Venus Gravity Assists Science Opportunity

Report of VeGASO Panel

VeGASO Report

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EXECUTIVE SUMMARY

It is somewhat ironic that Earth's closest neighbor and the most similar is also the most puzzling and challenging to understand. Its featureless (to the naked eye) constant thick cloud cover masks the intense exchange of energy and momentum within the atmosphere and its interior. European Space Agency's Venus Express mission monitored the planet for more than eight years from 15 April 2006 till 27 November 2014 until the last of fuel was exhausted. The data collected has raised new questions about the planet's atmosphere, surface and interior, which not only relate to the planet's origin and evolution but are also valuable in the study of earth-sized exoplanets.

Starting a few years from now as many as fifteen gravity assist fly-bys of Venus will occur by three spacecraft to be launched during 2017-2028. These include seven by NASA's Solar Probe Plus (SPP, to be launched on 31 July 2018), six by ESA's Solar Orbiter (SO, to be launched in October 2018) and two by BepiColombo (BC, launch date TBD). These three missions provide exciting opportunities to accomplish unique scientific observations of Venus and its interplanetary environment that will contribute to not only a better understanding of the planet but also provide clues about the atmosphere bearing terrestrial exo-planets and how they may be impacted by the parent star's activity. The two heliophysics missions carry capable instruments that may provide new information about the escape of the atmosphere from a planet with no intrinsic magnetic field and only an induced magnetic field, the extent of its ionosphere beyond what has been explored by prior missions to Venus, new information about cloud opacity in the upper portions of the Venus cloud layer through Ka band radio occultation probings (first time) and perhaps lightning/electrical activity at Venus. BepiColombo, being a planetary mission carries instruments that can also obtain data at Venus. The mission also carries a separate planetary orbiter from JAXA also capable of observing Venus but not all instruments can be deployed during the two Venus fly-bys due to the combined configuration of the two orbiters. Nevertheless, BepiColombo has the potential to contribute uniquely to new observations of Venus and its environment.

In the following chapters we report a detailed discussion on the use of the BepiColombo instruments. Please note that the utilization of the BepiColombo payload strongly depends on a stringent scientific case to operate the relevant instruments. Indeed, for the time being no cruise science is formally included in the mission scenario.

Through a joint effort of NASA/SMD's Heliophysics and Planetary Science Divisions, a panel was formed consider Venus Gravity Assists Science Observations (VeGASO) from the multiple fly-by opportunities with the support of the respective projects. This report summarizes the findings of this panel from interactive web/teleconferences and face to face meetings during October 2014-February 2015. The Panel considered the community consensus Goals, Objectives and Investigations (GOI) arrived at by the Venus Exploration Analysis Group (VEXAG) sponsored by NASA (www.lpi.usra.edu/vexag) in arriving at its findings and recommendations. VeGASO charter directed the working group to have minimal impact on the three projects with no hardware or mission impacting modifications allowed, only opportunistic Venus observations possible within the very constrained mission resources (power, telemetry, safety and budget).

The VeGASO Panel identified the following valuable science objectives possible during the fly-bys (SPP, SO and BC) in terms of science value or priority:

- Observations on the escape of neutral atmosphere and ions from Venus (SO, SPP and BC)
- Cloud opacity using Ka band through radio occultations as observed from Earth (SPP, BC)
- Neutral atmosphere and ionosphere structure at equatorial latitudes through Ka band (SPP) and/or X band (SO, BC) band radio occultations as observed from Earth
- Electric and Magnetic Field observations in the environment of Venus (SO, SPP)

And, from BepiColombo VGAs:

- Gravitation Constant (GM) from Italian Spring Accelerometer
- Refined values of Oblateness from Italian Spring Accelerometer
- Global thermal structure at 8-15 µm
- Signature of the extended ionosphere/magnetosphere of Venus
- Radiative balance of Venus in (EUV and thermal infrared)

What is unique or valuable about these suggested observations?

There have been several fly-bys of Venus since the beginning of planetary exploration with the Mariner 2 fly-by in December 1962, Mariner 5 (1971), Mariner 10 (1974), Galileo (1990), Cassini (2001), and most recently MESSENGER (2006, 2007). However, these were all planetary missions (NASA/PSD), and even then, only limited science observations could be done during the MESSENGER and Cassini fly-bys due to project imposed restrictions or budget constraints despite the fact that the spacecraft carried very capable instruments. The upcoming Venus fly-bys demonstrate a welcome collaboration between the Heliophysics and Planetary Science Divisions of NASA as well as the collaboration with and cooperation with the European Space Agency. Due to such close cooperation and capable instruments, we will be able to observe Venus situated in its interplanetary environment. All proposed and planned missions to Venus are likely to focus on the planet and/or its atmosphere. The flybys represent the remaining opportunities to observe Venus' impact on, and responses to, the space environment solar environment created by the constant solar wind, occasional Coronal Mass Ejections and major solar storms. One of the early questions about Venus was why and how Venus has retained its thick atmosphere despite absence of an intrinsic magnetic field, leading to a more comet-like solar wind interaction. We learned from Pioneer Venus about the significant role of the induced magnetic field, but Venus Express showed us that there is escape of atmosphere from Venus. Due to their relatively tight orbits around Venus, neither Pioneer Venus nor Venus Express explored the far environment of Venus that Solar Orbiter, Solar Probe Plus and BepiColombo can sample weeks before and after the closest approach.

Equipped with sensitive imaging instruments (WISPR on SPP, SOHI on SO), we have the potential to observe Venus as it responds to the impinging solar wind. Although the CMEs cannot be predicted, there is a chance of capturing the impact of a CME on Venus during the numerous fly-bys spread out over six or seven years.

Both SPP and SO carry X or Ka band transmitters that can probe the Venus ionosphere and neutral atmosphere. Venus will occult SO and SPP during some of the fly-bys geometries as viewed from Earth. Due to the polar inclination of Pioneer Venus and Venus Express orbiters, the radio occultations sampled the high-latitude regions of Venus very well but the crucial equatorial regions where major deposition of solar energy takes place were sampled very poorly. The X-band occultations from the three missions will be in equatorial latitudes, thereby improving the knowledge of the conditions significantly.

Ka band radio occultations will provide unprecedented vertical resolution of atmospheric profiles of structure and composition due to the higher frequency (9 mm wavelength) by virtue of a much smaller first Fresnel Zone (~ 300 m or less, compared to >~ 1 km at X-band). Further, the Ka band signal is absorbed more than S or X-band, thereby providing a better measure of the cloud opacity in the 50-75 km region, not well sampled previously by X and S-band occultations for cloud opacity.
Here below we report a summary table of possible investigation of the BC, SO and SSP payload during VGA's.

Venus Express provided many insightful measurements of the workings of the atmosphere of Venus, but as is always the case, resulted in new questions as well as answers. The Bepi-Colombo payload includes EUV and FUV spectrometers that can sense the atmosphere and may be able to detect the hot oxygen corona that provides a pathway for atmosphere escape, together with the hydrogen corona, up to 30,000 km above the planet. They could also allow mapping of CO and CO_2^+ emission lines at limb. Detection of NO on the disk, and possibly also on the night-side, could help the understanding of how the airglow is affected by super-rotating zonal winds. Auroral emissions may also be detected. The IR spectrometer and radiometer could allow sounding of the middle atmosphere in the altitude range 55-100 km and its cloud layer, including retrieval of temperature profiles both on the illuminated and on the night-side of Venus. The magnetometer would be able to sense all plasma boundaries that the spacecraft will pass through, ranging from the bow shock to the ion composition boundary. Also, the magnetotail and ionosphere down to ~300 km could be probed along a unique path. Finally, measurements at Venus of non-gravitational perturbation, gravity gradients, and oblateness with accelerometer, neutron and gamma ray emissions, hot plasma up to 15 keV/q and ion mass spectra up to 3 keV could be performed.

A brief summary of the relevant instruments and measurements for potential use during the Venus flybys are given below. As has always been the case in planetary exploration, it is never fully predictable what one might observe. The rarity and high value of the limited opportunities we will have at Venus in the foreseeable future argue for taking full advantage of these flybys.

BC (remote & in situ)

ISA
MPO-MAG
MERTIS
MGNS
MORE
PHEBUS
SERENA

-Venus Gravitational Mass constant (ISA)
-Oblateness (ISA)
-Atmospheric vertical structure, clouds, hazes, temperaturee (MERTIS, MORE)
-Lightning, electrical activity, airglow (PHEBUS, MPO-MAG)
-Escape of ions/neutral atmosphere (SERENA/ PICAM, SERENA/MIPA)
-Ion Cyclotron Waves and other Waves around Venus (MPO-MAG, SEREN/MIPA)
-Venus Bow Shock and Magnetotail at different ranges and times (MPO-MAG)
Surface properties (MGNS)

SO (in situ) &
SPP (remote & in situ?)

SO
SWA
RPW
MAG
EPD

SPP
WHISPR?
FIELDS?
ISIS?
SWEAP?

-Escape of ions/neutral atmosphere (WHISPR)
-Ion Cyclotron Waves and other Waves (FIELDS,
-Venus Bow Shock and Magnetotail (MAG, FIELDS)
-Lightning and electrical activity (MAG, ISIS, FIELDS)
-X/Ka* band radio ionospheric and
-neutral atmosphere occultation profiles**

*depending on final TLC configuration
** pointing required

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We will refer to the above individuals as "the panel" throughout the text

The panel held WebEX meetings and exchanged information via e-mail. A face to face meeting of Co-chairs, ESA members and NASA Division representatives was held in Washington, DC at ESA's Washington Office on 18th November 2014 and teleconferenced with some experts and panel members.

1. INTRODUCTION

1.1 Why Venus?

The Earth's closest neighbor and the most similar in size and perhaps in origin, is also the most puzzling and challenging to understand. Its surface is hidden (to the naked eye) by its perpetual thick cloud cover, which masks the intense exchange of energy and momentum within the atmosphere and its interior. The European Space Agency's Venus Express mission explored the planet for almost 9 years from November 9, 2005 until 27 November 2014 until its fuel was exhausted. The data collected has raised new questions about the planet's atmosphere, surface and interior, which not only relate to the planet's origin and evolution but, are also valuable as an analogue in the study or exo-terrestrials which are now being discovered and explored.

The question most solar physicists pose when they encounter Venus is – why does Venus still have its thick atmosphere, if it has no permanent magnetic field? Venus Express did observe escape of atmospheric species from the planet, but recent observations show that the induced magnetic field can also trigger processes that permanent magnetic fields cannot. (Candace Gray DPS abstract).

The panel was tasked to consider the plans for three missions with multiple Venus fly-bys. Solar Probe Plus (SPP), Solar Orbiter (SO) and Bepi-Colombo (BC) spacecraft offer unique opportunities for Venus science during gravity assist fly-by. Solar Orbiter and Solar Probe Plus offer many more opportunities (6 and 7 respectively) to observe the interplanetary environment of Venus for the first time while BepiColombo has only two Venus fly-bys.

1.2 Overall science rationale for Venus observations at these missions

The primary rationale for observing Venus from these gravity assist fly-by opportunities is to identify unique science observation that these space platforms can uniquely provide, as well as to maximize the science return from the missions. The benefits of this cross-discipline interaction among scientists from solar and planetary communities will produce greater insights into the sun's influences on planetary environments, and observing planets as "systems" influenced by the space environment in which they live. This is a key component of the Planetary and Heliophysics Decadal Plans.

1.3 Why are these observations unique?

The fact that two independent branches within NASA's Science Mission Directorate - Heliophysics Division and the Planetary Science Division emplaced the VeGASO panel is a subtle recognition that both fields contribute to investigating the planets as systems influenced by the radiant output their parent star rather, instead of isolated objects. This is relevant and essential as we embark on exploring and understanding other solar systems. We also know that conditions on planets change over the solar cycle, with season, and with other possible geophysical events (e.g. volcanic eruptions). Thus the opportunity to make measurements at close range is always of potential high value in contributing unique science.

The two heliophysics missions have substantial NASA-ESA collaboration in terms of instruments and members of the science teams. NASA is providing the launch vehicle for SO. Both SO and SPP have multiple opportunities weeks before and after closest approach to observe the escaping atmosphere from Venus to great distances. This is a unique opportunity for a planetary target. Prior Heliophysics missions have already observed this phenomenon at numerous comets, but never from Venus.

BC is uniquely equipped with the most advanced instruments platform for planetary observations, including one that is capable of probing the Venus atmosphere at Ka band by radio occultation for the first time. Venus has been explored so far by dedicated missions or by planetary spacecraft destined to other prime targets (Galileo, Cassini, MESSENGER, etc.). The BC spacecraft is particularly well equipped with instrumentation to study Venus as a secondary target.

Representative observations for these mission flyby opportunities are:

Ionosphere/Magnetosphere:

- Venus Bow Shock and Magnetotail
- Venus Ion Escape
- Ion Cyclotron Waves and Other Waves Observed Around Venus

Atmosphere:

- Vertical structure of the atmosphere – clouds, thermal structure, hazes
- Airglow
- Lightning/electrical activity

Surface and Interior

- Refinement of the Oblateness (C2 coefficient)
- A high accuracy, independent estimate of the Gravitational parameter (GM)

A brief summary of the radio occultation opportunities during the Venus fly-bys is presented in Appendix A. A summary of the ionosphere and magnetospheric investigations possible at Venus is presented in Appendix B.

2. OVERVIEW OF BEPICOLOMBO VENUS GRAVITY ASSISTS

BepiColombo is a dual spacecraft mission to Mercury carried out jointly by the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA). The mission will address a comprehensive set of scientific questions in order to gain knowledge about the planet, its evolution and its surrounding environment. Both spacecraft will be launched together in July 2016. An extensive suite of high resolution scientific instruments, flying on the two spacecraft, allow addressing a wide range of scientific questions that will provide important clues on the origin and formation of terrestrial planets.

One spacecraft, the Mercury Planetary Orbiter (MPO), is led by ESA and its payload comprises eleven experiments and instrument suites. The MPO will focus on a global characterization of Mercury through the investigation of its interior, surface, exosphere and magnetosphere. In addition, it will test Einstein's theory of general relativity. The second spacecraft, the Mercury Magnetosphere Orbiter (MMO), is led by JAXA and will carry five experiments or instrument suites to study the environment around the planet including the planet's exosphere and magnetosphere, and their interaction processes with the solar wind.

The BepiColombo trajectory employs a solar electric propulsion system so that a combination of low-thrust arcs and flybys at Earth, Venus, and Mercury are used to reach Mercury with low relative velocity. The baseline scenario foresees the launch by an Ariane 5 from Kourou of both spacecraft in a composite with a propulsion element, the MTM (Mercury Transfer Module). The composite spacecraft is launched on an escape trajectory that brings it into heliocentric orbit on its way to encounter Earth for a flyby gravity assist approximately one year after launch. Two consecutive Venus flybys (Figs 2.1 and 2.2) reduce the perihelion to Mercury distance with almost no need of thrust. A sequence of 4 Mercury flybys and a series of low thrust arcs reduce the relative velocity, such that Mercury will gently capture the spacecraft even if no insertion maneuver takes place. Thrust arcs inside Venus orbit can be carried out with up to 290 mN (2 thrusters in simultaneous operation), because of the increased power from the solar arrays while coming closer to the Sun. The thrust profile over the mission time is given in Figure 2.3. The total velocity increment to be provided by electric propulsion is 6.4 km/s.

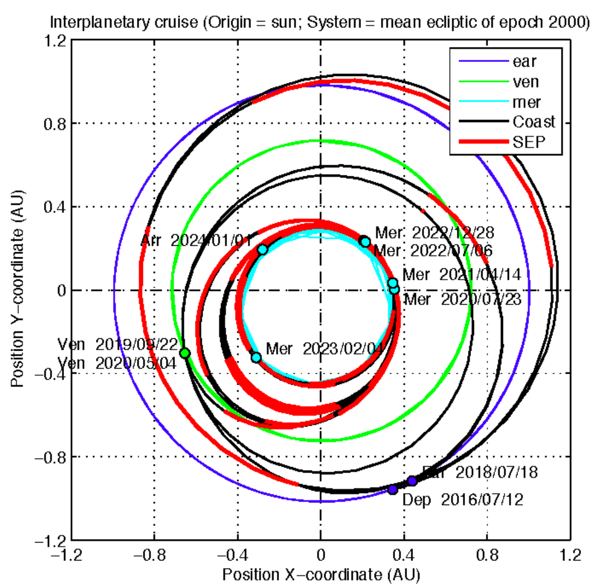


Figure 2.3. BepiColombo thrust profile

2.1 Brief description of BC Venus Gravity Assist mission

During cruise phase, the MMO will be shielded by MOSIF, and no operations will be possible. MPO instruments instead could make observations only when their pointing direction is out of the +Z direction (i.e., the nadir direction when orbiting around Mercury, see Figure 2.3. In addition to this, the composite spacecraft nominal attitude will be defined by the +Y axis pointed to the Sun and a rotation of 120 degrees/hour about the Sun vector. This attitude is required to point the radiator (-Y) opposite to the Sun and to minimize disturbance torques, respectively.

