Science on the fly! The importance of Venus flyby observations

C. Gray¹, P. K. Byrne², S. Curry³, J. G. O'Rourke⁴, Emilie Royer⁵

¹New Mexico State University – Apache Point Observatory, 1780 E University Ave, Las Cruces, NM 88003, ²North Carolina State University, Raleigh, NC 27695, ³Space Science Laboratory, University of California, Berkeley, CA 94720, ⁴School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85281, ⁵Planetary Science Institute, Tucson, AZ 85719

Candace Gray

575-646-6399

New Mexico State University – Apache Point Observatory

candaceg@nmsu.edu

Goal

The importance of executing flyby science, typically with missions that are performing a gravity assist or maneuver, cannot be understated. Making science observations during a gravity assist can provide:

- Feedback and calibration for the individual instruments;
- A primary science target to test instrument health when collecting data simultaneously;
- Science from state of the art instruments, which broaden the number of data points we have at Venus over different seasons, solar cycles and orbits; and
- Comparative paleontology between Venus and primary mission target.

In this white paper, we urge two recommendation for future missions:

- 1. Require any mission that plans to fly by Venus to take data at Venus**
- 2. Require the mission team to have a dedicated Flyby Coordinator either as an existing team member or via a solicitation similar to a Participating Scientist**

Motivation

As mission flight paths are known well in advance, Venus flyby science can be coordinated with other science teams, institutes, and facilities, increasing the science return of the mission as well as improving our understanding of Venus. By having a dedicated member on a mission team to promote and coordinate observations, the highest priority instruments to Venus science can be utilized. Furthermore, a dedicated Flyby Coordinator can organize ground-based coordinated campaigns and even other spacecraft missions with mission flybys, improving the overall impact of the mission.

A number of science investigations are well suited for Venus flyby campaigns. For example, the interaction of the solar wind with upper atmosphere (including atmospheric escape) can be studied with plasma measurements, such as measuring ions, electrons, solar energetic particles, plasma waves, and magnetic fields using electrostatic analyzers, solid state detectors, Langmuir probes, and magnetometers, respectively.

In the same vein, radio occultations can be performed depending on the orbit geometry to infer information about the lower and middle neutral atmospheric densities. Additionally, neutral mass spectrometers can make critical measurements about isotopes and major and minor neutral constituents in the atmosphere. Infrared imaging can be especially important for understanding the geomorphology and signatures of minerals that form in the presence of water. Imaging in infrared, visible, and the ultraviolet can capture cloud dynamics over a large range of altitude as well as upper atmospheric dynamics via airglow and aurora. **Figure 1** shows all missions to have collected data at Venus whether as an orbiter, lander, probe or flyby. It can be seen that while Venus missions have decreased, Venus flyby science has increased. **Table 1** lists all flyby missions that have collected data as well as instrumentation which was used.

Figure 1: Timeline of all mission that have collected data at Venus. Only those missions that successfully conducted *some* science at Venus are shown here; for a more complete table showing all missions, both attempted and successful, to observe Venus, please see <https://drive.google.com/file/d/1-ijhoBr81zWMammOWLvc3chzaLMqJe7S/view?usp=sharing>. Here, F: Flyby; P: Probe; O: Orbiter; L: Lander; B: Balloon. Groups of two letters denote multi-platform missions. Missions are color-coded by national space agency: blue: NASA; red: Soviet Union; purple: European Space Agency; orange: Japanese Aerospace Exploration Agency.

Table 1: Venus flyby missions and instruments used to collect data. For a more detailed table, please see <https://drive.google.com/file/d/1y5HGx6DWq5MZdnbb5ntG1QyvBAOQfaD3/view?usp=sharing>.

Mission	Dates		Instruments
	Launch	Venus Flyby	
Mariner 10	1973-11-03	1974-02-05	<ul style="list-style-type: none"> • Magnetometer • Television Photography Experiment • Infrared radiometer • Ultraviolet spectrometers • Plasma detectors
Galileo	1989-10-18	1990-02-10	<ul style="list-style-type: none"> • Solid State Imager (SSI) • Near-IR Mapping Spectrometer • UV/EUV Spectrometer • Spectrometer Telescope for Imaging X-rays (STIX) • Dust Detector Subsystem (DDS) • Magnetometer (MAG) • Plasma Wave Subsystem (PWS) • Plasma Subsystem (PLS) • Plasma Subsystem (PLS) • Energetic Particles Detector (EPD)
Cassini	1997-10-15	1999-08-18	<ul style="list-style-type: none"> • Magnetospheric Imaging Instrument (MIMI) • Radio and Plasma Wave Science (RPWS) • Imaging Science Subsystem Narrow Angle Camera (ISSNA) • Imaging Science Subsystem Wide Angle camera (ISSWA) • Visible and Infrared Mapping Spectrometer (VIMS-IR and VIMS-Vis)
MESSENGER	2004-08-03	2006-10-24 2007-06-05	<ul style="list-style-type: none"> • Mercury Dual Imaging System Narrow Angle Camera (MDIS-NAC) • Mercury Dual Imaging System Wide Angle Camera (MDIS-WAC) • Mercury Atmospheric and Surface Composition Spectrometer (MASCS) UV/VIS/IR • Radio science (RRS) • Gamma Ray Spectrometer (GRS) • Mercury Laser Altimeter (MLA) • Neutron Spectrometer (NS) • X-Ray Spectrometer (XRS) • Magnetometer (MAG) • Energetic Particle and Plasma Spectrometer (EPPS)

