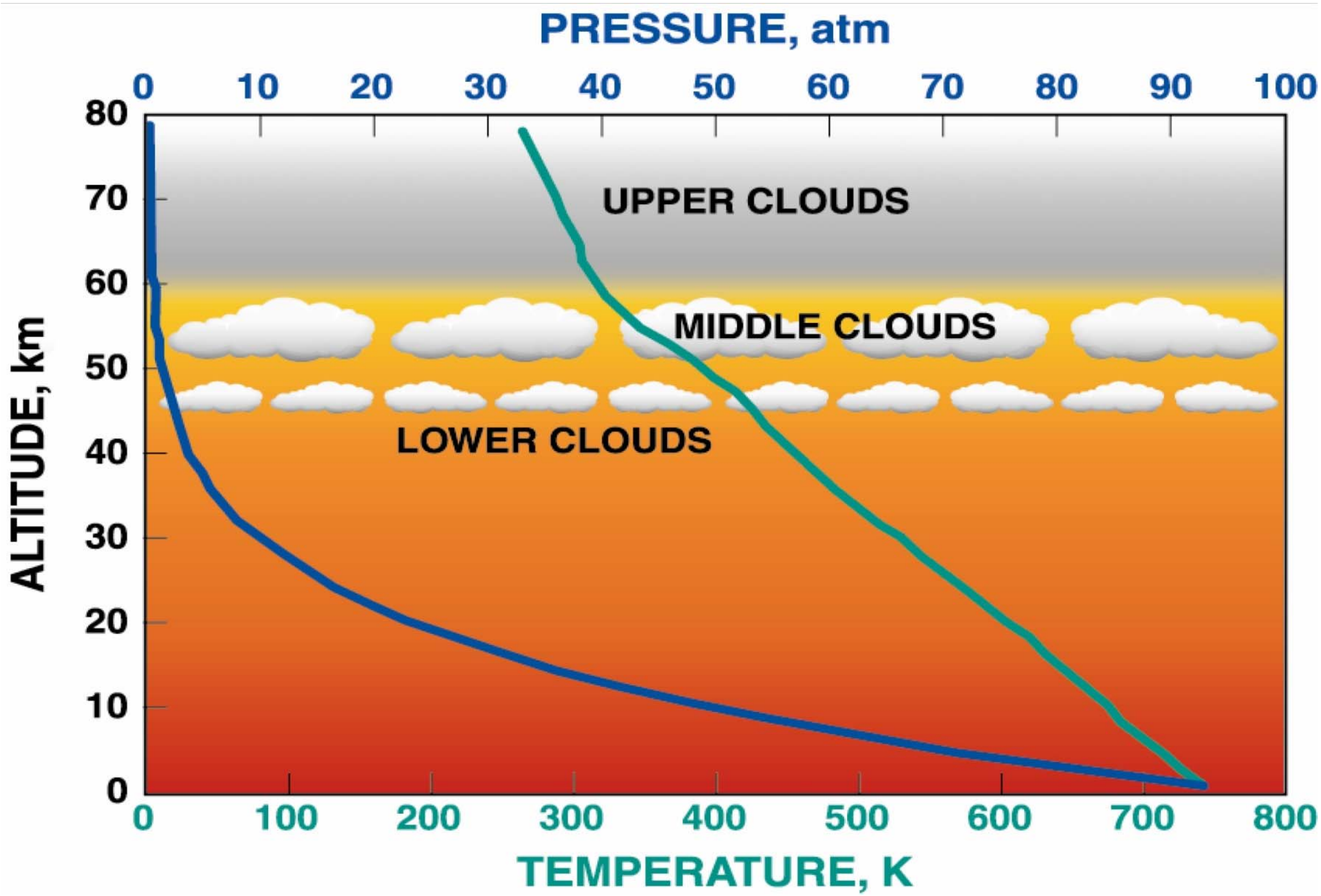
- 2nd planet from the sun
  - 0.72 AU
- A rocky, Earth-like planet
  - Not a gas or ice giant!
- Mean radius = 6,052 km (95% of Earth)
- Surface gravity = 8.87 m/s^2 (90% of Earth)
- Rotation period = 243 days (retrograde)
- Thick, dense, mostly CO_2 atmosphere
  - 460 °C surface temperature
  - 92 atm surface pressure
  - 100% cloud cover at all times
- Radar evidence of tectonic features: volcanoes, mountains, lava rivers, etc.
  - But it is unclear how much, if any, tectonic activity is current.

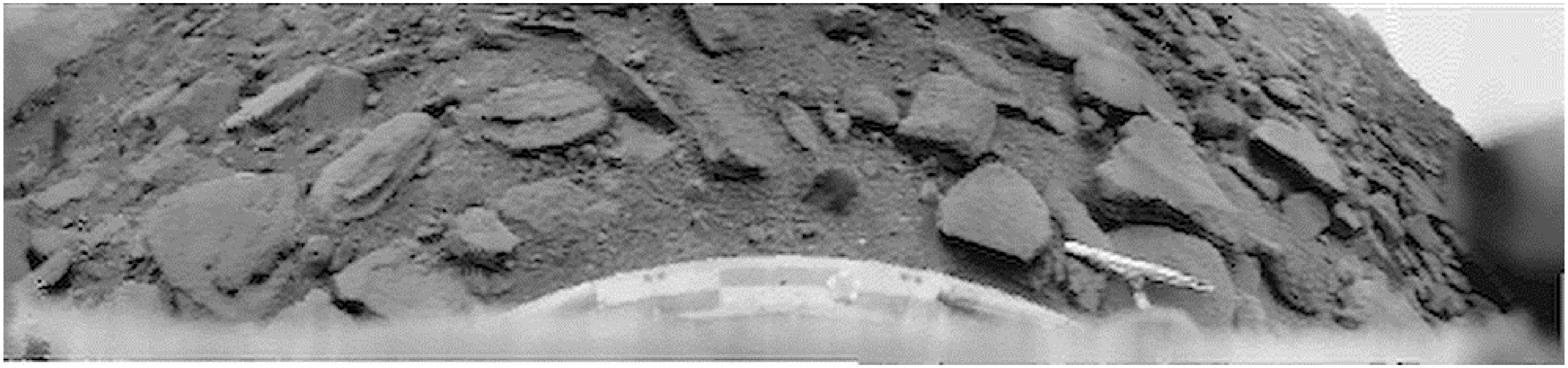
Visible image of Venus

Radar image of Venus

Venus Atmosphere

The atmosphere is very thick, with Earth-like temperatures and pressures around 55 km.