The two flybys at Venus will occur on September 22, 2019 and on May 5, 2020, respectively. The BepiColombo flybys at Venus will be a unique opportunity for collecting data to create new science, not only in the frame of comparative planetology (i.e. the same instruments will later probe and observe Mercury), but also compared to the previous missions devoted to Venus. In fact, many phenomena at Venus show peculiarities and an intrinsic variability, which are still not fully understood.

During flybys the rotation around the +Y axis and pointing +Y at the Sun will be nominally maintained. This means that the radiator face of MPO (-Y) where the PHEBUS and MERTIS instruments baffles are positioned will look at Venus only in the first part of the two flybys (see Fig. 2-3). The -X face will turn at Venus according to the rotation around +Y axis.

Finally, due to the type of measurements involved, ISA, MPO-MAG, MIPA, MGNS and PICAM will not have pointing requirements during flybys, but will need to be switched on for at least one Earth day before and one Earth day after closest encounter. Nevertheless, very precise attitude data at the time of operations are required by all of them.

MIPA requires that thrusting (including attitude control) should not be activated during operations, to avoid high voltage discharges.

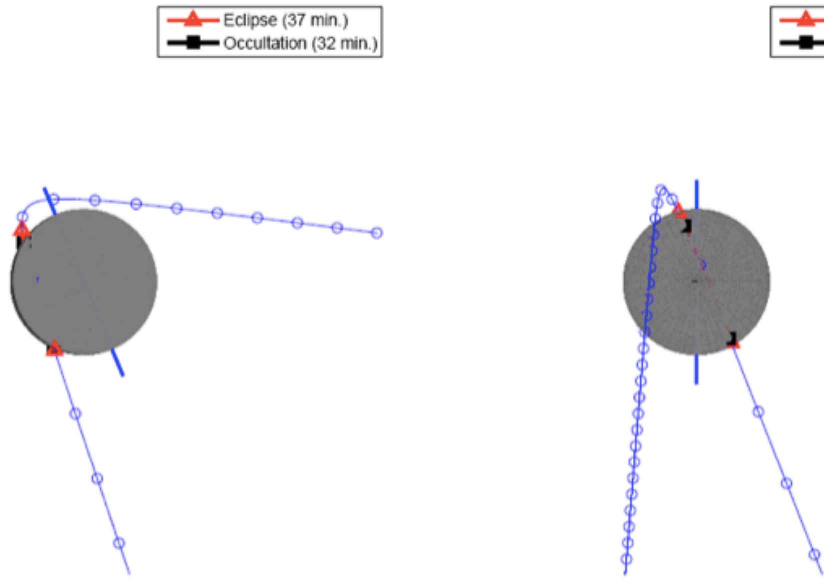


Fig.2.4 Venus fly-by as seen from Earth (left) and from the Sun (right). Tick marks represent 20 min intervals. Fly-by altitude is less than 1500 Km.

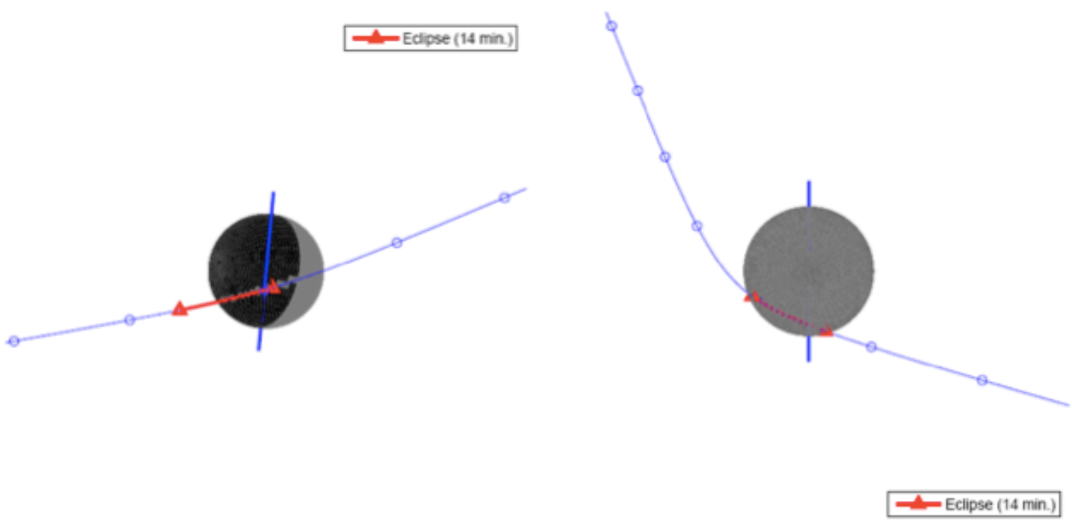


Fig.2.5 Venus fly-by 2 as seen from Earth (left) and the Sun (right). Tick marks represent 20 min intervals.

	Earth	Venus 1	Venus 2	M1	M2	M3	M4	M5
Flyby Date	2018- 7-18	2019- 9-22	2020- 5- 4	20-7-23	21-4-14	22-7-6	22-12-28	23-2-4
MJD2000	6773.5	7204.7	7429.4	7509.7	7774.6	8222.3	8398.0	8435.7
Solar Longitude	-64.4°	-155.1°	-155.2°	0.6°	5.7°	48.9°	47.0°	-133.8°
Flyby velocity	4.33 km/s	9.30 km/s	9.29 km/s	5.90	5.52	2.86	2.61	1.82
Flyby altitude	3521 km	1500 km	307 km	200	200	200	40000	300
Deflection angle	86.1°	38.8°	43.6°	22.3°	24.9°	60.7°	8.1°	90.1°
Pericentre								
Declination	22.7°	71.5°	-19.0°	-1.8°	-5.9°	-29.9°	-3.6°	-45.5°
Right ascension	46.7°	52.3°	66.0°	33.3°	55.3°	87.6°	-174.3°	-6.1°
Incoming velocity								
R-component	4.18 km/s	9.20 km/s	8.00 km/s	-2.20	-3.69	-0.48	-0.34	-0.02
S-component	-0.17 km/s	0.26 km/s	-1.28 km/s	5.46	4.07	2.47	-0.06	-0.06
T-component	1.10 km/s	1.31 km/s	-4.55 km/s	0.41	0.50	1.36	2.58	-1.82
Declination	14.7°	8.1°	-29.3°	3.9°	5.2°	28.4°	82.3°	-88.1°
Right ascension	-2.3°	1.6°	-9.1°	112.0°	132.2°	101.0°	-170.9°	-108.9°
Outgoing velocity								
R-component	0.45 km/s	8.01 km/s	5.35 km/s	-4.11	-5.04	-0.58	0.02	-1.82
S-component	-4.14 km/s	-1.29 km/s	-7.25 km/s	4.21	2.13	-0.04	-0.02	0.14
T-component	-1.18 km/s	-4.55 km/s	-2.30 km/s	0.48	0.74	2.80	2.61	0.02
Declination	-15.9°	-29.3°	-14.3°	4.7°	7.7°	78.2°	89.3°	0.6°
Right ascension	-83.8°	-9.2°	-53.6°	134.3°	157.1°	-176.5°	-38.2°	175.7°

Table 2.1 Venus fly-by's critical parameters

In the following, we refer to those instruments that could in principle make observations during the flybys.

For example, the two spectrometers of PHEBUS, alternatively operating in the EUV and FUV ranges can sense the atmosphere and may give novel detection of hot oxygen population (detected only by Pioneer Venus Orbiter and Venera 11 in early 80's), together with the more systematically observed hydrogen corona, extended up to 30,000 km above the planet. Moreover, mapping of CO and CO_2^+ emission lines at limb would be a very intriguing detection too, since previous data were contaminated by scatter light. Finally, detection of NO on the disk, and possibly also on the night-side, could help the understanding of the position of the bright spot mapped by Spicav/UV on Venus Express, which appears to be shifted from the expected antisolar point, probably due to super-rotating zonal winds.

The IR spectrometer and radiometer of MERTIS could allow sounding the middle atmosphere of Venus in the altitude range 55-100 km and its cloud layer. Specifically: CO_2, SO_2 and H_2SO_4 absorption bands can be observed, and the radiometric data obtained in parallel could allow retrieving temperature profiles both on the illuminated and on the night-side of Venus. Failure of PFS spectrometer onboard Venus Express and consequent lack of IR spectra of Venus will be partially counterbalanced by such measurements.

The magnetometer MAG, due to the flyby geometries, could be able to sense all plasma boundaries that the spacecraft will pass through, ranging from the bow shock to the ion composition boundary. Also, the magnetotail and possibly flux-ropes, i.e. bundles of twisted magnetic field surrounded by ionospheric plasma, will be probed.

In addition to these measurements, measurements at Venus of non-gravitational perturbation, gravity gradients, GM and oblateness with the ISA accelerometer, neutron and gamma ray emissions with the MGNS, hot plasma up to 15 keV/q with SERENA/MIPA and ion mass spectra up to 3 keV with SERENA/PICAM could be performed.

2.2 BC MPO payload to be operated at Venus

(indicates specific pointing requirements)*

2.2.1 ISA

The Italian Spring Accelerometer (ISA) will measure the non-gravitational perturbations acting on the spacecraft and gravity gradients. ISA has no need of dedicated pointing maneuvers, but access to the spacecraft attitude data is necessary to derive net measurements, as well as an accurate thermal control, 2-3 Earth-days before the flybys. Preliminary switch on could be useful also for calibration purposes.

Main task of the Italian Spring Accelerometer (ISA) – part of the BepiColombo Radio Science Experiment (RSE) suite – is the measurement of the non-gravitational perturbations acting on the Mercury Planetary Orbiter (MPO) spacecraft once in orbit around planet Mercury.

By construction, an ideal accelerometer measures only non-gravitational forces acting on it. A real, extended one, could also sense (as is the case for ISA) gravity gradients. It can also sense these if it is not placed at the spacecraft center of mass, as is the case (for technical reasons) of BepiColombo. These gravity gradient signals are considered, in the nominal mission, as a deterministic error, which has to be determined/minimized as much as possible. On the other side, during a Venus flyby this becomes a signal, which can be measured. Therefore, besides the non-gravitational perturbations acting on the Mercury Composite Spacecraft (MCS) during the flybys, ISA could measure the gravity gradients induced by the primary (i.e., Venus) gravitational field, enabling an independent estimate of its gravitational parameter GM and (hopefully) of the oblateness—related $C20$ parameter.

2.2.2 MPO-MAG

The magnetometer MPO-MAG is mounted on the long boom of the MPO and it requires no pointing maneuvers, too. Only the spacecraft attitude should be known to a precision of 720 arcseconds. In order to recalibrate the sensors, it is proposed to activate them 1 Earth-day before the flybys and leave them on at least 1 Earth-day after. Venus is said to exhibit an induced magnetosphere. This situation is found during nominal solar wind conditions when the atmosphere has sufficient pressure to withstand the solar wind. The first BepiColombo flyby has its closest approach on the dayside in the polar region with a minimal altitude of about 1500 km. Thus, the region of the most intense concentrated magnetic field could be studied passing through all plasma boundaries ranging from the bow shock and ion composition boundary. The second BepiColombo is closer to the planet with a closest approach altitude of only 300 km on the night-side above the planet. This will take the spacecraft into a region, which is yet unexplored by Venus Express. The minimum pericenter altitude of the Pioneer Venus Orbiter probe was about 200 km above the surface - comparable to the closest approach of the BepiColombo satellite.

The flyby geometry could allow us to study a phenomenon called flux ropes, i.e. bundles of twisted magnetic field lines surrounded by ionospheric plasma. These giant flux ropes occur quite often and all have strong core fields and diameters of hundreds of kilometers, which is about the vertical dimension of the ionosphere. The cause of these giant flux ropes remains unknown and speculative (Zhang et al., 2012).

2.2.3 MERTIS*

The MERTIS instrument is composed by two sensors: a push-broom IR grating spectrometer (TIS) to investigate the 7-14 µm emissivity, and a radiometer (TIR) to measure the surface temperature at day- and night-side in the spectral range 7-40 µm (corresponding to temperatures of 150°-700°K). MERTIS has two baffles: one of them will be obscured by the MTM during cruise phase, while the other (space-baffle) is on the radiator side (-Y direction) and can operate to sound the middle atmosphere of Venus in the altitude range of 55-100 km and its cloud layer. Specifically CO_2, SO_2 and H_2SO_4 absorption bands are in the TIS spectral range. The radiometric data obtained in parallel will allow retrieving temperature profiles both on the illuminated and on the night-side of Venus. The MERTIS observations would complement the data acquired by Venera 15 and Pioneer Venus with a much higher sensitivity.

2.2.4 MGNS

The MGNS instrument consists of four detectors of neutrons and one gamma-ray spectrometer and are designed to detect major surface lines of Na, Fe, Ti, Al, Mg, Si, Ca and O and radioisotopes like K, U and Th.

There are not special requirements to the MGNS instrument pointing during Venus flyby. The orientation and SC configuration should be made available to the MGNS team for numerical simulation of neutron and gamma-ray fluxes around MGNS instrument. Instrument should start to work in nominal configuration at least 6h before flyby, work continuously in the stable optimal configuration during the flyby and end to work after flyby at least 6h. Instrument will accumulate data for neutron and gamma-ray with a time resolution ranging from 2 to 20 sec.

2.2.5 MORE

MORE (Mercury Orbiter Radio-science Experiment) will address scientific goals in geodesy, geophysics and fundamental physics. It will help to determine the gravity field of Mercury as well as the size and physical state of its core, provide constraints to models of the planet's internal structure and test theories of gravity. MORE could be involved in the Venus flyby mostly to gather data for the improvement of Venus ephemerides. A "2-way" occultation (no USO onboard) in X and Ka-band could be performed too. Anyway, it should be pointed out that the Ka-band signal could be significantly attenuated due to the double exponential effect induced by the atmosphere and the limited transmitting power (1.9 W).

2.2.6 PHEBUS*

PHEBUS instrument is a double spectrometer for the EUV range (55-155 nm) and FUV range (145-315 nm), plus two channels at 404 and 422 nm for K and Ca respectively. Interesting measurements of the H and O hot coronas could be performed, as well as nightglow emissions of NO and lines of different species like O, O+, N, C, C+, CO, H, He. Stellar occultation method to sense the atmosphere at the limb could also be performed.

Due to power limit, only one detector (EUV or FUV) can be switched on at a given time during the flybys, (but they can be used alternatively). Both NUV can be switch on or off. Observations by PHEBUS can be done in the X-Z spacecraft plane thanks to its scanning mirror, however, during the cruise the full plane is not allowed due to the presence of the MTM of MPO. Hydrogen exospheric observations are not constrained due to the large extension of the hydrogen corona (~ 30,000 km), helium and oxygen emissions are more confined, but an altitude profile could be derived using an inertial mode if the line of sight is not too far from the planet. The EUV day glow emissions can be done if the disk is observed, that is the X-Z plane intersects Venus. In this case, the FUV detector should be switch off to avoid solar scatter light, the FUV day glow emissions will be much more difficult to observe without this scatter light (Chaufray et al. 2012b), and therefore we suggest to avoid it. The disk observations in the FUV range could be done only at the night-side to observe nightglow emissions, but it is not sure that such an observation will provide new information compared to the numerous observations done for example by Venus Express.

Stellar occultations are done in inertial mode and could be performed at EUV or at FUV if pointing at the night-side to avoid scatter light from the Venusian atmosphere (Montmessin et al. 2011). Calculations are needed to see if interesting stars in the EUV/FUV range are observable at this time given the observing constraints.

2.2.7 SERENA/MIPA

MIPA is an ion analyzer with a field of view of half hemisphere designed to measure positively charged particles of hot plasma with energy ranging from 10 eV/q to 15 keV/q. A similar sensor (ASPERA-4/IMA) is operating on Venus Express but with a lower time resolution. Night-side protons are best candidates for detection during flybys, particularly at low altitude.