Parker Solar Probe	2018-08-12	2018-10-03 2019-12-26 2020-07-11 2021-02-20 2021-10-16 2023-08-21 2024-11-06	<ul style="list-style-type: none"> • Electromagnetic Fields Investigation (FIELDS) • Integrated Science Investigation of the Sun (IS $\odot$ IS) • Wide-field Imager for Solar Probe (WISPR) • Solar Wind Electrons Alphas and Protons (SWEAP)
<u>BepiColombo</u> Mercury Planetary Orbiter (MPO)	2018-10-20	2020-10-15 2021-08-11	<ul style="list-style-type: none"> • BepiColombo Laser Altimeter (BELA) • Italian Spring Accelerometer (ISA) • Mercury Magnetometer (MPO-MAG, MERMAG) • Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS), • Mercury Gamma-ray and Neutron Spectrometer (MGNS) • Mercury Imaging X-ray Spectrometer (MIXS) • Mercury Orbiter Radio-science Experiment (MORE) • Probing of Hermean Exosphere by Ultraviolet Spectroscopy (PHEBUS) • Search for Exosphere Refilling and Emitted Neutral Abundances (SERENA) • Spectrometers and Imagers for MPO • BepiColombo Integrated Observatory System (SIMBIO-SYS) • Solar Intensity X-ray and Particle Spectrometer (SIXS)
<u>BepiColombo</u> Mercury Magnetospheric Orbiter (Mio)	2018-10-20	2020-10-15 2021-08-11	<ul style="list-style-type: none"> • Mercury Plasma Particle Experiment (MPPE) • Mercury Magnetometer (MMO-MGF) • Plasma Wave Investigation (PWI) • Mercury Sodium Atmosphere Spectral Imager (MSASI) • Mercury Dust Monitor (MDM)
Solar Orbiter	2020-02-11	2020-12-26 2021-08-08 2022-09-03 2025-02-18 2026-12-24 2028-03-17 2029-06-10 2030-09-02	<ul style="list-style-type: none"> • Solar Wind Plasma Analyser (SWA) • Energetic Particle Detector (EDP) • Magnetometer (MAG) • Radio and Plasma Waves (RPW) • Polarimetric and Helioseismic Imager (PHI) • Extreme Ultraviolet Imager (EUI) • Spectral Imaging of the Coronal Environment (SPICE) • Spectrometer Telescope for Imaging X-rays (STIX) • Multi Element Telescope for Imaging and Spectroscopy (METIS) • Solar Orbiter Heliospheric Imager (SoLoHI)

Previous Flyby Observations

The Galileo spacecraft exemplified how flybys can capture snapshots of atmospheric structure and dynamics to establish long-timescale baselines. For example, its ultraviolet spectrometer revealed variations associated with the periodicity of the rotation of the sun (Hord et al., 1991). The near-infrared mapping spectrometer found substantial heterogeneity in cloud opacity in the lower cloud levels, which permitted derivations of zonal and meridional winds (Carlson et al., 1991). These infrared images remain useful as updated techniques are applied to observations of Venus' unique atmospheric phenomena (e.g., Kouyama et al., 2012).

Cassini flew twice by Venus, on April 26, 1998 and June 24, 1999. Although very few scientific observations were taken during the first encounter, a change in project management by the time of the second flyby prompted the removal of previous restrictions. Cassini performed unprecedented investigations at Venus, such as a search for lightning, measurements of the electron density profile in Venus' ionosphere, and atmospheric observations using new wavelength ranges (Burton et al., 2001; Hubert et al., 2010, 2012; Gerard et al., 2011; Baines et al., 2000; Lorenz et al., 2001; Gurnett et al., 2001). Lessons learned from the Cassini observations at Venus motivated the development of new instrumentation targeting CO₂-dominated atmospheres. MAVEN instrumental requirements were designed keeping in mind the insightful measurements made by the Cassini spacecraft at Venus as well as previous missions, such as VEX and PVO.