Venera 9 surface panorama (D. Mitchell)

Venera 13 surface panorama (D. Mitchell)

The Environmental Challenges of Exploring Venus

- Orbiters:
  - 100% cloud cover obscures surface, can only “see” via radar and, to a limited extent, through some narrow IR wavelength “windows”.
  - Very slow planetary rotation makes for slow mapping of the entire surface.
  - Relatively strong gravity requires substantial propulsion and aerobraking to achieve circular or near circular orbits.
- Balloons:
  - Clouds (45-60 km) are mostly made of sulfuric acid aerosols, pose a significant corrosion problem for any vehicle trying to fly through them.
  - Altitudes below the clouds are hot (>120 °C), posing a challenge to payload survivability over long durations (more than a few hours).
- Landers:
  - The high temperature (460 °C) and high pressure (92 atm.) pose severe challenges for electronic payloads.
  - Some terrain types (e.g., tesserae) are rough and difficult to safely land on and, for rovers, to drive on.

2. A Brief History of Venus Robotic Exploration

Robotic Exploration of Venus

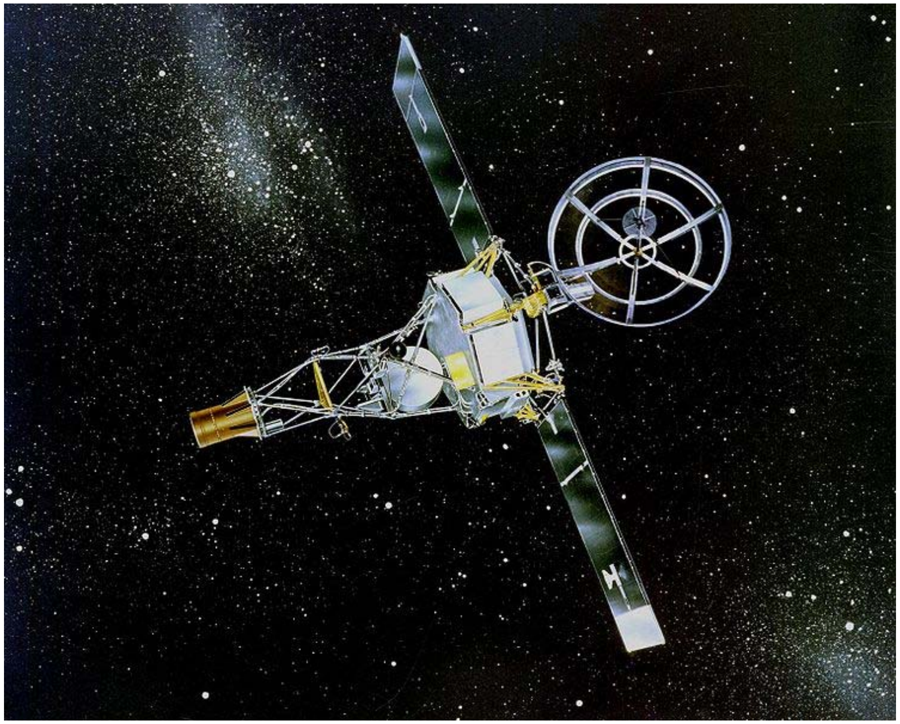
- Venus was an obvious target to visit as the Space Age got underway in the late 1950s and 1960s since it was so close to the Earth and so little was known.
- Altogether, there have been 23 robotic spacecraft missions specifically to Venus that have returned useful data.
  - See summary table on the next slide.
- Most of the missions occurred early in the space age:
  - 5 missions in the 1960s
  - 9 missions in the 1970s
  - 6 missions in the 1980s
  - 1 mission in the 1990s
  - 3 missions between 2000 and 2013 (2 ongoing)
- Why did the missions mostly stop?
  - Soviet Union disintegrated in the late 1980s, and their planetary exploration program, largely focused on Venus, came to a halt.
  - Mars exploration ramped up in the 1990s with the advent of mobile rovers and consumed a disproportionate fraction of the monetary resources.
  - The "easy" stuff at Venus has already been done, difficult to take the next steps because of the significant environmental challenges.

Summary Of Venus Spacecraft Missions

Year	Mission	Country	Vehicle	Synopsis
1962	Mariner 2	USA	flyby	First robotic space probe to visit another planet. Measured very high surface temp.
1967	Venera 4	USSR	lander	First data returned from atmosphere, but crushed by pressure before reaching surface. Found mostly CO2 in atmosphere. Only designed for 25 atm pressure.
1967	Mariner 5	USA	flyby	Discovered that surface pressure was ~100 atm (radio occultation experiment)
1969	Venera 5	USSR	lander	Crushed by pressure, sent 53 mins of atmospheric data
1969	Venera 6	USSR	lander	Crushed by pressure, sent 51 mins of atmospheric data
1970	Venera 7	USSR	lander	First data from the surface. But it was a hard landing (parachute failure) and very limited data returned. Confirmed 460 C surface temperature.
1972	Venera 8	USSR	lander	Successful landing, 50 minute transmission from surface. Found sufficient light for surface photography.
1973	Mariner 10	USA	Flyby	Made UV measurements of the atmosphere on its way to Mercury (gravity assist).
1975	Venera 9	USSR	Orbiter+lander	First orbiter, first photograph from surface.
1975	Venera 10	USSR	Orbiter+lander	Successful landing, second photograph from surface.
1978	Venera 11	USSR	Orbiter+lander	Landed, but lens cap did not separate and soil analyzer failed.
1978	Venera 12	USSR	Orbiter+lander	Landed, but lens cap did not separate and soil analyzer failed.
1978	Pioneer Venus 1	USA	Orbiter	First US orbiter, did radar mapping
1978	Pioneer Venus 2	USA	4 probes	All probes sent data from atmosphere, but were plagued by instrument failures below 15 km.
1982	Venera 13	USSR	flyby+lander	Lander set record of 127 minutes transmission from surface.
1982	Venera 14	USSR	flyby+lander	Lander survived for 57 minutes on surface.
1984	Venera 15	USSR	orbiter	Radar mapping spacecraft, partial surface coverage at 1-2 km resolution.
1984	Venera 16	USSR	orbiter	Radar mapping spacecraft, partial surface coverage at 1-2 km resolution.
1985	VEGA 1	USSR	flyby+lander+balloon	Lander signal lost after 20 minutes on surface. Balloon flew successfully for 46 hours.
1985	VEGA 2	USSR	flyby+lander+balloon	Lander survived for 60 minutes on surface. Balloon flew successfully for 46 hours.
1990	Magellan	USA	orbiter	Provided extensive radar mapping of surface (98%) at 100 to 300 m resolution. First use of aerobraking at end of mission.
2006	Venus Express	ESA	orbiter	Still operational. Focused on atmospheric science. Confirmed presence of lightning.
2010	IKAROS	Japan	flyby	Solar sail tech demo, very limited science return
2010	Akatsuki	Japan	orbiter	Failed to enter orbit in 2013, will try again in 2015.