With a nominal operation of MIPA during gravity assist one can add further data points of: the solar wind in the Venus environment; the boundary crossings [Martinecz et al, 2008]; pickup ions from the bow shock [Yamauchi et al., 2011], or ion escape flux from Venus ionosphere and its composition [e.g. Barabash et al. 2007b]. However, we note that not much scientific information would be added from two flybys, apart from verification of the 11yr periodicity of the solar wind activity.

2.2.8 SERENA/PICAM

PICAM is an ion mass spectrometer able to derive velocity distributions and mass spectrum for ions over a half hemisphere, from thermal up to 3 keV energies and a mass range up to 132 amu. Operating PICAM at Venus could allow detection of ions accelerated by solar wind pick-up, by instabilities and the induced magnetosphere boundary and by polarization electric fields (i.e. when passing through the terminator and the wake of Venus).

Ions at Venus are known to be accelerated by solar wind pick-up, by instabilities at the induced magnetosphere boundary and by polarization electric fields. The Venus fly-by characteristics may allow observing such ions when passing through the terminator and the wake of Venus. PICAM should be operating about ±1 hour at closest approach (or longer in the terminator downstream region), where ToF measurements can give information about the mass and energies of the detected ions. Additional measurements in image mode will determine the bulk flow direction of the particles. Both measurements will then allow figuring out the origin (solar wind or planetary) of the observed ions. Due to the 2π FoV of PICAM, no severe pointing constraints are expected, though an orientation of PICAM's FoV into the sunward direction would be preferable.

3. SOLAR ORBITER

A mission profile for Solar Orbiter has been developed that will, for the first time, make it possible to study the Sun with a full suite of in-situ and remote-sensing instruments from as close as 0.28 AU and provide imaging and spectral observations of the Sun's polar regions from out of the ecliptic. This proximity to the Sun will also have the advantage that the spacecraft will have periods of reduced angular velocity of the spacecraft with respect to the solar surface, allowing observations of solar surface features and their connection to the heliosphere for significantly longer periods than from near-Earth vantage points.

The baseline mission is planned to start in October 2018 with a launch on a NASA-provided launch vehicle from Cape Canaveral, placing the spacecraft on a ballistic trajectory that will be combined with planetary gravity assist maneuvers (GAM) at Earth and Venus. The second Venus GAM places the spacecraft into a 4:3 resonant orbit with Venus at a perihelion radius of 0.284 AU. The first perihelion at this close distance to the Sun is reached 3.5 years after launch. This orbit is the start of the sequence of resonances 4:3-4:3-3:2-5:3 that is used to raise gradually the solar inclination angle at each Venus GAM. The resulting operational orbit has a period of 168 days during the nominal mission with a minimum perihelion radius of 0.28 AU. The end of the nominal mission occurs 7 years after launch, when the orbit inclination relative to the solar equator reaches 25°. The inclination may be further increased during an extended mission phase using additional Venus GAMs, to reach a maximum of 33° for the October 2018 baseline.

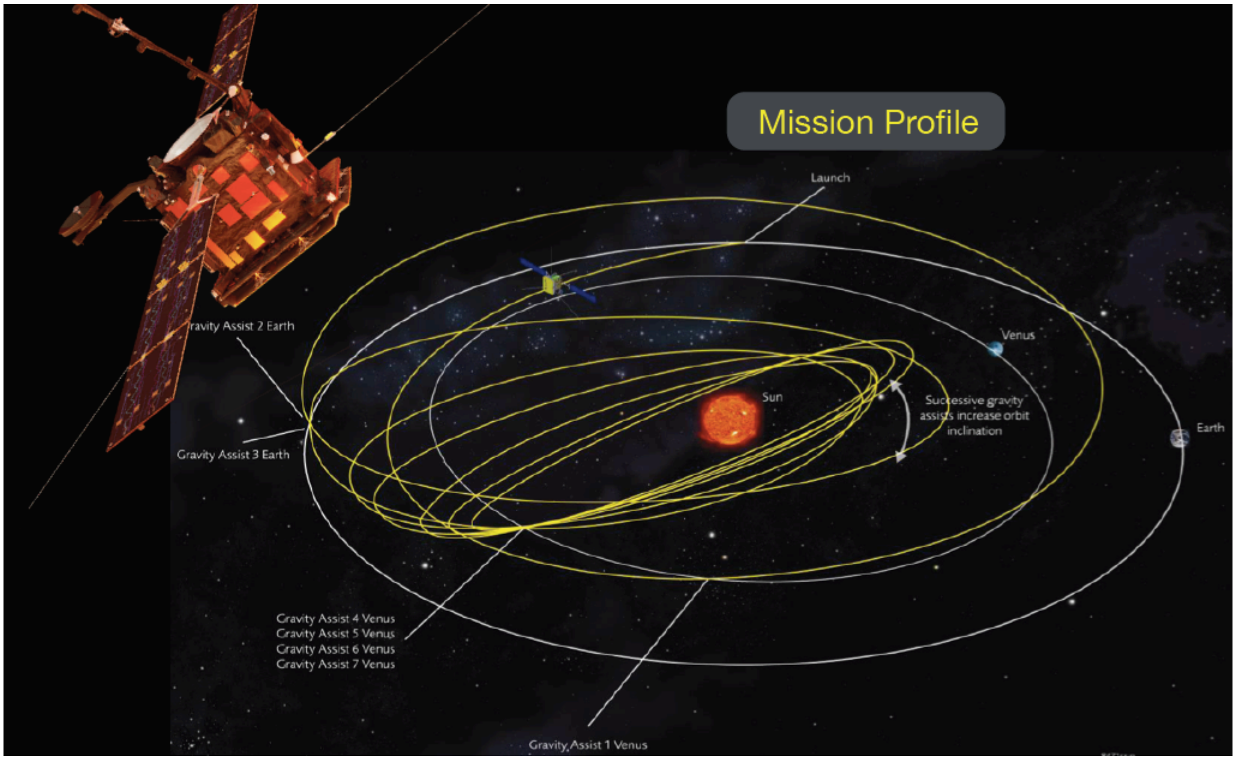


Fig.3.1 The Solar Orbiter spacecraft in flight configuration and its complex mission scenario

Solar Orbiter is an ESA-led mission with strong NASA participation. Specifically, NASA will provide the launch on an evolved expendable launch vehicle (EELV), and parts (1 complete instrument, 1 sensor) of the scientific payload. The mission also has important synergies with NASA's Solar Probe Plus mission, and coordinated observations are expected to enhance greatly the scientific return of both missions. In the overall international context, Solar Orbiter is ESA's primary contribution to the International Living With a Star (ILWS) initiative, and joint studies incorporating data from all missions operating in the inner heliosphere (or providing remote-sensing observations of the near-Sun environment) will contribute greatly to our understanding of the Sun and its environment.

3.1 Solar Orbiter (SO) Scientific Payload

3.1.1 The in-situ instruments

The Solar Wind Analyser (**SWA**) instrument suite (C. J. Owen, PI, UK) will fully characterize the major constituents of the solar wind plasma (protons, alpha particles, electrons, heavy ions) between 0.28 and 1.4 AU.
The Energetic Particle Detector (**EPD**) experiment (J. R. Pacheco, PI, Spain) will measure the properties of suprathermal ions and energetic particles in the energy range of a few keV/n to relativistic electrons and high-energy ions (100 MeV/n protons, 200 MeV/n heavy ions).

The Magnetometer (**MAG**) experiment (T. S. Horbury, PI, UK) will provide detailed in-situ measurements of the heliospheric magnetic field.
The Radio and Plasma Waves (**RPW**) experiment (M. Maksimovic, PI, France) will measure magnetic and electric fields at high time resolution and determine the characteristics of electromagnetic and electrostatic waves in the solar wind from almost DC to 20 MHz.

3.1.2. The remote-sensing instruments

The Polarimetric and Helioseismic Imager (**PHI**, S. K. Solanki, PI, Germany) will provide high-resolution and full-disk measurements of the photospheric vector magnetic field and line-of-sight velocity as well as the continuum intensity in the visible wavelength range.

The Extreme Ultraviolet Imager (**EUI**, P. Rochus, PI, Belgium) will provide image sequences of the solar atmospheric layers from the photosphere into the corona.

The Spectrometer/Telescope for Imaging X-rays (**STIX**) (S. Krucker, PI, Switzerland) provides imaging spectroscopy of solar thermal and non-thermal X-ray emission from ~4 to 150 keV.

The **METIS** Coronagraph (E. Antonucci, PI, Italy) will provide imaging of the inner corona in polarized visible-light (580-640 nm) and narrow-band ultraviolet HI Ly α (121.6 nm).

The Solar Orbiter Heliospheric Imager (**SOLOHI**, R. A. Howard, PI, U.S.) will image both the quasi-steady flow and transient disturbances in the solar wind over a wide field of view by observing visible sunlight scattered by solar wind electrons.

A European-led extreme ultraviolet imaging spectrograph, **SPICE**, with contributions from ESA member states and ESA. This instrument will remotely characterize plasma properties of regions at and near the Sun, based on the Spectral Imaging of the Coronal Environment (**SPICE**) investigation previously selected by NASA.

3.2 The SO Spacecraft and its VGA's

The Solar Orbiter spacecraft is a Sun-pointed, 3-axis stabilized platform, with a dedicated heat shield to provide protection from the high levels of solar flux near perihelion. Feed-throughs in the heat shield (with individual doors) provide the remote-sensing instruments with their required fields-of-view to the Sun. Tiltable solar arrays provide the capability to produce the required power throughout the mission over the wide range of distances from the Sun using rotation about their longitudinal axis to allow management of the array temperature throughout the mission, particularly during closest approach to the Sun. An articulated high-temperature high-gain antenna provides nominal communication with the ground station, and a medium gain antenna and two low gain antennas are included for use as backup.

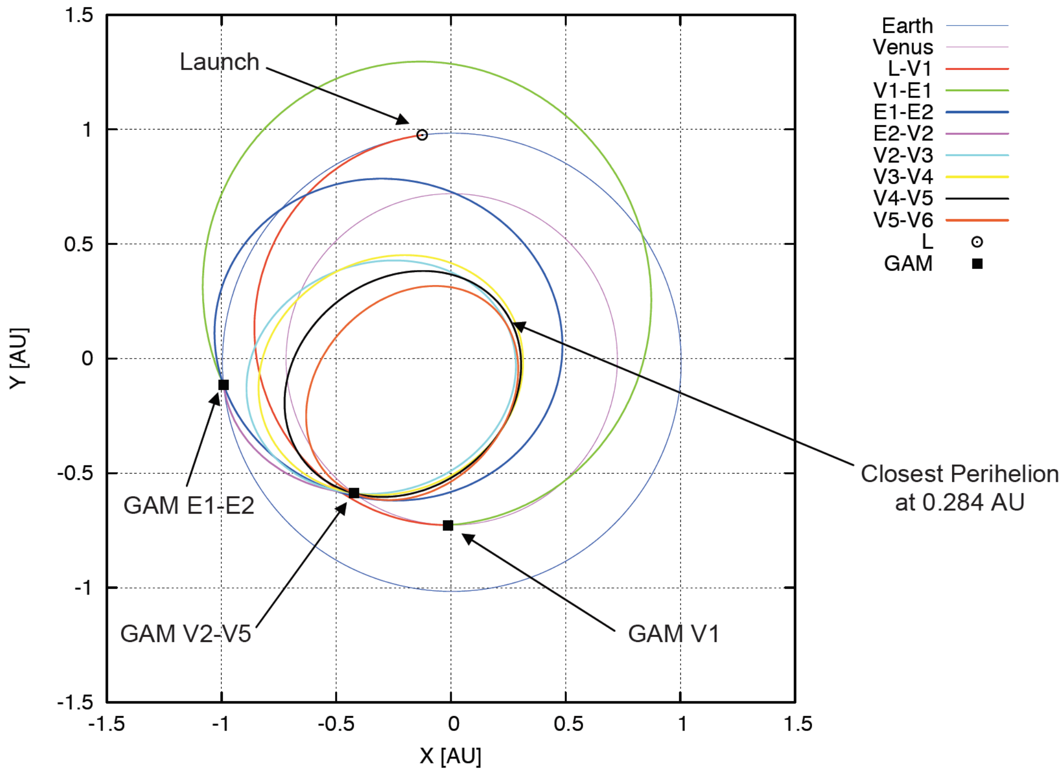


Fig. 3.2 Trajectory of Solar Orbiter viewed from above the ecliptic plane for the original launch date of 2017

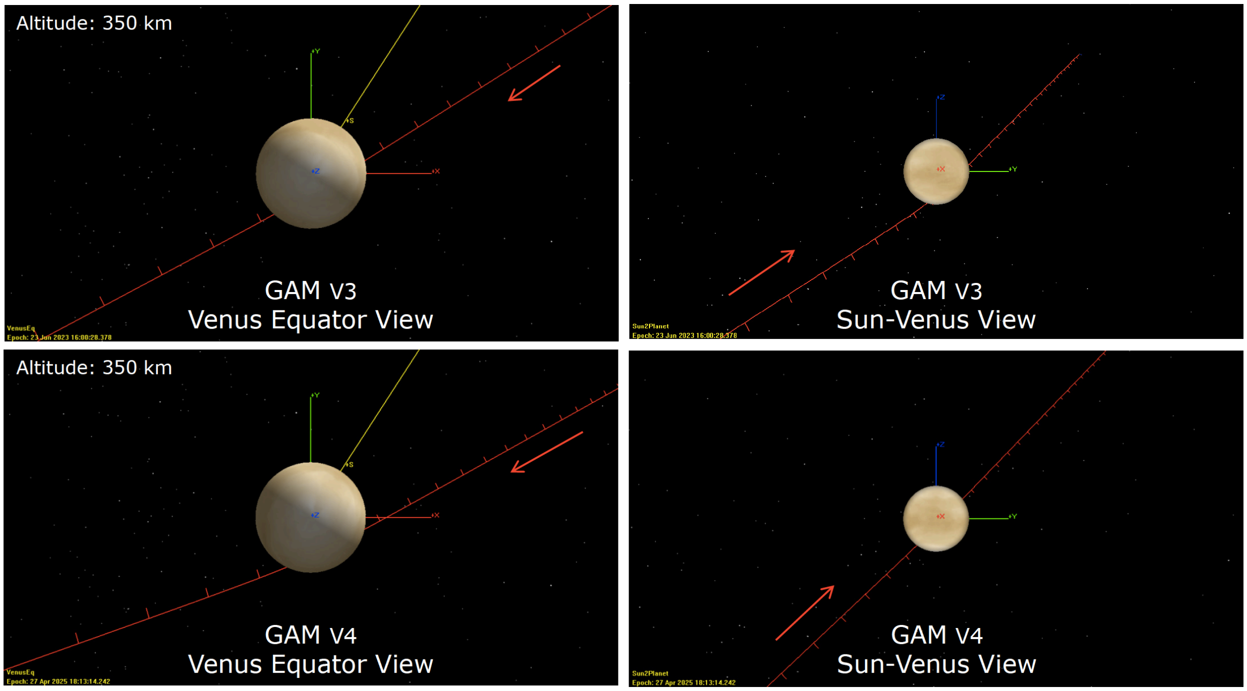


Fig.3.3 Simulation of a Gravity Assist Manouver (GAM) for a 350 Km fly-by . Launch opportunity July 2017.