The MESSENGER spacecraft was too far from Venus for meaningful scientific measurements during its first flyby, in 2006; however, the spacecraft passed within 338 km during its second encounter with the second planet in 2007 (Slavin et al., 2009). This second flyby was carried out as a “dress rehearsal” for eventual orbital operations at Mercury (McNutt et al., 2008). Numerous instruments on the MESSENGER payload were used to acquire data during this second flyby, including the X-Ray Spectrometer, the Mercury Laser Altimeter, and the Ultraviolet and Visible Spectrometer and the Visible and Infrared Spectrograph components of the Mercury Atmospheric and Surface Composition Spectrometer (McNutt et al., 2008).

Notably, the second MESSENGER flyby coincided with orbital operations of the ESA Venus Express spacecraft, which returned observations of Venus from 2006 through 2014. As a result, it was possible to compare and even coordinate measurements by MESSENGER and Venus Express. During the MESSENGER flyby, Venus Express was situated outside the Venus magnetosphere, and showed that the interplanetary magnetic field (IMF) changed direction four times as MESSENGER traveled through the inner magnetosphere (Benna et al., 2009). Such coordinated observations indicate the value of science performed opportunistically by a spacecraft flying by Venus when another spacecraft is in orbit of the planet.

The MESSENGER spacecraft acquired views of Venus with the 1.00 μ and 1.02 μ filters of the Mercury Dual Imaging System (MDIS) wide-angle camera (McNutt et al., 2008). Those images returned some view of the Venus surface, mirroring observations by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) and the Venus Monitoring Camera (VMC) on Venus

Express (e.g., Helbert et al., 2008), and the IR1 camera carried by the JAXA Akatsuki spacecraft (Nakamura et al., 2016).

The Parker Solar Probe (PSP) mission is currently studying the solar corona in intense detail, and will fly closer to the Sun than any spacecraft before by performing seven gravity assists at Venus. These gravity assists provide a rare opportunity to study the Venusian atmosphere, the induced magnetosphere, and the solar-wind interaction at Venus using the plasma instrumentation aboard PSP. Venus's upper atmosphere hosts several atomic species such as hydrogen, helium, oxygen, carbon, and argon, some of which are energized in the upper atmosphere to escape energies or ionized and carried away from the planet. *What is special about Venus, as opposed to Mars, is that virtually all significant present-day atmospheric escape of heavy constituents is in the form of ions.*

Using the Solar Wind Electrons Alphas and Protons Investigation (SWEAP) and Fields experiment (FIELDS), plasma observations from the PSP Venus gravity assists will be analyzed [Bale et al., 2016; Kasper et al., 2016]. A coordinated ground-based campaign was designed around the PSP Venus flybys with three observatories monitoring the Venusian aurora: Apache Point Observatory, Lick Observatory, and Keck Observatory.

Additionally, the solar wind measurements observed during the flybys can be used as initial inputs into magnetohydrodynamic (MHD) models to present a global picture of the induced Venusian magnetosphere and the subsequent ion precipitation, escape, and magnetic topology throughout each of the flybys. Each of these flybys can be studied and compared to understand how the solar wind evolves over solar cycle 25, as well as how the Venusian atmosphere responds to the solar wind and solar transient structures.

The BepiColombo spacecraft will fly by Venus on October 15, 2020 and August 11, 2021, providing extensive measurements of the atmosphere by all instruments onboard. The inclusion of guest participating scientists to BepiColombo during flybys have broadened the team's expertise. The BepiColombo Venus flybys will allow for unique joint observations with the current JAXA Akatsuki spacecraft. The scientific return will then be tripled by completing the set of observations with simultaneous ground-based measurements of Venus, enabling us to view the planet from three different angles at the same time. The combination of BepiColombo, Akatsuki, and ground-based operations at Venus sets a gold standard regarding flyby science of the second planet in particular, and of flybys of planets generally. Furthermore, in order to help facilitate coordinated observations, The Akatsuki team developed software to identify viewing geometries from different viewing platforms with an example shown in Figure 2. Their software allows users to display observational geometries of Venus seen from BepiColombo, Parker Solar Probe, Akatsuki, and from the Earth. A similar tool developed for all missions that conduct Venus flyby is greatly desired and can improve the coordination of various teams.

To enhance scientific return on mission and thus improving return on investment, we suggest the NASA mission directorate adopt the lessons learned from this joint ESA-JAXA

opportunity and provide resources for U.S.-based researchers to better assess and take advantage of the possible combined efforts between teams having spacecraft flying by the same target.