Ongoing missions highlighted in green. Does not list those missions that failed to send back useful data.
Does not list Galileo, Cassini and Messenger missions that did Venus gravity assist flybys and collected some data.

Venus Spacecraft Images

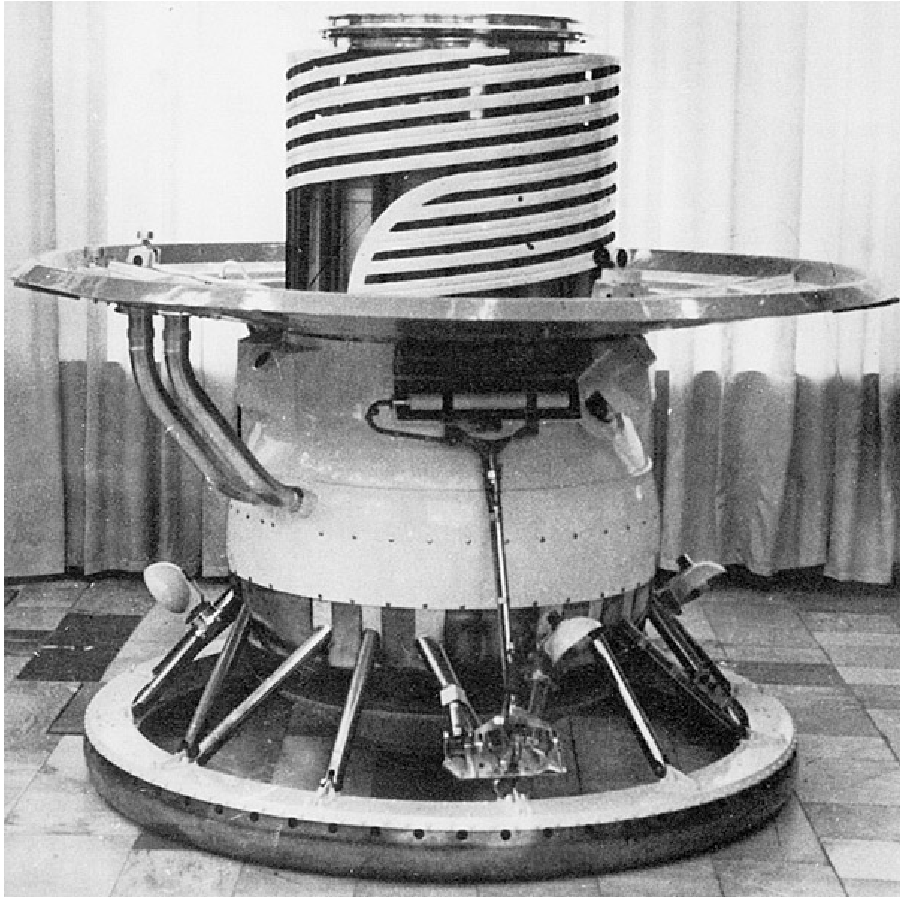


Mariner 2 flyby spacecraft (200 kg).

Venera 4 flyby + lander (1100 kg).

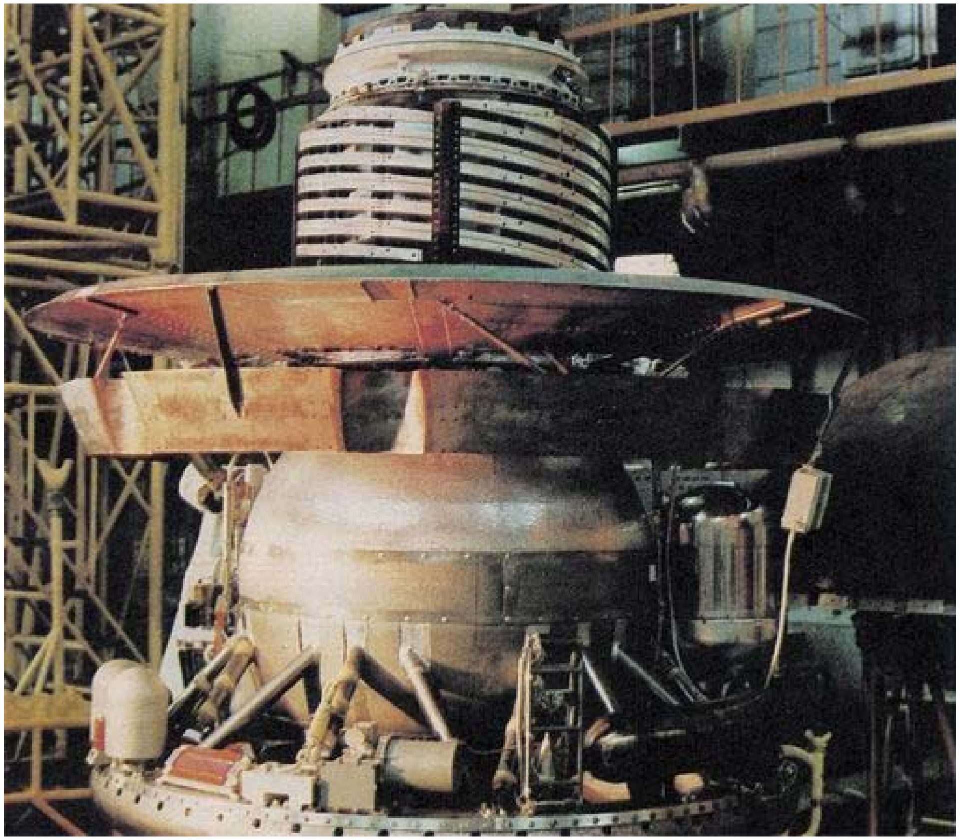
Venus Spacecraft Images (2)

Pioneer Venus Multiprobe (315 kg large, 3x90 kg small)



Venera 9 Lander (660 kg)

Venus Spacecraft Images (3)