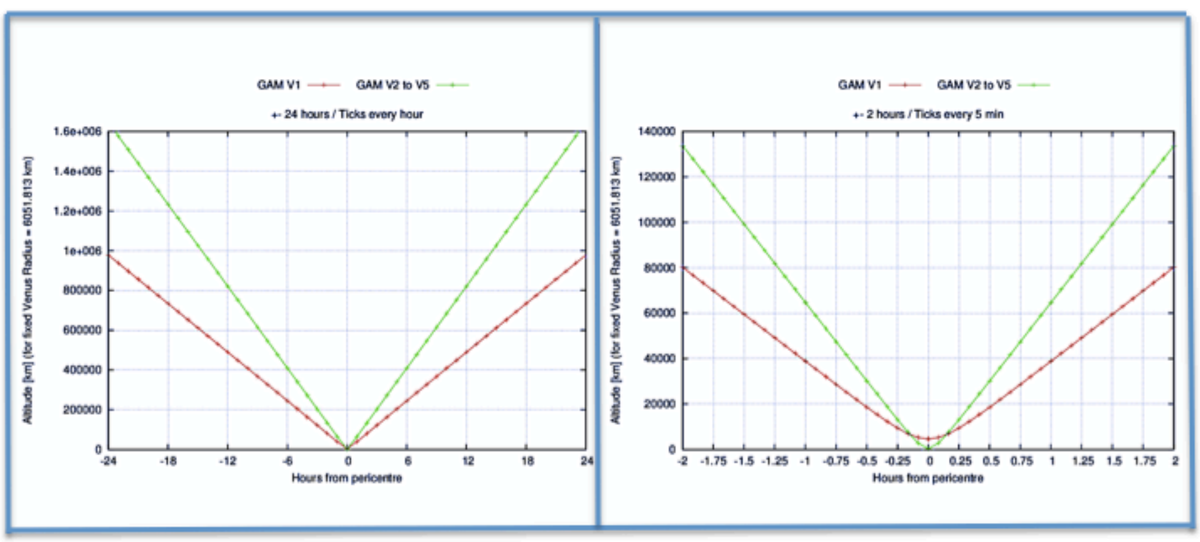


Fig. 3.4Variation of the fly-by altitude in different GAM. Trajectories calculated for a July 2017 launch.

3.3 SO operability during VGA

Nominally, the S/C will remain Sun-pointed during encounters, but it may have to roll to align the thrusters for the maneuver. Thermal conditions during fly-by are presently under study by S/C prime contractor spacecraft [Airbus Defense Systems]. As for the science instruments, the baseline is that they will be powered off. However, depending on bus and payload health-and-safety concerns and risk posture, they could be turned on. A very compelling science case should be identified that would help the Project to justify studying the case and carry out a risk-reward assessment. Do the instruments have the dynamic range to observe Venus? Unfortunately this is not known at this stage. Instrument teams would need to receive a fly-by illumination model (Sun + Venus albedo) in order to assess this. Due to the recent change of launch date to 2018 the illumination model needs to be reviewed. It seems clear that the magnetometer, the solar wind composition instrument, and the radio-and-plasma wave instrument are the most likely candidates for VGA measurements. There could be a possibility to use the telecom/radio science subsystem for Venus occultations (i.e X-band).

4. SOLAR PROBE PLUS (SPP)

Solar Probe Plus (SPP) will be the first mission to fly into the low solar corona, revealing how the corona is heated and the solar wind and solar energetic particles are accelerated. Understanding these fundamental phenomena has been a top-priority science goal for over five decades, dating back to the 1958 Simpson Committee Report. The scale and concept of such a mission has been revised at intervals since that time, yet the core has always been a close encounter with the Sun. The primary science goal of the Solar Probe Plus mission is to determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what mechanisms accelerate and transport energetic particles. The SPP mission will achieve this by identifying and quantifying the basic plasma physical processes at the heart of the Heliosphere. SPP uses an innovative mission design, significant technology development and a risk-reducing engineering development to meet the SPP science objectives. The SPP mission was confirmed in March 2014 and is under active development as a part of NASA's Living with a Star Program. SPP is scheduled to launch July 31, 2018, and will perform 24 orbits over a 7-year nominal mission duration. The mission design utilizes seven Venus gravity assists to gradually reduce perihelion from 35 solar radii (R_S) in the first orbit to <10 R_S for the final three orbits. The best opportunity to observe Venus would be orbit 21 VGA-7.

SPP will travel much closer to the Sun (< 10 R_S from the Sun's center) than any other spacecraft to repeatedly investigate the coronal conditions leading to the nascent hot stream of plasma (i.e., solar wind) and eruptive transients, ultimately creating space weather. The seven-year prime mission lifetime will permit observations to be made over a significant portion (>60%) of a solar cycle. Direct plasma, magnetic field, and energetic particle measurements that cannot be accomplished in any other way, will allow testing of and discrimination among a broad range of theories and models that describe the Sun's coronal magnetic field and the heating and acceleration of the solar wind and energetic particle acceleration. Primary science objective of the SPP mission is to determine the structure and dynamics of the Sun's coronal magnetic field and to understand how the corona is heated, the solar wind accelerated, and how energetic particles are produced and their distributions evolve. The SPP mission will achieve this by identifying and quantifying the processes that cause the heating and acceleration of the solar wind and solar energetic particles in the Sun's corona. In order to advance the scientific knowledge needed to characterize the inner heliosphere, the SPP mission has defined three overarching science objectives. These objectives with their associated fundamental questions are as follows:

1. Trace the flow of energy that heats the solar corona and accelerates the solar wind.

1a. How is energy from the lower solar atmosphere transferred to, and dissipated in, the corona and solar wind?

1b. What processes shape the non-equilibrium velocity distribution observed throughout the heliosphere?

1c. How do the processes in the corona affect the properties of the solar wind in the heliosphere?

2. Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind.

2a. How does the magnetic field in the solar wind source regions connect to the photosphere and the heliosphere?

2b. Are the sources of the solar wind steady or intermittent?

2c. How do the observed structures in the corona evolve into the solar wind?

3. Explore mechanisms that accelerate and transport energetic particles.

3a. What are the roles of shocks, reconnection, waves, and turbulence in the acceleration of energetic particles?

3b. What are the source populations and physical conditions necessary for energetic particle acceleration?

3c. How are energetic particles transported in the corona and heliosphere?

The SPP spacecraft will fly through the region where the solar wind is accelerated, making in-situ measurements and remote observations from <10 RS and at least out through 0.25 AU. By making direct, in-situ measurements of the region where the solar wind is born and where some of the most hazardous solar energetic particles are energized, SPP will make fundamental contributions to our ability to characterize and forecast the dynamics of the inner heliosphere and its radiation environment, in which space explorers live and work. The required measurements include magnetic and electric fields, plasma waves, quasi-thermal noise and radio emissions, thermal ions and electrons, energetic electrons, protons and heavy ions, and visible broadband images.

4.1 SPP Scientific Payload

The SPP instrument Science Investigations, selected by NASA in September 2010, are: the Electromagnetic Fields Investigation (FIELDS); the Integrated Science Investigation of the Sun, Energetic Particle Instruments (ISIS); the Solar Wind Electrons Alphas and Protons Investigation (SWEAP); and the Wide Field Imager for Solar Probe Plus (WISPR). In addition to the four instrument investigations, there is also a theory and modeling investigation - Heliospheric origins with Solar Probe Plus (HeliOSPP).

The FIELDS investigation (PI Stuart Bale, University of California, Berkeley) comprises two fluxgate magnetometers, a search coil magnetometer and five electric antennas measuring electric and magnetic fields and waves, Poynting flux, absolute plasma density and electron temperature, spacecraft floating potential and density fluctuations, and radio emissions.

The SWEAP investigation (PI Justin Kasper, Smithsonian Institute for Astronomy & University of Michigan) has two electrostatic analyzers and a Faraday cup. This investigation will count the most abundant particles in the solar wind -- electrons, protons and helium ions -- and measure their properties such as velocity, density, and temperature.

The ISIS energetic particle instrument suite (PI David McComas, Southwest Research Institute) is composed of two independent instruments (EPI-Hi and EPI-Lo) covering different (and overlapping) energy ranges This suite will make observations of energetic electrons, protons and heavy ions that are accelerated to high energies (10s of keV to 100 MeV) in the Sun's atmosphere and inner heliosphere, and correlate them with solar wind and coronal structures.

The WISPR white light telescope (PI Russ Howard, Naval Research Laboratory) will take images of the solar corona and inner heliosphere. The experiment will also provide images of the solar wind, shocks and other structures as they approach and pass the spacecraft. This investigation complements the other instruments on the spacecraft providing direct measurements by imaging the plasma the other instruments sample.

The HelioSPP PI, Dr. Marco Velli from University of California, Los Angeles, serves as the Observatory Scientist for the SPP Project, and carries out an inter-disciplinary science investigation that focuses on the goals and objectives of the SPP mission. He provides theoretical input and independent assessment of scientific performance to the Science Working Group (SWG) and the SPP Project to maximize the scientific return from the mission.

4.2 SPP Mission Operations

SPP operations fall into two categories: science data collection, and cruise/downlink. Instrument measurements are mostly collected during the solar encounter phase of an orbit, with all instruments nominally on at 100% duty cycle during this phase. All instruments perform science measurements simultaneously, allowing for coordinated collection of data during interesting events ("burst mode") and a high degree of integration between science investigations. Detailed planning of each solar encounter is done for each orbit, coordinated by the SPP SWG.

Given that communications are limited during the solar encounter phase, science data is stored on the solid-state recorders (SSRs) for downlink during the cruise/downlink phase of each orbit. The Sun-Probe-Earth geometry varies through the mission, and so opportunities for communication and downlink rates vary as well, requiring detailed planning unique to each orbit. In some cases, the downlink opportunities are insufficient to retrieve an entire orbit's data; the SSRs are sized to store data from two orbits to allow Mission Operations to balance downlink opportunities to return all data.

The cruise/downlink phase is also used for navigation contacts and trajectory correction maneuvers, as well as Venus gravity assists. Since the spacecraft is further away from the Sun during this phase, the thermal input from the Sun is significantly lower. Off-sun pointing attitudes are used between 0.7 and 0.76 AU to enable the HGA to point to Earth for increased downlink opportunities. Outside of 0.82 AU, the spacecraft is pointed 45 degrees off-sun exposing the anti-ram side of the spacecraft to the sun to maintain temperatures high enough to avoid freezing in the cooling system, and to reduce heater power requirements in the spacecraft and instruments. During this phase, instruments can be operated when power allows.

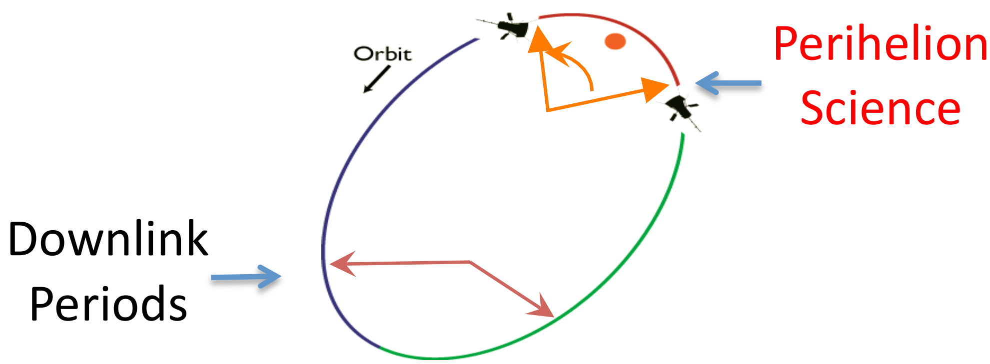


Figure 4.1 SPP Orbit Profile showing prime science location inside 0.25 AU

4.3 SPP Venus Flyby Information

To reach regions of space below 10 Rs from the center of the Sun, SPP uses a Venus intercept launch trajectory, allowing a gravity assist about 6 weeks after launch for insertion into an elliptical orbit around the Sun with perihelion near 35 Rs (0.16 AU) and aphelion near 1 AU. Six subsequent Venus gravity assists through a total of 24 orbits decrease the perihelion in stages to a final perihelion at 9.86 Rs (0.0459 AU) in the final three orbits. Launching between 31 July and 18 August 2018, the trajectory is designed to complete the mission science objectives over 7 years. Figure 6.2 shows the trajectory and timeline for initial and final perihelia and all seven Venus flybys. Figure 6.3 gives Sun-probe distance through the mission, focusing on the periods when the spacecraft is inside 53.7 Rs (0.25 AU) showing the effect of each Venus gravity assist on the following perihelia.

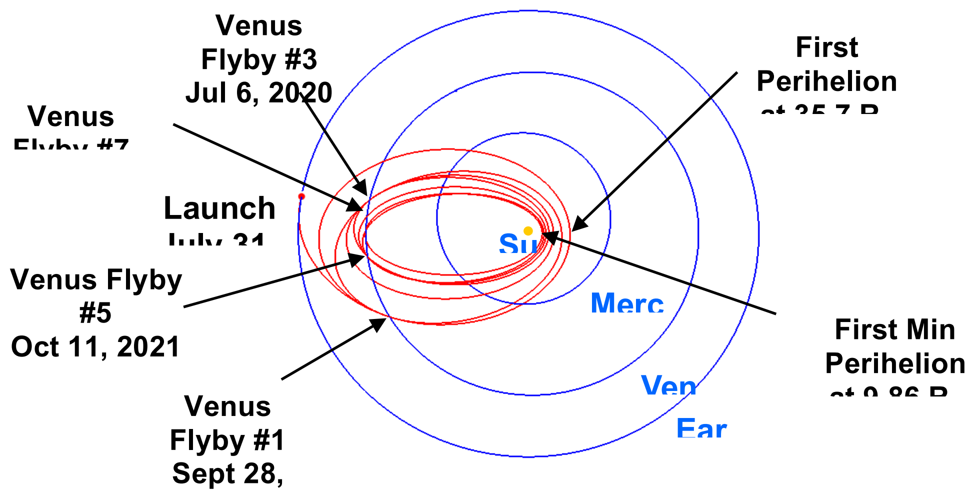


Fig 4.2 SPP trajectories viewed from above the ecliptic plane showing Venus gravity assists and first minimum perihelion.

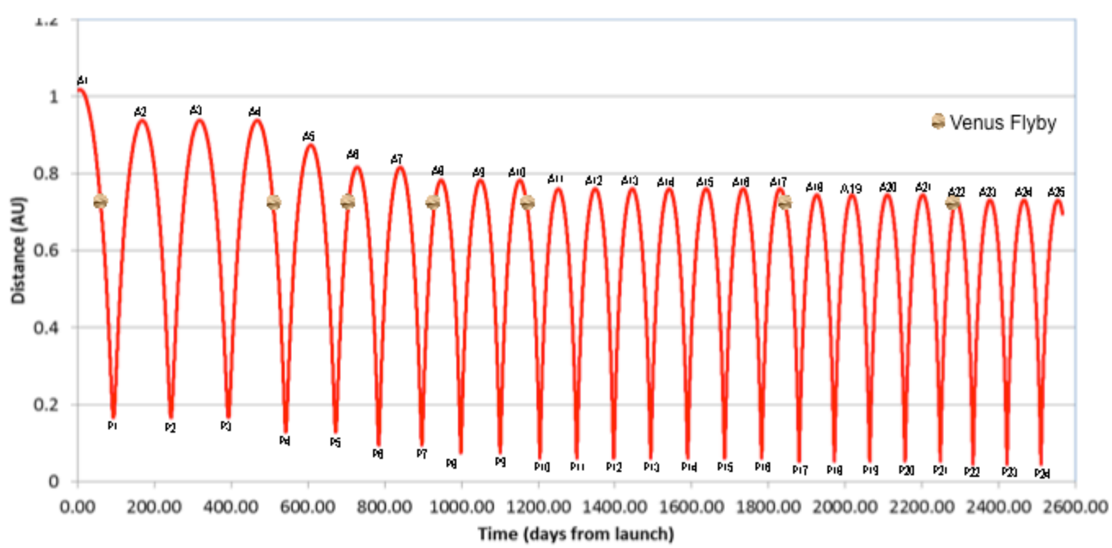


Fig 4.3 SPP Sun distance through the mission, showing walkdown to minimum perihelion.

The current ConOps states that all instruments will be powered off during the 7 VGA periods. SPP science data downlink contacts occur as close to the sun as 0.28 AU and through to Aphelion. The downlink schedule is notional at this time, and opportunities to downlink need to be preserved to ensure SPP meets the science data volume downlink requirements. Given the geometry of the SPP trajectory, each orbit is unique in the details of telecommunications and trajectory correction. The goal is to have instruments powered on outside of 0.25 AU solar distance provided that data downlink is not occurring and power is available, among other constraints.

Venus flybys are identified (as a "V") in the preliminary downlink opportunity schedule shown in figure 6.4. In each case, except one, the flyby occurs when the mission geometry allows for good downlinks to Earth to transmit stored Solar science data and therefore the instruments would be unable to collect Venus data. Also that there are trajectory correction maneuvers (TCM) before each Venus flyby.