Figure 2: Example of viewing geometry widget developed by the Akatsuki spacecraft team to determine viewing geometries from Akatsiku, Bepicolombo, Parker Solar Probe, and the Earth.

Conclusions

Science performed during flybys, with a suite of instruments designed for another planets, have led in the past original discoveries (Hubert et al., 2010, 2012; Gerard et al., 2011; Baines et al., 2000) and have provided new sets of guidelines for the design of future instrumentation toward planets used for gravity assist. Numerous missions that have flown past Venus were equipped with camera systems capable of either imaging the full disk of the planet or, if in the infrared or ultraviolet, resolving cloud structure or even features on the surface. Even if not part of any planned imaging or science campaign, **the opportunistic acquisition of images of Venus may offer value to later investigators in the form of time series observations of atmospheric structure and evolution.** Therefore, there is a compelling reason, within the constraints of data volume and instrument capability, to image or otherwise observe Venus during gravity assist maneuvers if at all possible.

Currently, coordination with ground-based observers and other spacecraft missions are handled uniquely within each mission. In order to improve a mission's science return as well as improve Venus science, we recommend that **(1) any mission that plans to fly by Venus to take data at Venus and (2) the mission team to have a dedicated Flyby Coordinator.**

References

- S. D. Bale *et al.* The FIELDS Instrument Suite for Solar Probe Plus. *Space Science Reviews*, 204 (1), 49–82 (2016)
- K. H. Baines *et al.*, Detection of Sub-Micron Radiation from the Surface of Venus by Cassini/VIMS. *Icarus*. **148**, 307–311 (2000).

- M. Benna *et al.*, Modeling the response of the induced magnetosphere of Venus to changing IMF direction using MESSENGER and Venus express observations. *Geophys. Res. Lett.* **36**, 1–5 (2009).
- M. E. Burton, B. Buratti, D. L. Matson, J.-P. Lebreton, The Cassini/Huygens Venus and Earth flybys: An overview of operations and results. *J. Geophys. Res. Sp. Phys.* **106**, 30099–30107 (2001).
- R. W. Carlson *et al.*, Galileo infrared imaging spectroscopy measurements at Venus. *Science*. **253**, 1541–1548 (1991).
- S. M. Curry *et al.*, Parker Solar Probe Venus gravity assists: flyby #1 and #2, *Geophys. Res. Lett* (*under review*)
- J. C. Gérard *et al.*, EUV spectroscopy of the Venus dayglow with UVIS on Cassini. *Icarus*. **211**, 70–80 (2011).
- D. A. Gurnett *et al.*, Non-detection at Venus of high-frequency radio signals characteristic of terrestrial lightning. *Nature*. **409**, 313–315 (2001).
- J. Helbert *et al.*, Surface brightness variations seen by VIRTIS on Venus Express and implications for the evolution of the Lada Terra region, Venus. *Geophys. Res. Lett.* **35**, 1–5 (2008).
- C. W. Hord *et al.*, Galileo ultraviolet spectrometer experiment: Initial Venus and interplanetary cruise results. *Science*. **253**, 1548–1550 (1991).
- B. Hubert *et al.*, UVIS observations of the FUV OI and CO 4P Venus dayglow during the Cassini flyby. *Icarus*. **207**, 549–557 (2010).
- B. Hubert *et al.*, Cassini-UVIS observation of dayglow FUV emissions of carbon in the thermosphere of Venus. *Icarus*. **220**, 635–646 (2012).
- J. C. Kasper *et al.*, Solar Wind Electrons Alphas and Protons (SWEAP) Investigation: Design of the Solar Wind and Coronal Plasma Instrument Suite for Solar Probe Plus. *Space Science Reviews*, 204 (1), 131–186.
- R. D. Lorenz *et al.*, Cassini Radio Detection and Ranging (RADAR): Earth and Venus observations. *J. Geophys. Res. Sp. Phys.* **106**, 30271–30279 (2001).
- M. Nakamura *et al.*, AKATSUKI returns to Venus. *Earth, Planets Sp.* **68** (2016), doi:10.1186/s40623-016-0457-6.
- J. A. Slavin *et al.*, MESSENGER and Venus Express observations of the solar wind interaction with Venus. *Geophys. Res. Lett.* **36**, 1–6 (2009).
- R. L. McNutt, S. C. Solomon, D. G. Grant, E. J. Finnegan, P. D. Bedini, The MESSENGER mission to Mercury: Status after the Venus flybys. *Acta Astronaut.* **63**, 68–73 (2008).