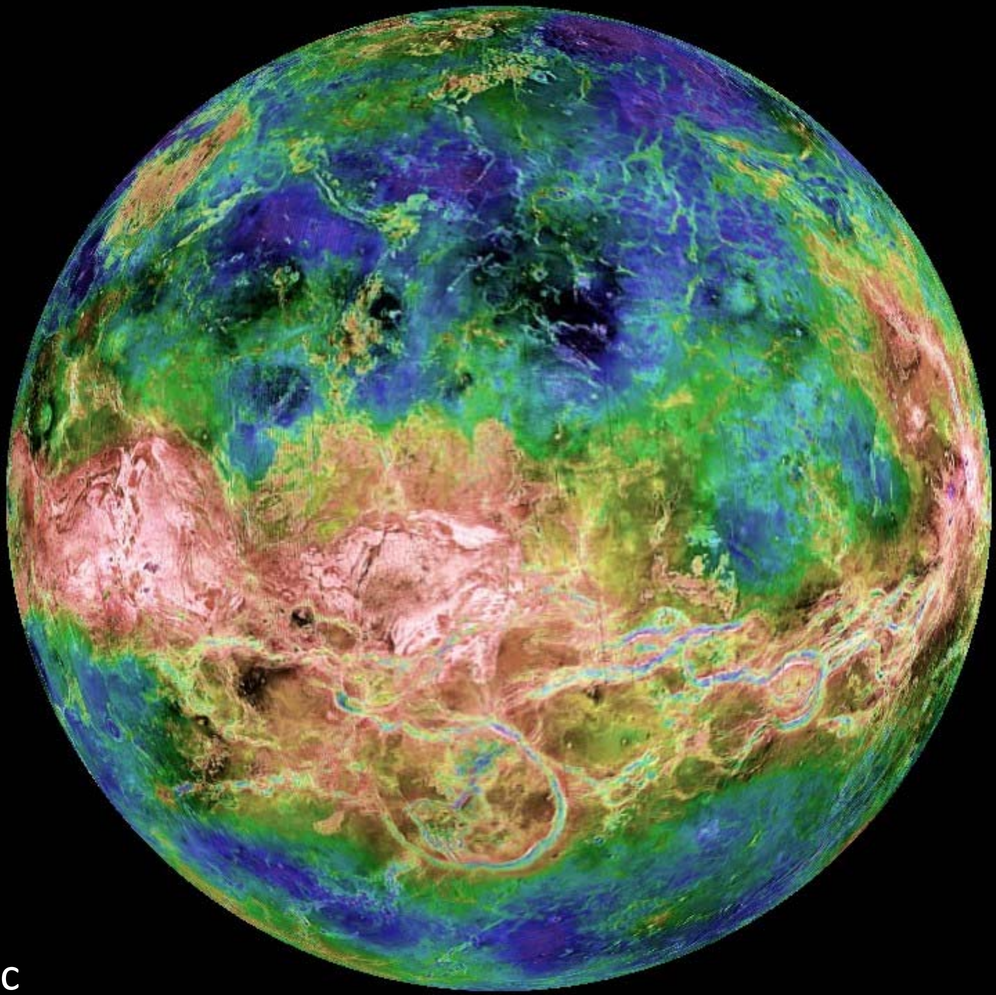


VEGA lander (750 kg)

VEGA balloon (22 kg)

Magellan Orbiter (1989 to 1994)

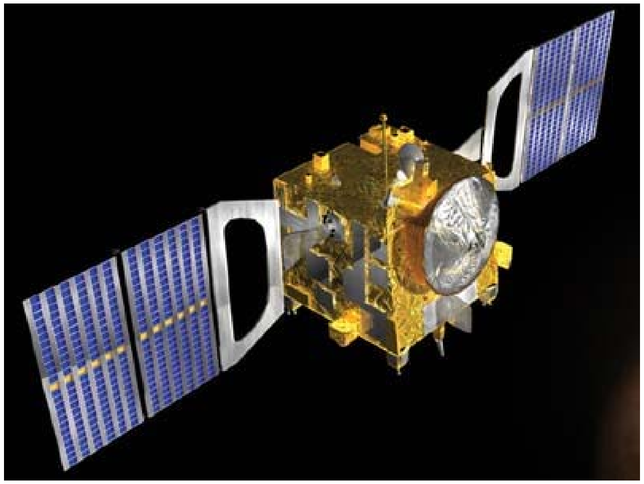
Magellan orbiter (1035 kg)



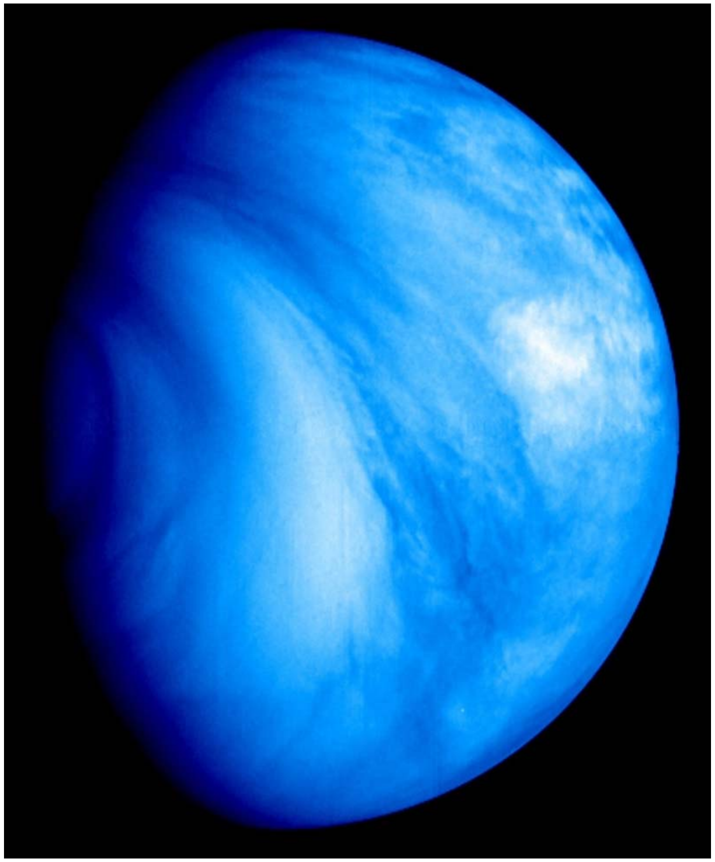
Global map of Venus with Synthetic aperture Radar revealed the surface of Venus as we currently know it

Venus Express

- Launched in 2005, it is the only spacecraft currently operational at Venus



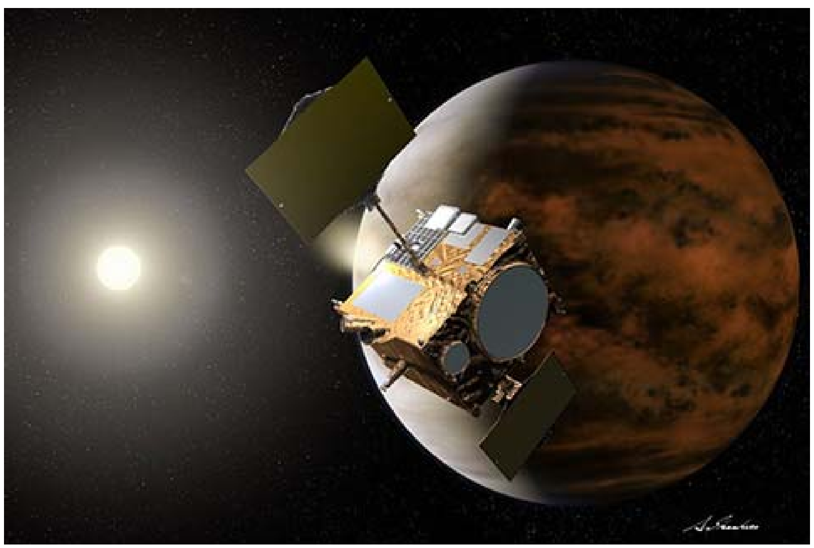
- Key results:
  - Extensive mapping of upper atmosphere winds with VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) instrument.
  - Detailed mapping of cloud structure over many different regions.
  - Confirmation of lightning on Venus (more common than on the Earth).
  - First large scale temperature maps of the southern hemisphere surface.