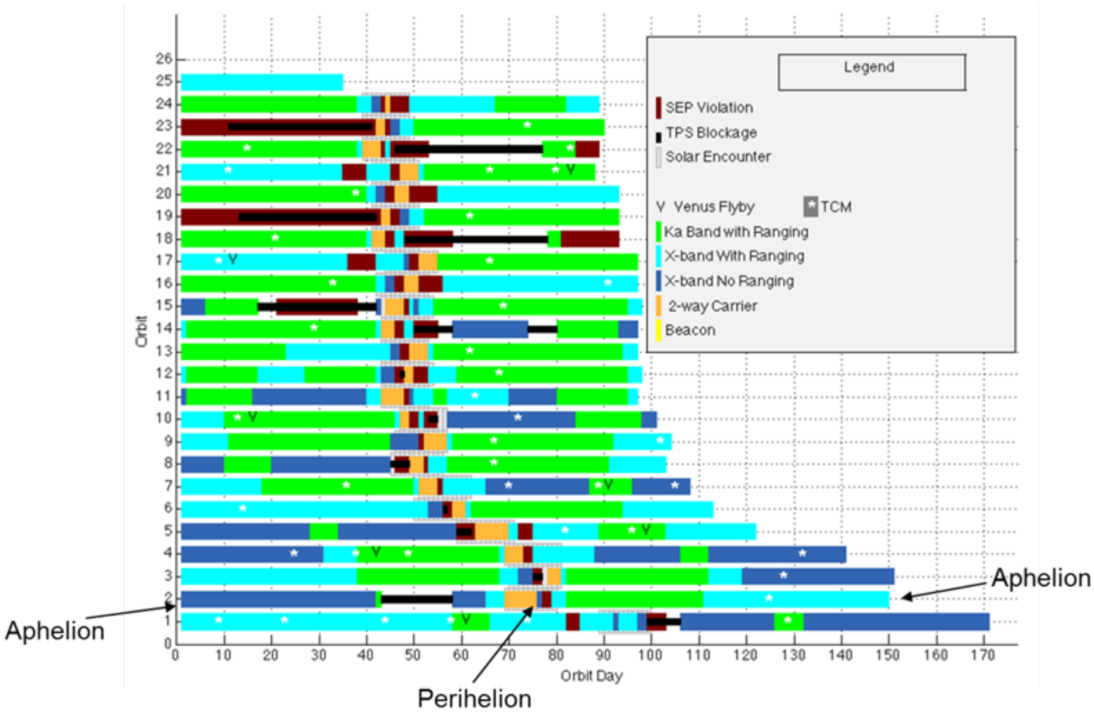


Figure 4.4 Preliminary downlink opportunity schedule

Even for VGA-6 when the spacecraft is not using the Ka-band antenna to downlink science data, the spacecraft will be in ground contact via the X-band antenna which will require that all instruments are powered off.

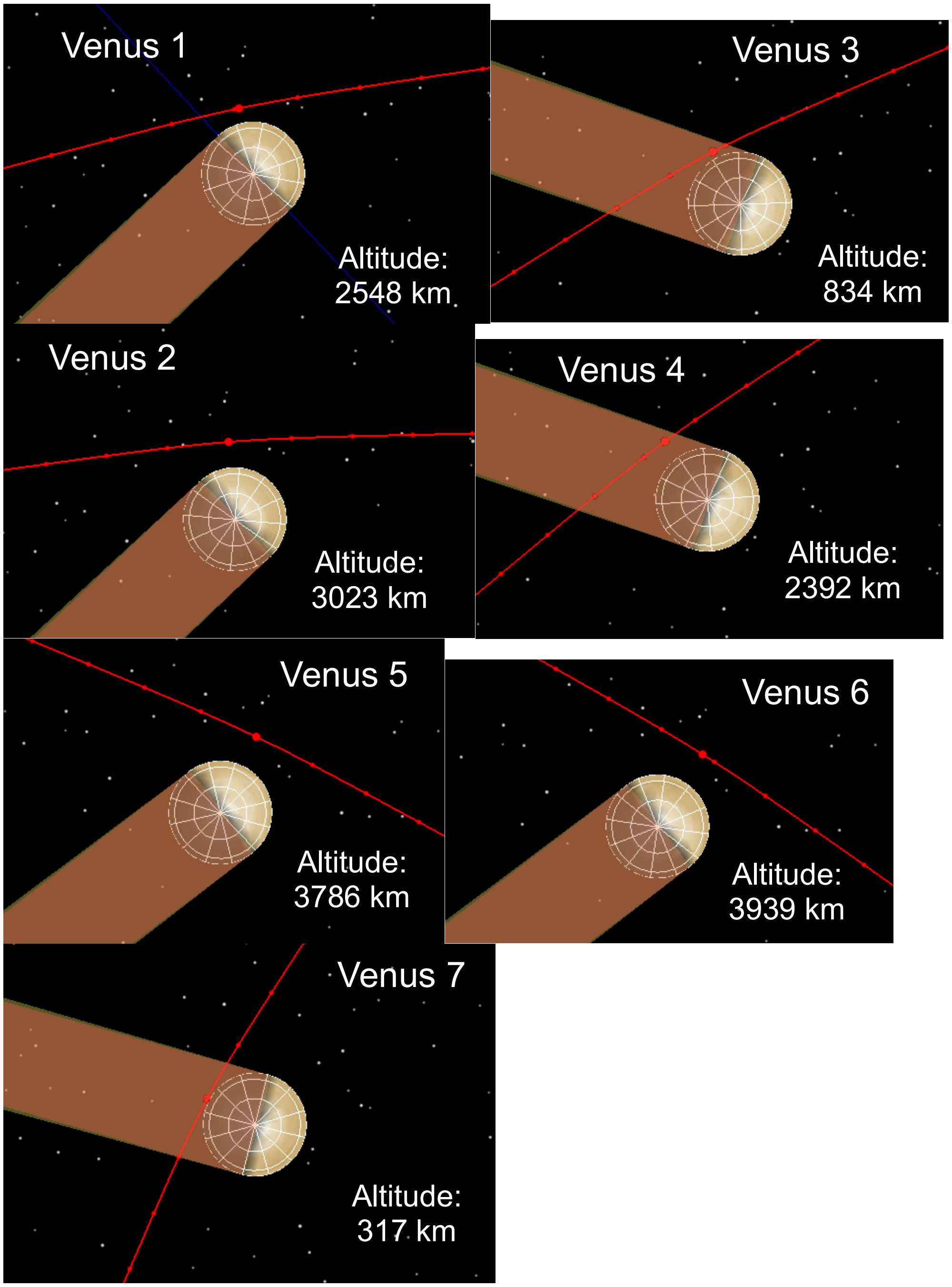


Figure 4.5 Baseline Mission Trajectory: Venus Flyby Geometry

The variation in the altitude range for the seven fly-bys is from 317 km to 3939 km is detailed in the table 4.1 below.

Eclipse Number	Altitude
1	2548 km
2	3023 km
3	834 km
4	2392 km
5	3786 km
6	3939 km
7	317 km

Table 4.1. Altitude of closest approach to Venus for each of the seven gravity assist maneuvers for SPP

5. Set of findings/possible observations for Bepi, SPP, SO in ranking/weight (table)

What is new science (ka-band occultations, etc)
Ka band occultation studies of Venus will be new. Only X/S, and 32 cm (L band) observations have been made by US and Soviet missions to Venus respectively.
Ka band is more susceptible to absorption by sulfuric acid, so the atmospheric profiles have the potential to infer the sulfuric acid abundance/opacity in the upper cloud not measured from X/S occultations from previous missions
Venus space environment unique science opportunities
Planetary ions are clearly seen escaping from Venus on both PVO and VEX. Their fluxes and energies are fairly well characterized, although the PVO detections to ~12 Rv were limited to O+ energies less than ~8 keV. (Note Gruenwald and Neugebauer et al. have even reported Venus O+ detection at 1 AU on SOHO- GRL 1997)

-Escaping ions at low energies are more confined to the solar wind wake-especially in the tail plasma (current) sheet.

-Pickup ion energies and fluxes are enhanced by 'space weather' events

Fly-by science vs. approach and departure science observations

5.1 Proposed unique observations mapped against the VEXAG goals, observations and investigations (i.e. lightning, etc).

Payload	Possible investigations
BC (remote & in situ) ISA MPO-MAG MERTIS MGNS MORE PHEBUS SERENA	-Venus Gravitational Mass constant (ISA) -Oblateness (ISA) -Atmospheric vertical structure, clouds, hazes, temperatures (MERTIS, MORE) -Lightning, electrical activity, airglow (PHEBUS, MPO-MAG) -Escape of ions/neutral atmosphere (SERENA/ PICAM, SERENA/MIPA) -Ion Cyclotron Waves and other Waves around Venus (MPO-MAG, SEREN/MIPA) -Venus Bow Shock and Magnetotail at different ranges and times (MPO-MAG) Surface properties (MGNS)
SO (in situ) & **SPP (remote & in situ?)** ***SO*** SWA RPW MAG EPD ***SPP*** WISPR? FIELDS? ISIS? SWEAP?	-Escape of ions/neutral atmosphere (WISPR) -Ion Cyclotron Waves and other Waves (FIELDS) -Venus Bow Shock and Magnetotail (MAG, FIELDS) -Lightning and electrical activity (MAG, ISIS, FIELDS) -X/Ka* band radio ionospheric and -neutral atmosphere occultation profiles** *depending on final TLC configuration ** pointing required

Table 5.1 Summary of possible investigation of the BC, SO and SSP payload during VGA's

6. VCO/Akatsuki possible synergistic observations with other VGA missions (SPP, SO, BepiColombo)

JAXA's Akatuski mission to Venus (also known as Venus Climate Orbiter) is expected to begin orbiting Venus in late November/early December 2015. Designed to explore the atmospheric superrotation of Venus, Aktasuki has primarily planetary imaging instruments operating at ultraviolet and infrared wavelengths. It lacks instruments to observe the plasma environment of Venus while orbiting the planet in a seven to ten day near equatorial orbit.

Akatsuki is expected to enter into a very large, near equatorial orbit with a period of approximately one week with a periapsis altitude of a few hundred km according to the Akatsuki Project. Consequently there will be fewer radio occultation opportunities over the planned two year operations, which may be extended later. Thus there is a good chance of some overlap between Akatsuki observations and some of the fly-bys by SO, SPP and BC.

7. CONCLUSIONS

The fifteen Venus fly-bys to be made during September 2018 – November 2024 by SPP (7), SO (6) and BepiColombo (2) provide opportunities to obtain observations of Venus in its interplanetary environment, with the potential to improve the knowledge of the planet and its solar wind interaction. The most valuable and desirable observations include:

From SPP and/or SO:

- Escape of ions/neutral atmosphere from imaging observations from WISPR (SPP) and SOHI (SO) - weeks before and after the closest approach if S/C pointing to keep Venus out of the field of view (so as not to saturate the detector) is feasible
- Ion Cyclotron Waves and other Waves observed around Venus – ~ days before and after closest approach
- Venus Bow Shock and Magnetotail at different ranges and times from Venus – ~ days before and after
- Lightning and electrical activity
- X/Ka band radio occultation profiles of the ionosphere and neutral atmosphere

From BepiColombo:

- Gravitational Mass constant (GM) for Venus (ISA)
- Oblateness (ISA)
- Vertical structure of the atmosphere, clouds, hazes and temperature (MERTIS, MORE)
- Lightning and electrical activity (MPO-MAG)
- Airglow observations (PHEBUS)
- Escape of ions/neutral atmosphere (SERENA/PICAM, SERENA/MIPA)
- Ion Cyclotron Waves and other Waves observed around Venus (MPO-MAG, SEREN/MIPA)
- Venus Bow Shock and Magnetotail at different ranges and times from Venus (MPO-MAG)
- Surface properties (MGNS)

We wish to emphasize that there desire to collect these observations may not translate into actual implementation as there are spacecraft, instrumental, thermal and communication constraints that will prevail. Since Venus observations were not considered during the early planning, the assumed risk posture is that most instruments will be off and that high gain antenna pointing is dictated by telemetry and/or thermal considerations. Certain observations (e.g. radio occultation, escape of atmosphere) will need some pointing requirements that will likely collide with other constraints and will require study by these projects.

To conclude, the Heliophysics and Planetary Science Divisions of NASA/SMD have reached a key milestone by initiating this inquiry into collaborative studies of broader interest. We acknowledge the excellent cooperation of the three projects and the respective Project Scientists with our efforts. Our aim is to assess valuable science during the VGAs. The potential science observations may result in a milestone for understanding planetary systems behavior.

NOTES

APPENDIX A

Radio Occultations at Venus with Solar Probe Plus (SPP), Solar Orbiter (SO), and BepiColombo (BC) Missions

Paul G. Steffes,Georgia Institute of Technology,December 10, 2014

A.1 INTRODUCTION

Study of the temporal and spatial variability of the Venus clouds and cloud-related gases provides insights into both short and long term atmospheric dynamics. Previous atmospheric radio occultation studies from Pioneer Venus (Jenkins and Steffes, 1991) and Magellan (Jenkins et al., 1994; Hinson and Jenkins 1995; Kolodner and Steffes, 1998) provided insight into Hadley cell circulation, atmospheric stability, and atmospheric composition and structure. The large number of X-band (and a few S-Band) radio occultations conducted with Venus Express provided detailed information about the abundance of H_2SO_4(g) above the main cloud layer (Oschlisniok et al., 2012) and atmospheric structure above the cloud layer (Piccialli et al, 2012).

Since all prior missions (except Mariners 5 and 10) were in polar or highly inclined orbits, very few profiles of the equatorial structure and composition have been measured. Since the equator plays a unique role in the Hadley cell circulation, more information about this important zone is of high scientific value. Additionally, no previous occultation experiments have been conducted at Ka-Band (9.2 mm). Ka-Band radio occultations, because of their short wavelength, provide higher vertical resolution than the longer wavelength occultation experiments, and are also sensitive to cloud condensates. This makes possible the vertical profiling of cloud bulk density (Fahd and Steffes, 1991), with vertical resolutions on the order of 100 meters.

The depths in the Venus atmosphere which can be probed with radio occultations during the SPP, SO, and BP Venus flybys will vary with the spacecraft track and the spacecraft transmitter systems. At X-band (3.6 cm) Magellan probed down to 35 km altitude (well below the clouds), but the actual depth achievable during gravity-assist flybys will depend on the range to earth and on spacecraft transmitter power and antenna gain. At Ka-Band (9.2 mm), it is expected that the signals will be detectable down to the base of the main cloud layer (48 km).
Thus, radio occultation measurements of the Venus atmosphere conducted with SPP, SO, and BP provides unique science for a moderate investment in investigator time and spacecraft resources.

A.2 VENUS RADIO OCCULTATION OPPORTUNITIES FROM SOLAR PROBE PLUS (20180731 Trajectory):

The Solar Probe Plus mission will have 7 flybys of Venus in the currently planned V_7GA trajectory with the first occurring September 28, 2018 and the last on November 2, 2024. During 5 of the flybys, Venus occults the spacecraft as viewed from earth, providing opportunities for atmospheric profiling near the Venus equator. Information is given regarding the potential for both Ka-Band and X-Band radio occultations. However, simultaneous downlinks are not possible with both Ka and X-Band, so we will need to focus most likely on Ka-band.

Venus 1:
The Venus 1 flyby occurs on September 28, 2018 and SPP flies almost directly behind Venus (as viewed from earth) at an altitude of 2,548 km, providing both entry and exit occultations (each lasting approximately 3 minutes) over a period of 12 minutes. While exit occultations can be difficult to conduct when the spacecraft transponder operates in a "two-way" mode (i.e., locking to an uplink signal from the earth station), the stability of SPP internal oscillator (Allan deviation less than 10^{-10} over 100 seconds) makes possible conduct of one-way radio occultations, greatly simplifying operational requirements for both entry and exit occultation measurements. Since the range to earth will be relatively small (0.375 AU), the carrier-to-noise ratio with modulation shut off can be very high, assuming the spacecraft HGA (High Gain Antenna) can be employed.
Using the HGA downlink at Ka-band (assuming a limb-track maneuver designed to keep the HGA pointed toward the entry and exit limbs of the planet), it will be possible to probe through the main cloud layer (profiling cloud bulk density with a vertical resolution of 250 meters) and then probe into the sub-cloud sulfuric acid vapor layer for an additional 1-2 km before loss of signal (LOS). Using the HGA downlink at X-band (assuming a similar limb-track maneuver), it would be possible to probe through the main cloud layer (profiling sulfuric acid *vapor* abundance from the top of the cloud layers down to the deep troposphere (~35 km altitude) with a vertical resolution of 500 meters). If mission limitations only allow conduct of radio occultations using the X-band medium gain antenna (MGA, or fan-beam), the resulting profiles of sulfuric acid *vapor* would only go down to the top of the main of the cloud layer. This would provide only an incremental contribution to the knowledge provided by radio occultation profiles obtained with Venus Express, in that it would provide some additional equatorial coverage.

Note that the above analysis assumes ground station support at Ka-band using a DSN 34-meter beam-waveguide (BWG) antenna and X-band support using one of the 70-meter antennas.

Venus 4:
The Venus 4 flyby occurs on February 16, 2021 and SPP flies almost directly behind Venus (as viewed from earth) at an altitude of 2,392 km, providing both entry and exit occultations over a period of 15 minutes. Since Venus will be only 9 degrees from superior conjunction, the spacecraft will be eclipsed from sunlight during much of the occultation. Because of the long distance to earth, use of the high gain antenna (HGA) will be necessary. At Ka-band (assuming a limb-track maneuver designed to keep the HGA pointed toward the entry and exit limbs of the planet), it will be possible to probe through most of the main cloud layer (profiling cloud bulk density with a vertical resolution of 250 meters). Using the HGA downlink at X-band (assuming a similar limb-track maneuver), it would be possible to probe through the main cloud layer (profiling sulfuric acid *vapor* abundance from the top of the cloud layers down to the ~43 km altitude, with a vertical resolution of 500 meters).

Venus 5:
The Venus 5 flyby occurs on October 11, 2021, and SPP flies in a path almost directly away from earth as it is occulted by Venus (as viewed from earth). As a result, the entry occultation (alone) will last more than 10 minutes, and the subsequent exit occultation will have an even

longer duration. Since the distance to Venus during the exit occultation will be extremely large, no reasonable vertical resolution could be expected. For the entry occultation, the Ka-band vertical resolution will be approximately 400 meters and at X-band the vertical resolution will be approximately 0.8 km. Since the range to earth will be relatively large (0.8 AU), operation with the HGA is necessary. Of all of the SPP occultation opportunities, this is probably the least desirable.

Venus 6:
The Venus 6 flyby occurs on August 15, 2023 when Venus is very close to earth (0.29 AU) and very close to the sun (only 8 degrees from inferior conjunction). SPP flies almost directly behind Venus (as viewed from earth) at an altitude of 3,939 km, providing both entry and exit occultations over a period of 12 minutes. (The duration of each occultation is only about 2 minutes.) Using the HGA downlink at Ka-band (assuming a limb-track maneuver designed to keep the HGA pointed toward the entry and exit limbs of the planet), it will be possible to probe through the main cloud layer (profiling cloud bulk density with a vertical resolution of 300 meters) and then probe into the sub-cloud sulfuric acid vapor layer for an additional 1-2 km before loss of signal (LOS). Using the HGA downlink at X-band (assuming a similar limb-track maneuver), it would be possible to probe through the main cloud layer (profiling sulfuric acid *vapor* abundance from the top of the cloud layers down to the deep troposphere (~35 km altitude) with a vertical resolution of 500 meters). If mission limitations only allow conduct of radio occultations using the X-band medium gain antenna (MGA, or fan-beam), the resulting profiles of sulfuric acid *vapor* would go down to the top of the main of the cloud layer. (Comparable with Venus Express. (This would provide only an incremental contribution to the knowledge provided by radio occultation profiles obtained with Venus Express, in that it would provide some additional equatorial coverage.)

Venus 7
The Venus 7 flyby occurs on November 2, 2024 and SPP flies in a path with a partial velocity component toward earth as it is occulted by Venus (as viewed from earth). As a result, the entry occultation (alone) will last more than 5 minutes, but the subsequent exit occultation will have a more tractable 4 minute duriation. Since the distance to Venus during the exit occultation will be very small (the closest approach is 317 km), the vertical resolution in the exit occultation would be 200 meters (Ka-band) and approximately 400 meters at X-band. Since the range to earth will be relatively large (1.17 AU), operation with the HGA is necessary.

A.3 VENUS RADIO OCCULTATION OPPORTUNITIES FROM BEPI COLUMBO

The Bepi Columbo Team was very generous in providing detailed information about Venus radio occultation opportunities. During the first Venus flyby, there will be an entry occultation at about 45 degrees south latitude and an exit occultation about 30 minutes later at 60 degrees north latitude. The biggest scientific opportunity would involve using the Ka-band tranponder to probe the cloud bulk density, but the X-band signal will likewise be necessary so as to characterize the cloud-related gases. (Note that there are no radio occultation opportunities with the second flyby. B-C flies almost directly behind Venus (as viewed from earth) at an altitude of 1,500 km, providing both entry and exit occultations (each lasting approximately 3 minutes) over a period of 32 minutes. Since the range to earth will be relatively large (1.68 AU), the carrier-to-noise ratio with modulation shut off can be made acceptable, assuming the spacecraft HGA (High Gain Antenna) can be employed. Using the HGA downlink at Ka-band (assuming a limb-track maneuver designed to keep the HGA pointed toward the entry and exit limbs of the planet), it will be possible to probe through the main cloud layer (profiling cloud bulk density with a vertical resolution of 250 meters) to its base. Using the HGA downlink at X-band (assuming a similar limb-track maneuver), it would be possible to probe through the main cloud layer (profiling sulfuric acid *vapor* abundance from the top of the cloud layers down approximately 40 km, with a vertical resolution of 500 meters.

A.4 VENUS RADIO OCCULTATION OPPORTUNITIES FROM SOLAR ORBITER (SO, July 2017 Trajectory):

The Solar Orbiter (SO) has 5 Venus flybys in its trajectory plan. However, if a later launch (November 2018) is employed, there will be 6 Venus flybys. Unlike SPP, SO's radio occultation opportunities will occur at a number of different latitudes. Additionally, since SO only supports X-band downlinks, the output products will be similar to those obtained with Venus Express. The analysis below pertains to the planned mission with a launch date of July 27, 2107. Note that for this trajectory (launch date) there are only 3 Venus flybys providing occultations of the spacecraft by the Venus atmosphere.

GAM (Gravity Assistance Maneuver) 1:
The first Venus flyby occurs on May 15, 2020, with a minimum altitude of 4579 km. Both radio occultations will occur in the northern hemisphere relatively close to the equator. Vertical resolution of approximately 1 km can be achieved and sulfuric acid vapor abundance should be detectable down to the 40 km level assuming the HGA with a limb-tracking maneuver can be employed, since the range to Venus is only 0.34 AU.

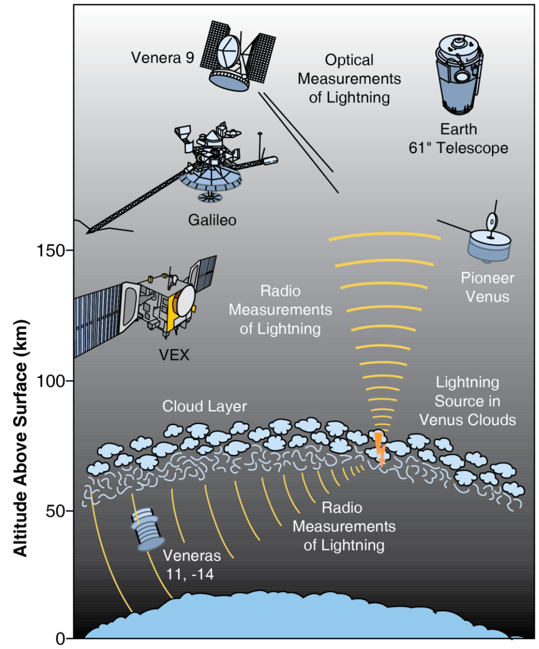
GAM (Gravity Assistance Maneuver) 2:
The second Venus flyby occurs on January 5, 2021, with a minimum altitude of 350 km. Both radio occultations will occur within a period of 20 minutes of each other. The entry occultation will occur in the southern hemisphere and the exit occultation will be close to the equator. Because of the proximity to Venus, vertical resolution of approximately 800 m can be achieved, but sulfuric acid vapor abundance would be detectable only down to the base of the main cloud (~48 km), since the range to Venus is large (1.57 AU).

GAM (Gravity Assistance Maneuver) 4:
The fourth Venus flyby occurs on April 27, 2025, with a minimum altitude of 350 km. SO flies in a path almost directly toward from earth as it is occulted by Venus (as viewed from earth). The duration of the occultations (entry and exit) will be extremely long because of the spacecraft motion vector. Also, because the spacecraft will be quite distant from Venus during the occultations themselves, the vertical resolution will be quite poor. Of all of the SO occultation opportunities, this is probably the least desirable.

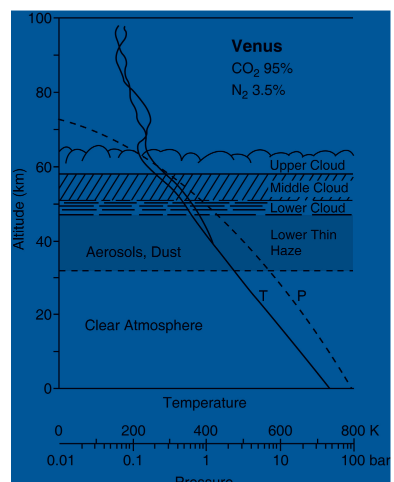
APPENDIX B. Lightning/Electrical Activity, Ionosphere and Magnetosphere Observations

Janet Luhmann and Chris Russell

B.1 Venus Lightning Observations

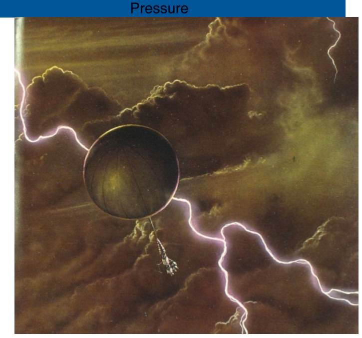


- Lightning on Venus can and has been detected on Venus by several missions.
  - Optically: Venera 9 Spectrometer; ground-based telescope
  - Radio waves: Galileo flyby, Cassini flyby
  - ELF/VLF waves: Venera 11-14 landers; PVO dipole antenna, VEX fluxgate
- Lightning on Venus is probably generated by electrostatic discharges in clouds from 50-60 km, but the exact cause(s) and rate of lightning is not well-constrained
  - PVO surveyed only in solar occultation only at 100 Hz.
  - Venus Express has surveyed only at high northern latitudes ≥ 70° from 0 to 64 Hz.



Why is Lightning Important?

- Lightning raises the temperature and pressure of the gas in the lightning stroke to high values. This allows chemical reactions not possible at LTE values. Is activity sufficiently great to significantly alter Venus' atmosphere?
- Electromagnetic energy flux in Venus lightning is similar to those at Earth.
- Nitric oxide concentration produced by lightning is similar at Venus and Earth.
- Volcanoes are known to be associated with lightning on Earth. Do Venus lightning rates depend on volcanic activity?
  - SO2 haze a high altitudes is variable (sudden onset, slow decay).
  - The rate of lightning and volcanism may be linked through the SO2 content and the production of H2SO4 in the clouds.



- Venus lightning has been reported optically, using radio waves, using electric field detectors and using magnetometers (fluxgates and coils).

Summary

- The two most extensive surveys have been with PVO (but only in darkness) and Venus Express (but only at high latitudes).
- Venus Express is moving to lower latitudes but will soon enter the atmosphere.
- Lightning appears to occur at all local times, but more often on the dayside. (However, magnetic field connections to the dayside sources are needed to detect it.)
- Its strength (as determined from the energy flux in ELF waves) is comparable to that on Earth.
- The concentration of nitric oxide at Earth and Venus are similar, consistent with lightning production at both planets.

B.2 Venus Bow Shock and Magnetotail:

Orbital Sampling of Venus- Solar Wind Interaction on PVO and VEX

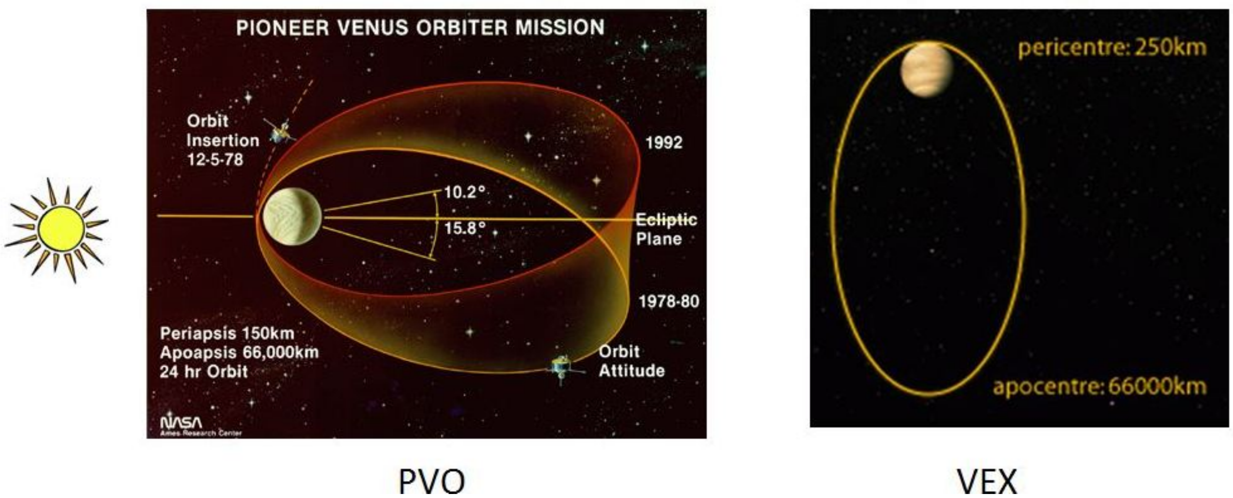
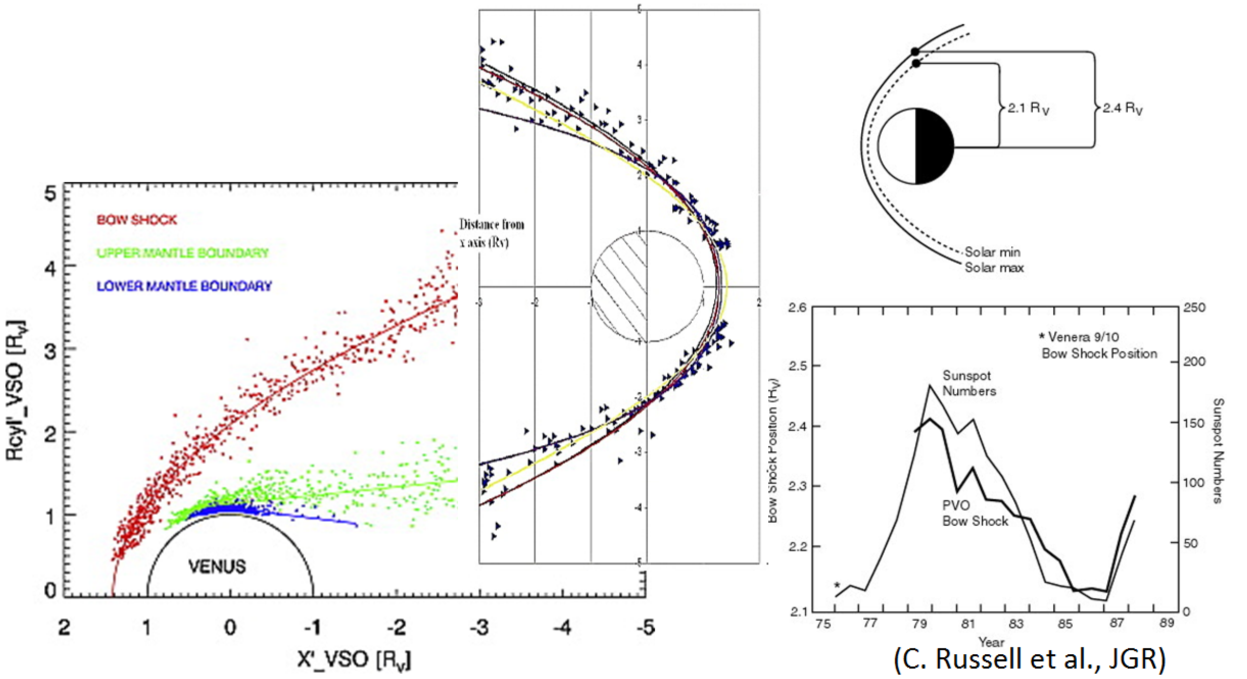


Figure B.1 Orbital geometries of Pioneer Venus and Venus Express orbiters.