Venus Express UV image (false color) of Venus southern hemisphere.

Akatsuki

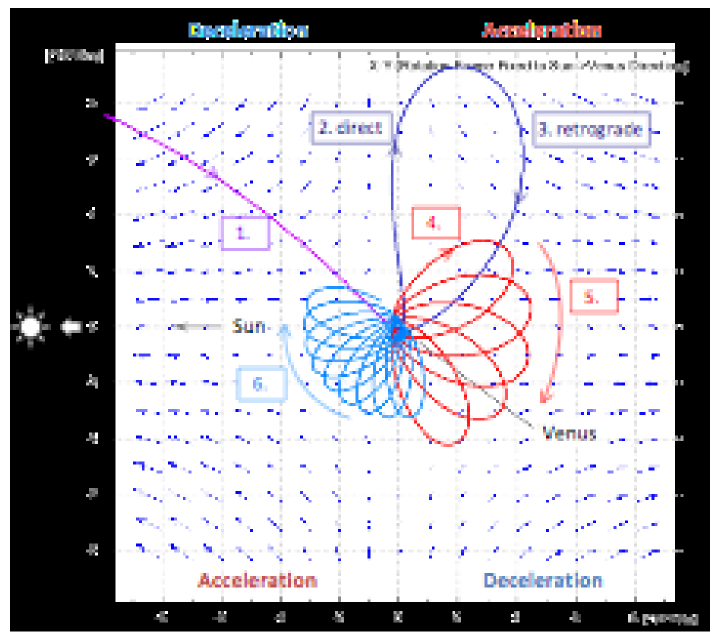
- Akatsuki is Japan's first scientific mission to Venus
- It's main propulsion system failed when it attempted to enter Venus orbit on December 2010
- The spacecraft is still operational and will attempt to enter Venus orbit in November 2015 using attitude control thrusters only



Akatsuki: The 500 kg spacecraft is based on the design of the Mars spacecraft Nozomi

- **Instruments: t**he scientific payload consists of six instruments
- Lightning and airglow camera (LAC),
- Ultraviolet imager (UVI),
- Longwave infrared camera (LIR),
- 1 μm camera (IR1),
- 2 μm camera (IR2)
- Radio science (RS) experiment.

Akatsuki – Orbit Insertion Design



3. Characteristics of Venus Orbiters, Balloons and Landers

Venus Orbiters

- In most respects, Venus Orbiters are not particularly challenging and can take advantage of Earth and Mars orbiter technology.
  - Indeed, Venus Express was heavily adapted from the Mars Express spacecraft bus.
  - Perhaps the key challenge is thermal control of the spacecraft given the high solar flux and backscattered solar radiation from the clouds, but this is an engineering problem, not a new technology requirement.
- Orbiters of more than 1000 kg are certainly possible.
- Solar power is abundant.
- All orbiters to date have utilized highly elliptical orbits to save on propellant mass needed to circularize the orbit after propulsive orbit insertion.
  - Magellan did an aerobraking demonstration at the end of its mission, paving the way for subsequent aerobraking usage at Mars. There is no reason why future Venus orbiters could not use aerobraking as well to achieve low circular orbits if necessary.

Venus Balloons

- There are many different kinds of balloons possible depending on the altitude, flight duration, payload mass and trajectory controllability required.
- The long history of ballooning on Earth provides a starting point for Venus balloon designs.
  - Many key examples are given on the next slide.
- Venus balloons must tolerate the extreme environment on Venus, which is primarily sulfuric acid at higher altitudes and hot temperature and pressures at lower altitudes.
  - Teflon was used by the VEGA balloons to survive the sulfuric acid.
  - Thin-walled metal balloons can be used in the dense, hot lower atmosphere.
    - Although some early prototyping has been done on metal balloons, much technology development work is still required.
- The VEGA balloons were 3.5 m in diameter and carried a 7 kg payload at 53-54 km.
  - Recent JPL work has produced superpressure balloon prototypes in the 5.5 to 7 m diameter range that are capable of carrying 40-100 kg at 55 km altitude.
  - Larger payloads are certainly possible, especially in the more dense lower atmosphere.

Standard Balloon Types

Type	Description	Altitude Control
Superpressure	Sealed, constant volume balloon. Balloon changes pressure instead of volume. (e.g. VEGA)	Inherently stable in altitude until pressurization is lost.
Zero pressure	Vented balloon through long ducts. Most common scientific balloon used on Earth.	Requires active control. Typically achieved with gas venting and ballast drops.
Weather	Highly flexible rubber balloon, designed for one vertical profile only.	Unstable in altitude. Performs one ascent, then bursts upon reaching max altitude.
Hot air	Vented through hole at bottom of balloon. Heat source (chemical, sun, nuclear) provides buoyancy.	Requires active control of buoyancy through opening and closing of apex valve and/or burner variations for chemical heat sources.
Blimp	Sealed, streamlined, constant volume balloon. Internal compartment (ballonet) fills/unfills with ambient atmosphere to maintain internal pressure and hence shape.	Requires active control via onboard propulsion system and control surfaces (like an airplane).





JPL Venus Superpressure Balloon Development

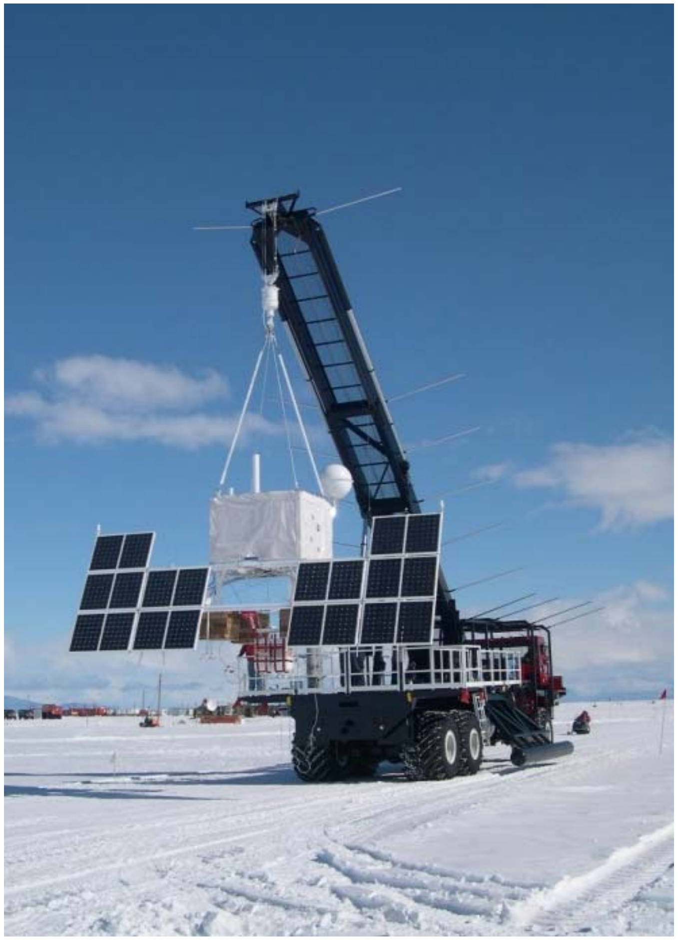
- JPL and its partners designed, fabricated and tested two 5.5 m diameter balloons in recent years.
  - Payload capacity is 45 kg at 55 km.
  - Lifetime is predicted to be in excess of 30 (Earth) days.
- A new 7 m prototype is under construction that can carry 110 kg at 55 km.
- These full scale balloons have been accompanied by multiple subscale prototypes and materials testing to assess buoyancy, leakage, sulfuric acid resistance and folding/packaging robustness.

	VEGA	JPL
Diameter (m)	3.5	7.0
Carry mass (kg)	7	110
Lifetime (days)	2	10+

First 5.5 m Venus prototype balloon in lab testing.

Balloon Payloads

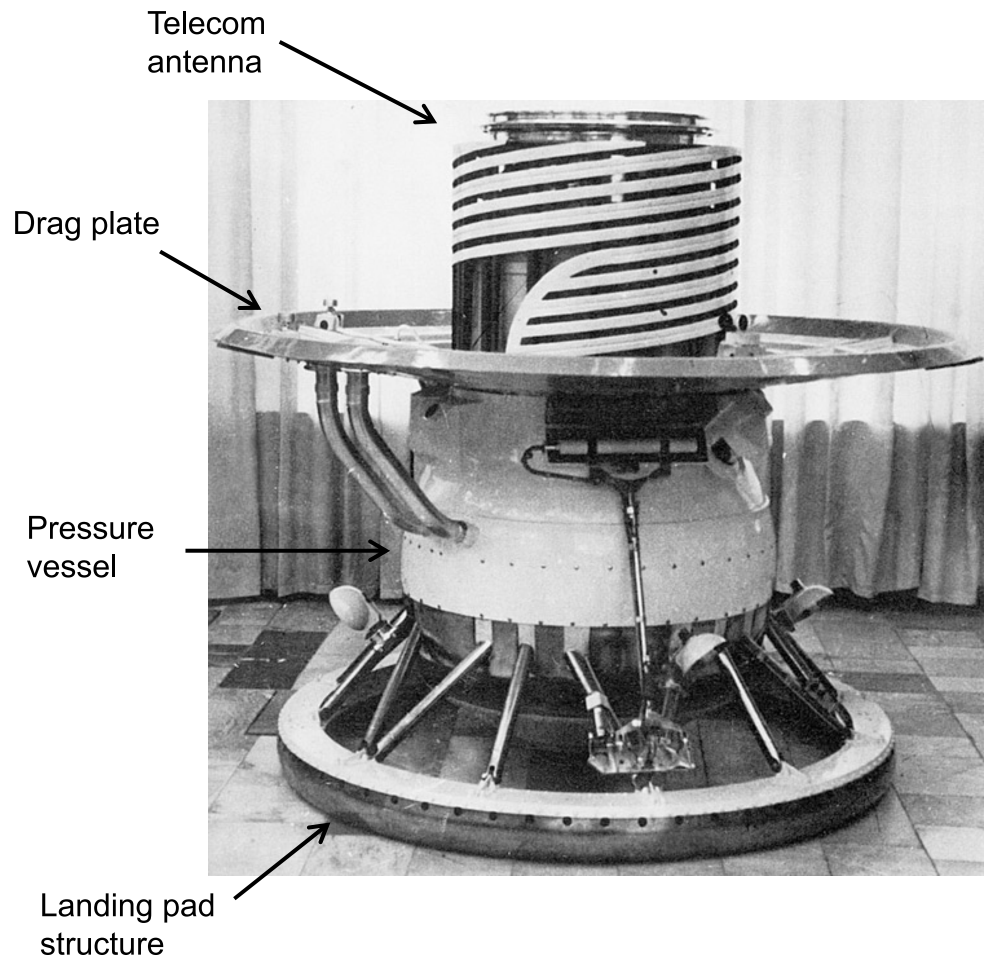
- The payload compartment hanging below the balloon is often called the “gondola”, analogous to the term used for passengers on a terrestrial balloon.
- On Earth, gondolas range from 100 gram radiosondes on weather balloon to 2000 kg payloads for large astrophysical missions in the stratosphere.
- For a Venus space mission, the gondola will house all of the required spacecraft elements needed to explore:
  - Scientific instruments.
  - Telecommunications system.
  - Command and data handling electronics.
  - Electrical power generation and distribution.
  - Support structure and environmental enclosure.
  - Thermal control system.
- More sophisticated self-propelled balloon vehicles (e.g., blimps) will also require propulsion and guidance and control systems.



Terrestrial “CREAM” experiment 2005 (NASA and Univ. of Maryland)

Venus Landers

- All Venus atmospheric probes and landers to date have used insulated pressure vessels to protect the payload from the high temperature, high pressure environment.
  - However, survival lifetimes have been limited to only a couple of hours because the payload eventually heats up and dies.
  - Better insulation and new phase change heat sink materials can at best provide survival lifetimes on the order of a day.



Venera 9 Lander

Venus Landers (cont.)

- There are only two options for persistent (weeks, months) operation on the surface of Venus:
  - Develop very substantial nuclear-powered refrigeration technology (many kW of power) to enable survival of currently available electronic payloads.
  - Develop new electronic payloads that can operate for long periods at 460 °C.
- What is the status of these two options?
  - Although conceptual designs exist for nuclear powered refrigeration systems on Venus, development is not funded and planned U.S. production of plutonium-238 may not be sufficient to support both Venus and other planetary science priorities in the near-term.
  - High temperature electronics are under development across many institutions, but to date only a very limited set of components can operate at 460 ° C.