Typical PVO periapsis (prime mission) at ~150 km
Typical VEX periapsis at ~250 km
PVO prime mission periapsis at _15 deg N latitude
VEX periapsis generally above 78 deg N latitude (~polar)
PVO prime mission at solar max
VEX prime mission mostly low solar activity

Bow shock locations have been determined from both missions and solar cycle dependence investigated



Observations from papers by Russell et al., Martinecz et al.,, Whittaker et al.

Figure B.2 Observations from papers by Russell et al., Martinecz et al., Whittaker et al.

A BATS-R-US MHD fluid model reproduces many features like these:
bow shock, sheath, wake-seen in Venus magnetic field data statistics. The combined measurements showed more of the induced magnetotail (Figure B.3)

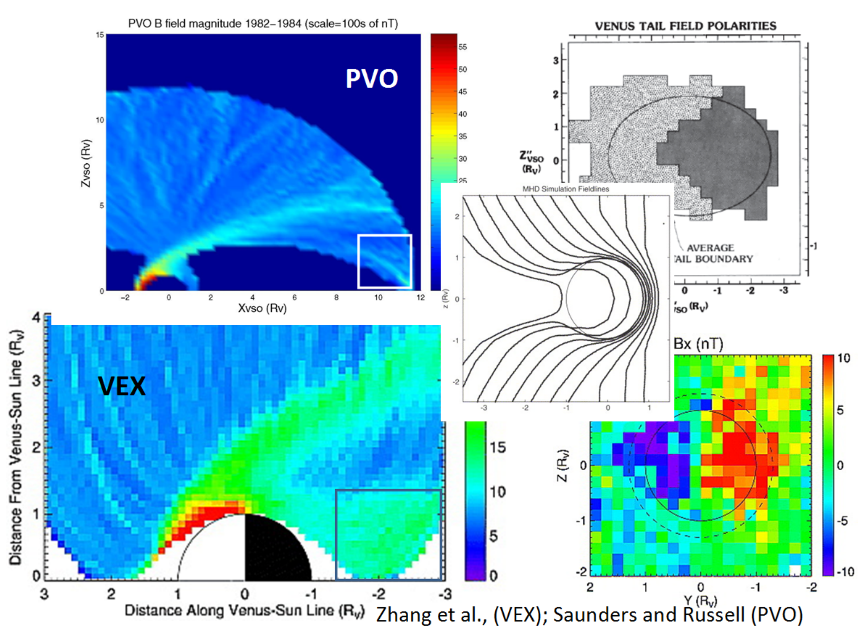


Figure B.3 The Ma MHD Venus model mag. field for Solar Max (top left) and Min (bottom right)

Zhang et al., GRL 2010 identified a well-defined induced tail asymmetry
that could be described by global hybrid models of the solar wind interaction

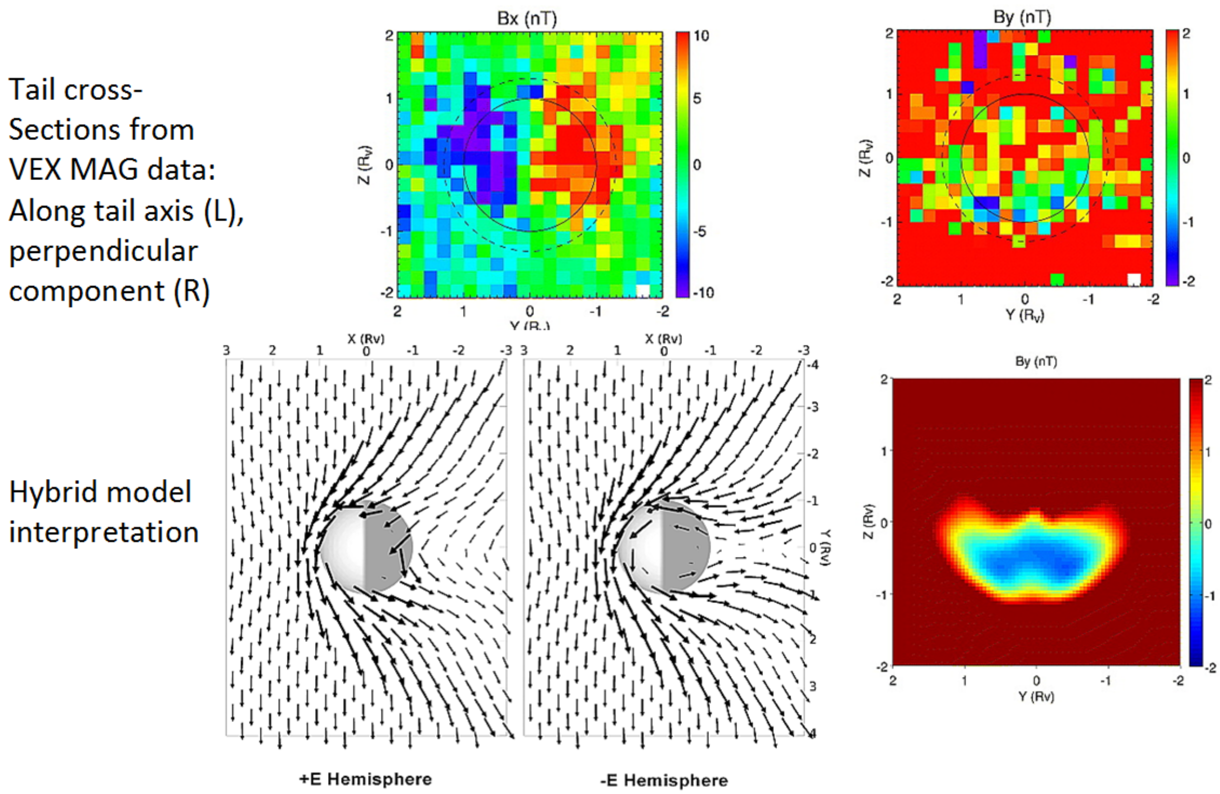


Figure B.4 Tail asymmetry observations by Zhang et al. (2010).

Zhang et al. also found evidence for Induced-Tail Reconnection (a plasmoid) from VEX. Sunward Plasma Flows in wake from VEX (Fedorov et al) are consistent with these observations.

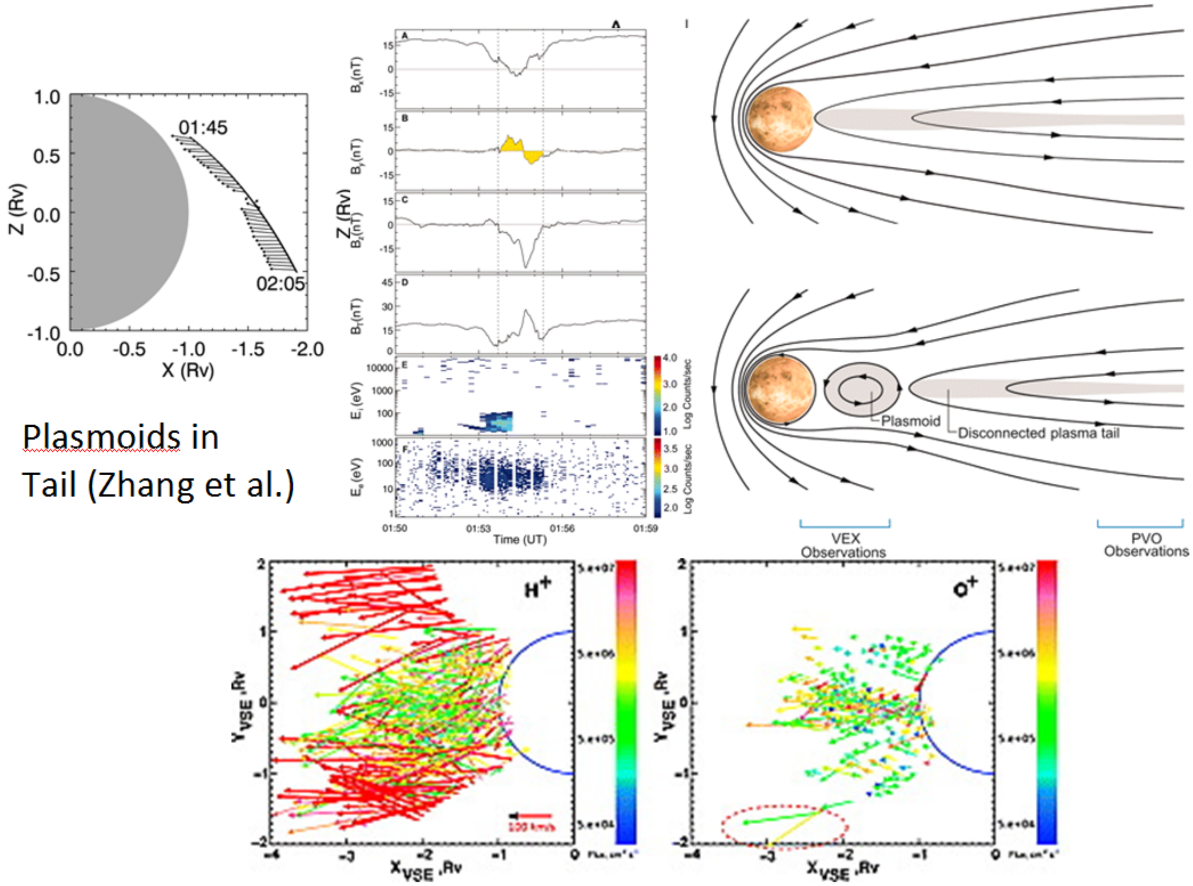


Figure B.5. Evidence for Induced-Tail Reconnection (a plasmoid) from VEX (Zhang et al., 2010)

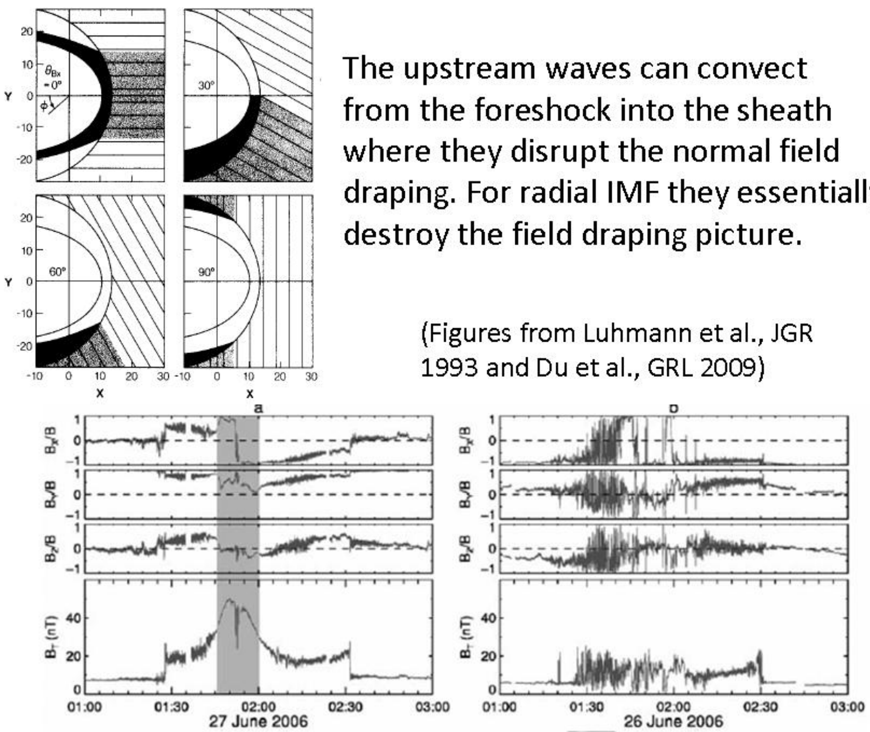
Summary:

-Bow shock and obstacle boundary are well-characterized
out to the PVO apoapsis at ~12 Rv

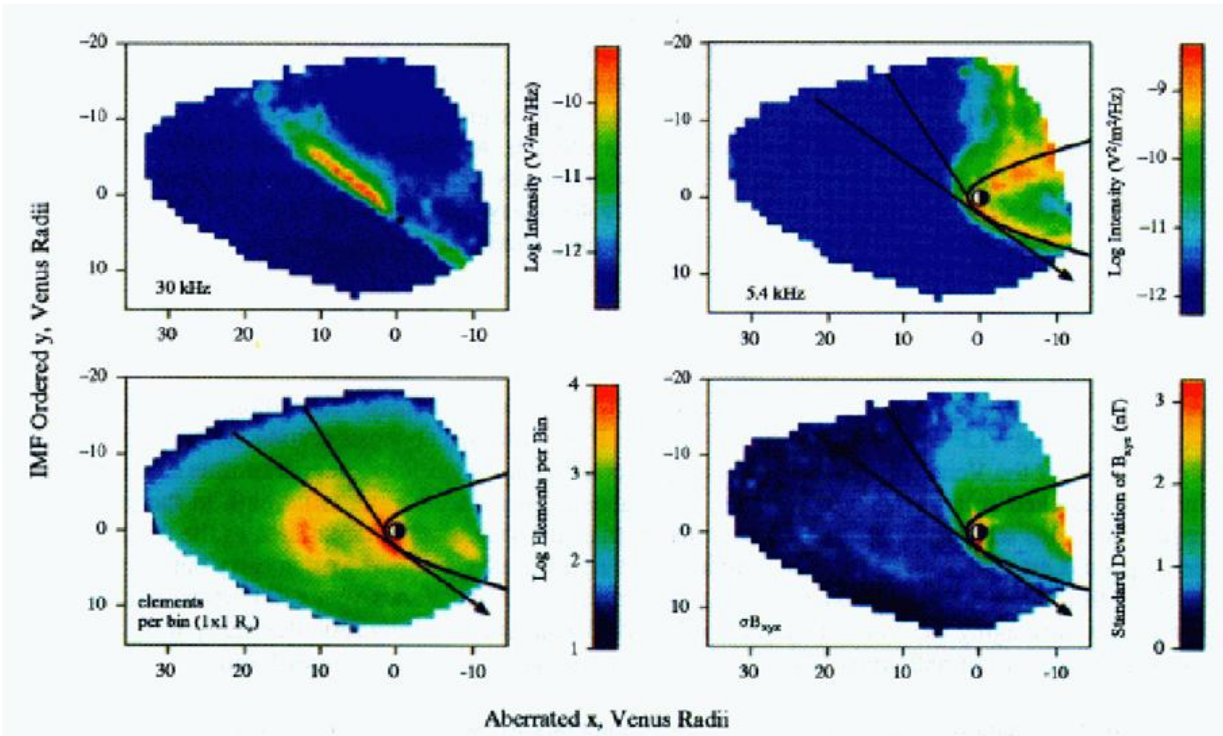
-Sheath draping is consistent with induced magnetosphere

-Magnetotail looks largely (if not all) induced, and seems to exhibit an asymmetry in draping controlled by the solar wind electric field. Reconnection seems to be occurring in the magnetotail current sheet and producing plasmoids in the region observed with VEX.