High Temperature Actuators and Mechanisms

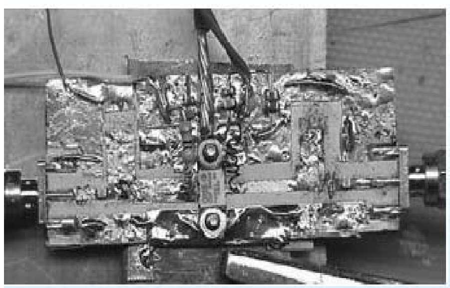
- The Venera missions successfully demonstrated drills on the surface of Venus
- NASA has been developing mechanisms that could be applied in manipulators and for sample acquisition
- NASA Glenn Research Center has also built and demonstrated a seismometer for operation at 500 ° C
- Operation at Venus surface temperatures of 460 °C requires:
  - Wide band gap semiconductors such as SiC and GaN.
  - Thermionic vacuum devices.

Switched-Reluctance Motor: 8,000 rpm at 540°C

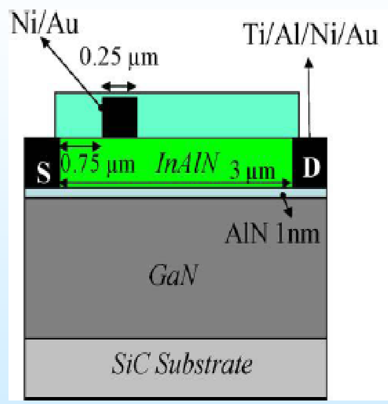
High Temperature Seismometer Mechanism

High Temperature Electronics (500 °C operation)

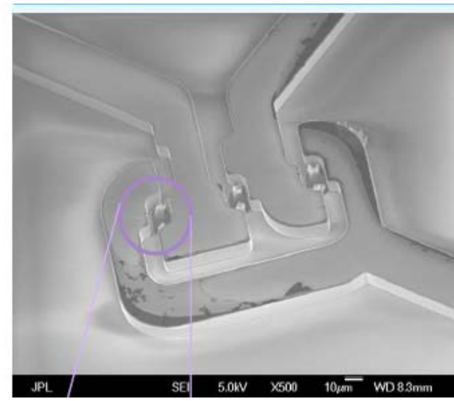
- *Silicon carbide semiconductors: B*asic electronic components have been demonstrated with long-term operation of thousands of hours at 500 °C. The level of complexity is low and memory is has high power consumption.
- *Gallium Nitride Semiconductors*: High-electron-mobility transistor (HEMT) devices have been demonstrated at 500 °C. More advanced circuits are under development. This technology is still at a very low level of maturity.
- *Digital Vacuum Electronics:* Recent efforts in this area have exploited the properties of carbon nanotube electron sources which operate as field emitters without the need for a heated cathode. Unlike semiconductors, there are no temperature-dependent leakage currents to deal with. This field is immature



High Temperature SiC RF Amplifier Prototype (Softronics)



InAlN/GaN HEMT Design

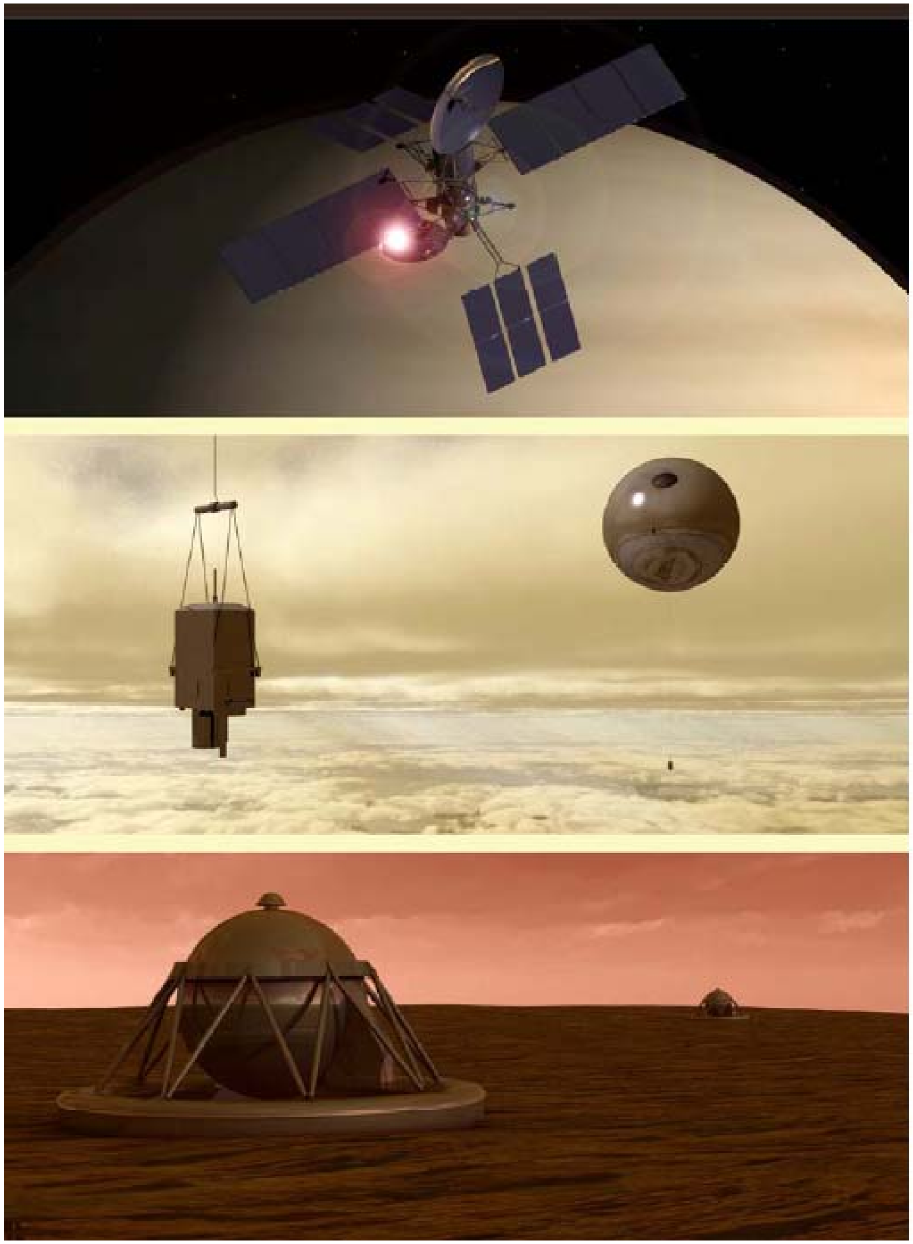


CNT IMG developed at NASA JPL

4. Plans and Possibilities for Future Venus Missions

Venus Flagship Mission

- A NASA sponsored study completed in April 2009.
- Key elements were:
  - A capable long lived orbiter with high resolution radar imaging and topography
  - 2 instrumented balloons at 55 km altitude and 1 month lifetime
  - 2 landers with extended surface life of 5 hours
- The study also examined the impact of various advanced technologies on a Venus mission
- Although never implemented the study has influenced many of the concepts subsequently developed.



NASA Strategic Missions

- NASA's Planetary Science Decadal Survey of 2011 recommended two strategic missions to Venus for the decade 2013 to 2022:

  1. Venus Climate Mission (VCM)
     - Instrumented gondola carried by a balloon.
     - Miniprobes and microprobes
     - Carrier relay orbiter

  2. Venus In Situ Explorer (VISE)
     - Single lander with a lifetime of several hours

- VCM has been deferred to the next decade. VISE will be competing for an opportunity in the NASA New Frontiers Program with an expected launch in 2023.

Venera-D – Proposed Russian Mission

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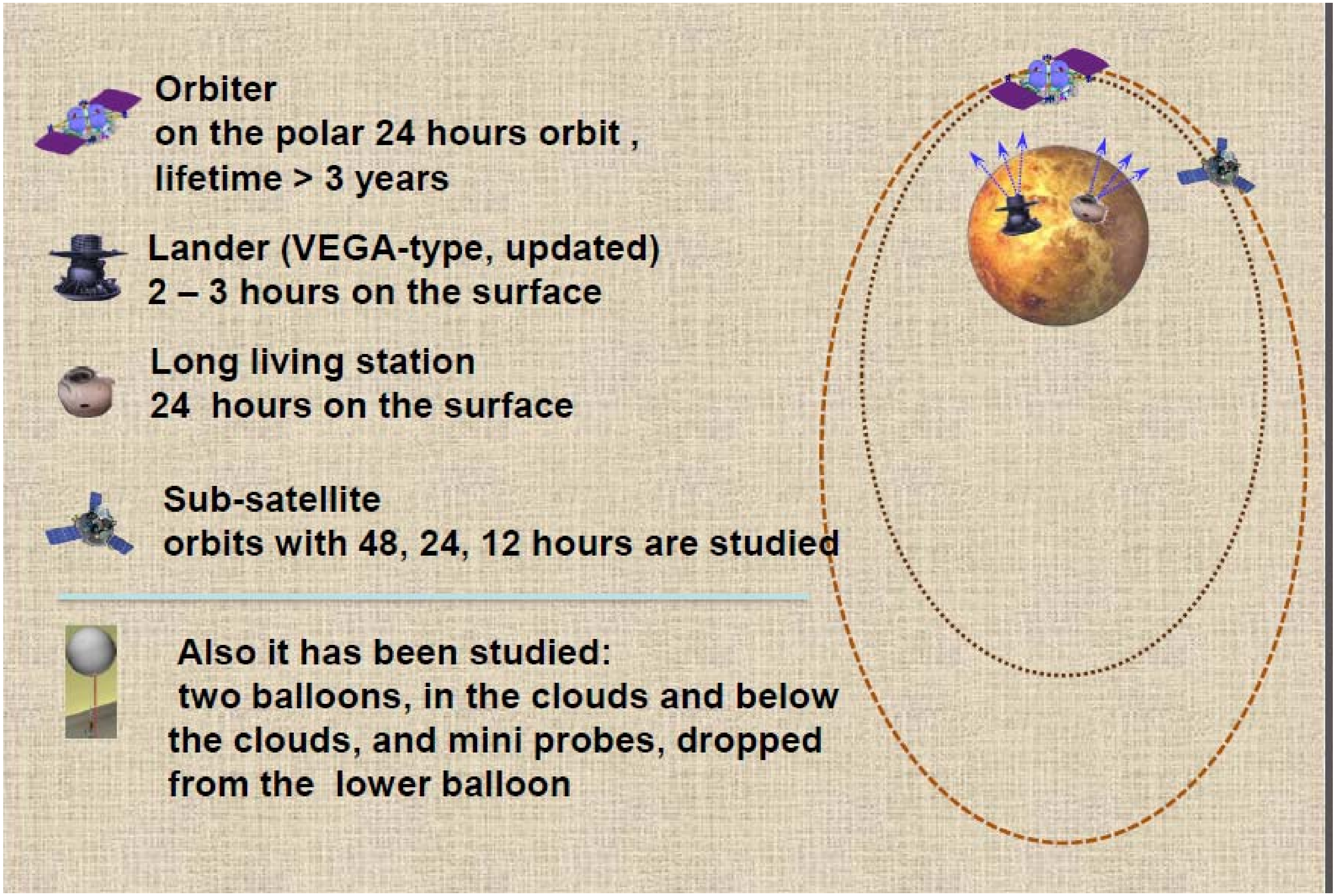

NASA began a partnership with Russia on Venera D in January 2014. This was suspended in April 2014 following the Crimea invasion

Discovery (NASA) and M-Class(ESA) Opportunities

- Both NASA and ESA lack a defined Venus exploration program; therefore, Venus missions must be won through competitive programs.
- There are two opportunities in 2014 to propose a Venus mission:
  - NASA's Discovery Program (D13, launch Dec 2021)
  - ESA's M-Class Program (M4, launch Dec 2024?)
- After 15 years of the Discovery program, there is yet to be a successful Venus proposal. At the last opportunity three years ago there were seven unsuccessful proposals including:
  - Orbital missions targeted at both surface and atmospheric science
  - Balloon missions – 55 km above the surface
  - Descent probe missions – going to the surface
- The Venus science community believes a Discovery selection is long overdue and has been work hard to lay the ground work for a successful proposal. Nevertheless several separate proposals are still expected.
- The Europeans have decided to focus their efforts on a single Venus concept called EnVision – an orbiter with an interferometric radar based on ESA's Sentinel radar.

Conclusions

- Venus has been and will be explored in the future with orbiter, balloon, probe and lander vehicles.
- Scientific progress at Venus requires more ambitious missions than have been done in the past.
  - The "easy" stuff has been done already, and it wasn't very easy to begin with.
- There are significant environmental challenges for Venus exploration platforms, particularly for deep atmosphere and landed platforms that must tolerate very high temperatures of up to 460 °C.
- Technology exists today that can enable many exciting Venus missions.
  - These form the basis of competed mission proposals to the NASA Discovery, NASA New Frontiers and ESA Cosmic Visions programs.
- New technology is required for many other kinds of desirable Venus missions including:
  - Persistent deep atmosphere or surface missions.
  - Altitude-cycling or controllable altitude balloons.
  - Airplanes and gliders.