Venus Ion Escape from PVO and VEX: A short summary of observations (from Janet Luhmann)

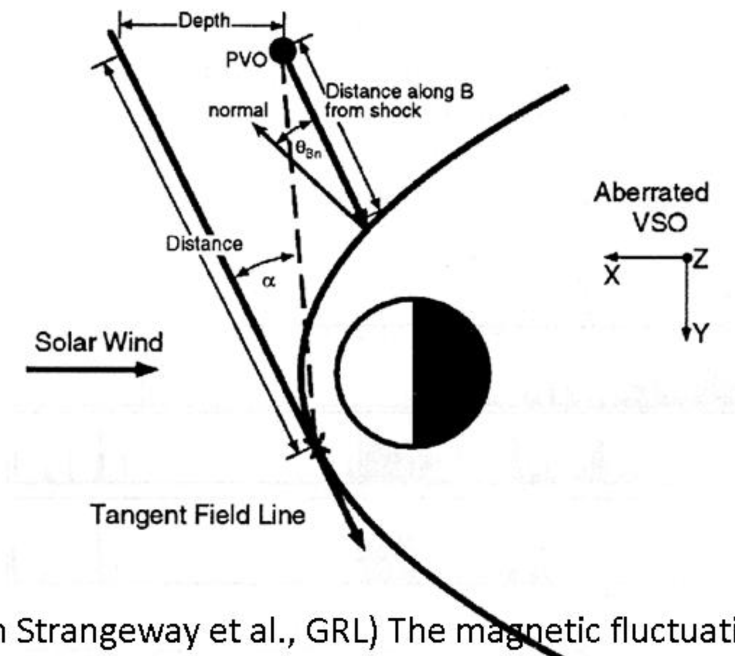


PVO Plasma Wave foreshock observation statistics



(Strangeway et al., GRL)

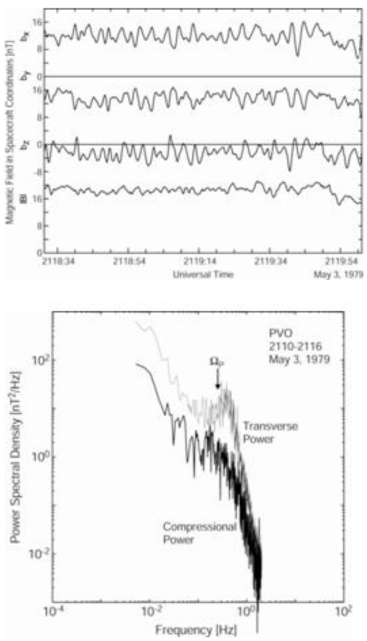
Complicating the picture: the role of “foreshocks”.
“Foreshocks” are characterized by plasma waves and magnetic field fluctuations upstream of the bow shock



(figure from Strangeway et al., GRL) The magnetic fluctuations can be convected into the sheath and affect the plasma interaction with the atmosphere/ionosphere by making it more ‘turbulent’.

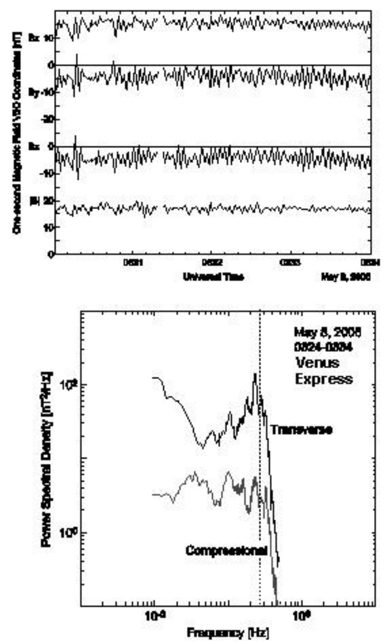
Proton Cyclotron Waves Observed at Venus: Frequencies and Power Spectra

In magnetosheath (PVO)



(From Russell et al., 2006)

In solar wind near Venus (VEX)



(From Delva et al., 2007)

- Russell et al saw the PCWs only in the magnetosheath; Delva et al saw the waves everywhere in the region around Venus and they were not controlled by the solar wind electric field.
- The exospheric density implied by the observations of Delva et al is unusually large and inconsistent with the observed exosphere and fast neutrals.

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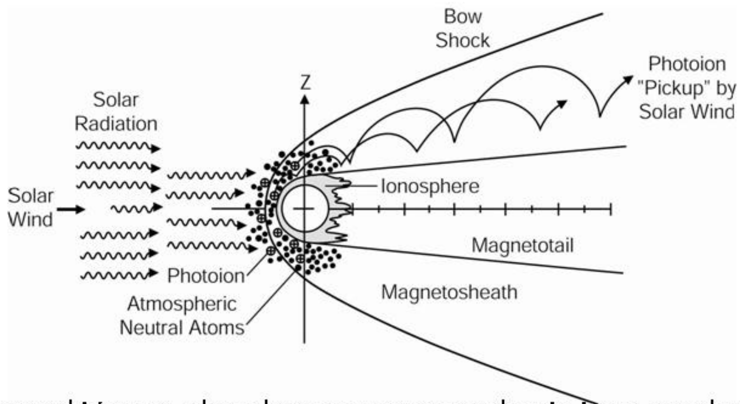
ICWs Generated by Ion Pickup



- At Mars and Venus, the planetary atmospheric ions produced in the solar wind and in the magnetosheath are accelerated by the interplanetary magnetic field and electric field, and carried away (or 'picked up') by the solar wind
- Ion cyclotron waves are generated by these 'pick-up ions'. These can be seen in magnetometer data. These waves provide good diagnostics for the processes at work, and can help us to determine the atmosphere extent and the rate of atmospheric loss.

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Ion Cyclrotron Waves and Other Waves
Observed Around Venus
(Slides adapted from a presentation
by Hanying Wei, IGPP-UCLA)

Summary

-Planetary ions are clearly seen escaping from Venus on both PVO and VEX. Their fluxes and energies are fairly well characterized, although the PVO detections to ~12 Rv were limited to O+ energies less than ~8 keV. (note Gruenwald and Neugebauer et al. have even reported Venus O+ detection at 1 AU on SOHO (GRL 1997))

-Escaping ions at low energies are more confined to the solar wind wake-especially in the tail plasma (current) sheet.

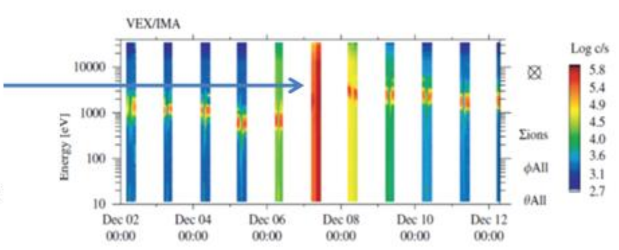
-Pickup ion energies and fluxes are enhanced by 'space weather' events

VEX ASPERA-4 results also show escape enhancements

Ion count enhancement

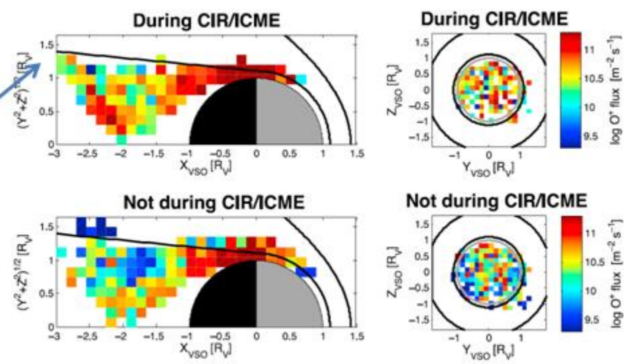
in spectrogram from Futaana et al. (2007) due to 'space weather'

(but high background)



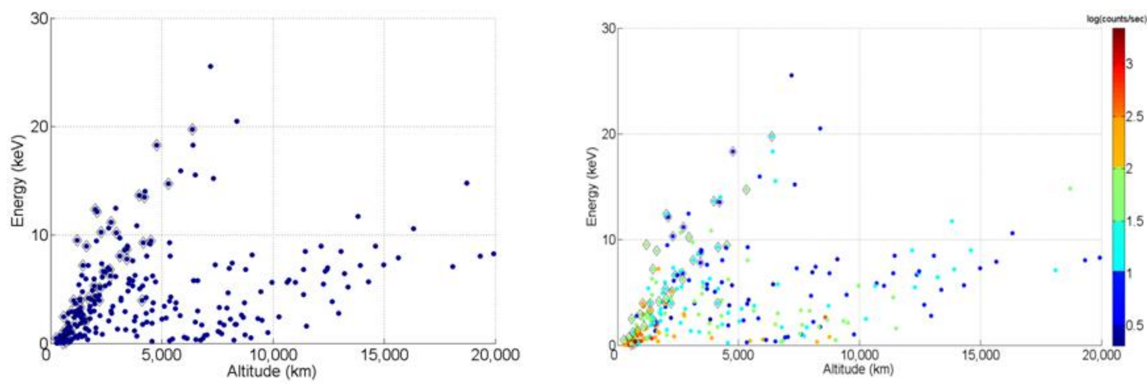
Enhancement in statistics of high dynamic pressure vs quiet cases

(Edberg et al., 2010)



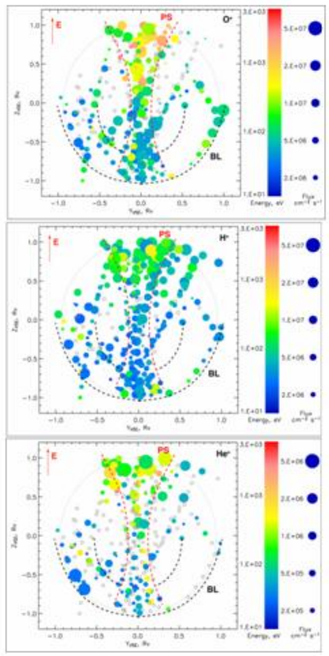
Fluxes of heavy ions

VEX IMA O+ Ion 'Beam' Energies

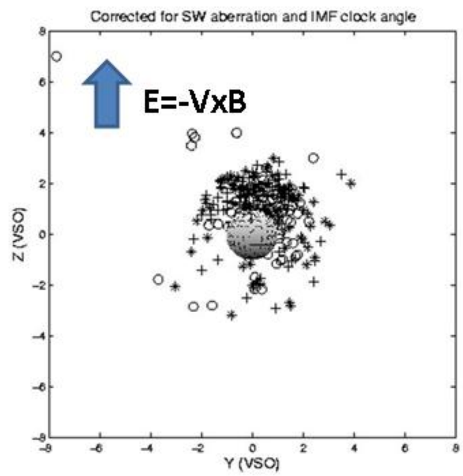


Diamonds in the left panel mark cases where VEX magnetic field data suggest passage of an ICME (from T. McEnulty et al., PSS, 2010). Right panel is color coded by flux. ICMEs seem to enable faster ion acceleration (likely due to higher Solar wind V and B during these events).

Statistical ion wake observations from both VEX (left) and PVO(right) show characteristic pickup ion asymmetries (solar wind electric field controlled) in both the near and far tail

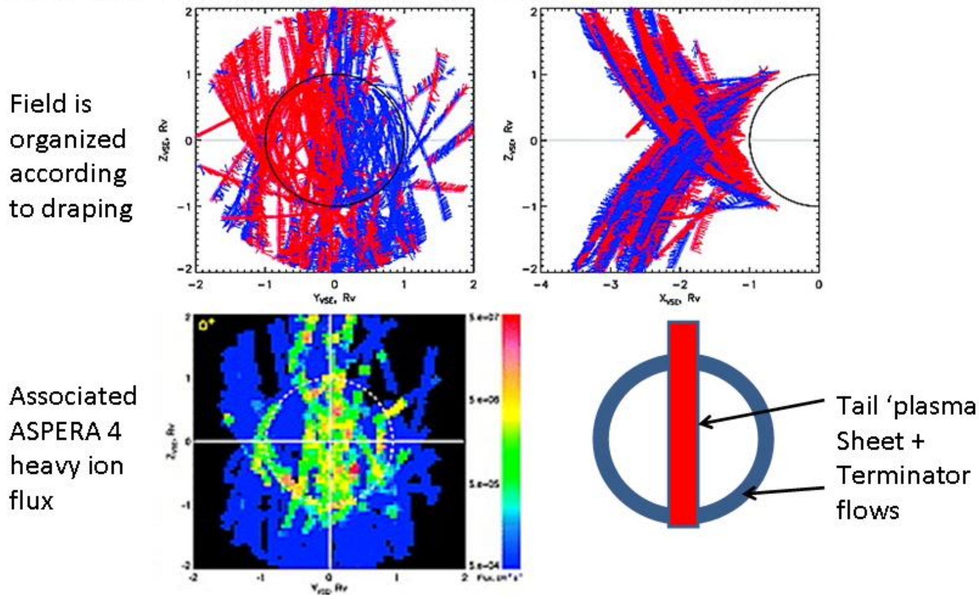


(from Barabash et al., Nature, 2007)



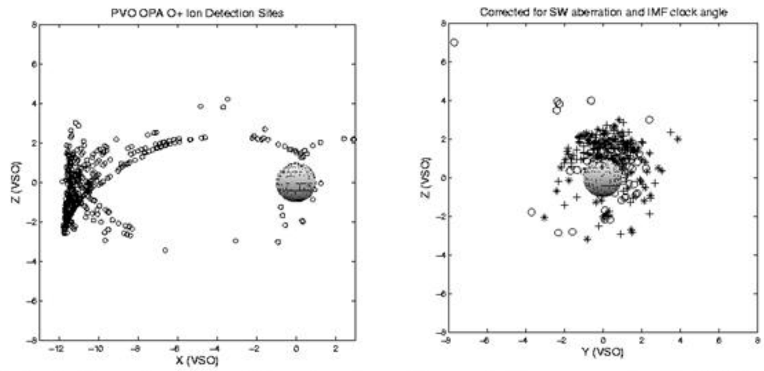
(from Luhmann et al., PSS, 2006)

VEX results suggest this pattern of most of the O+ escape, which they find is dominated by the lower energies

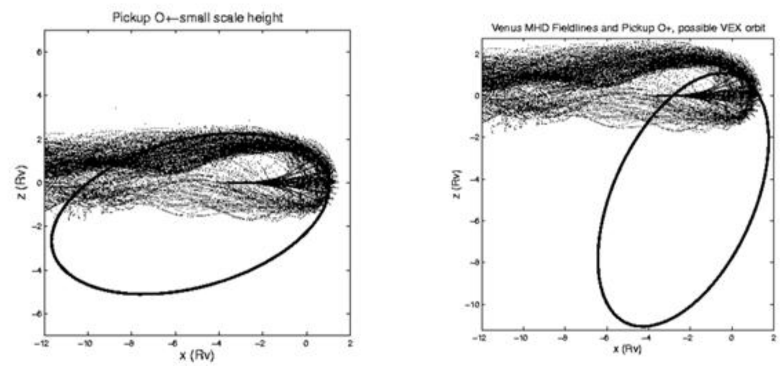


Fedorov et al. (2011) analysis of tail field (top) and O+ escape on VEX

Locations of the PVO O+ detections organized by field draping

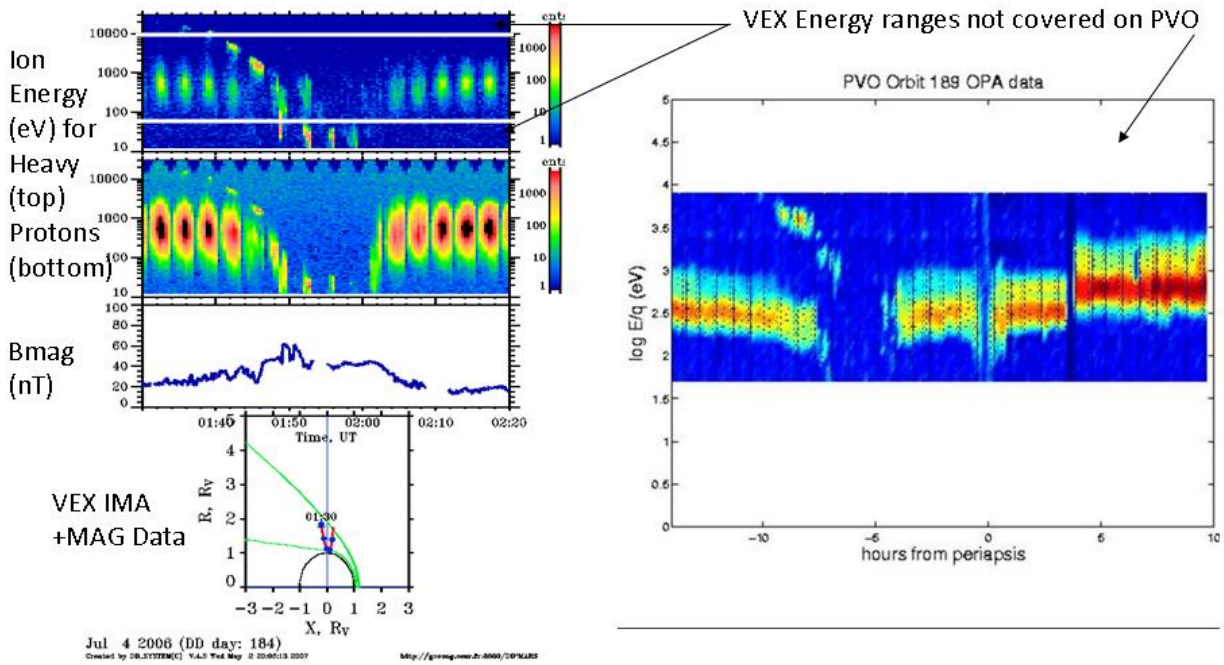


Meridian view and Sun's view from Luhmann et al., PSS

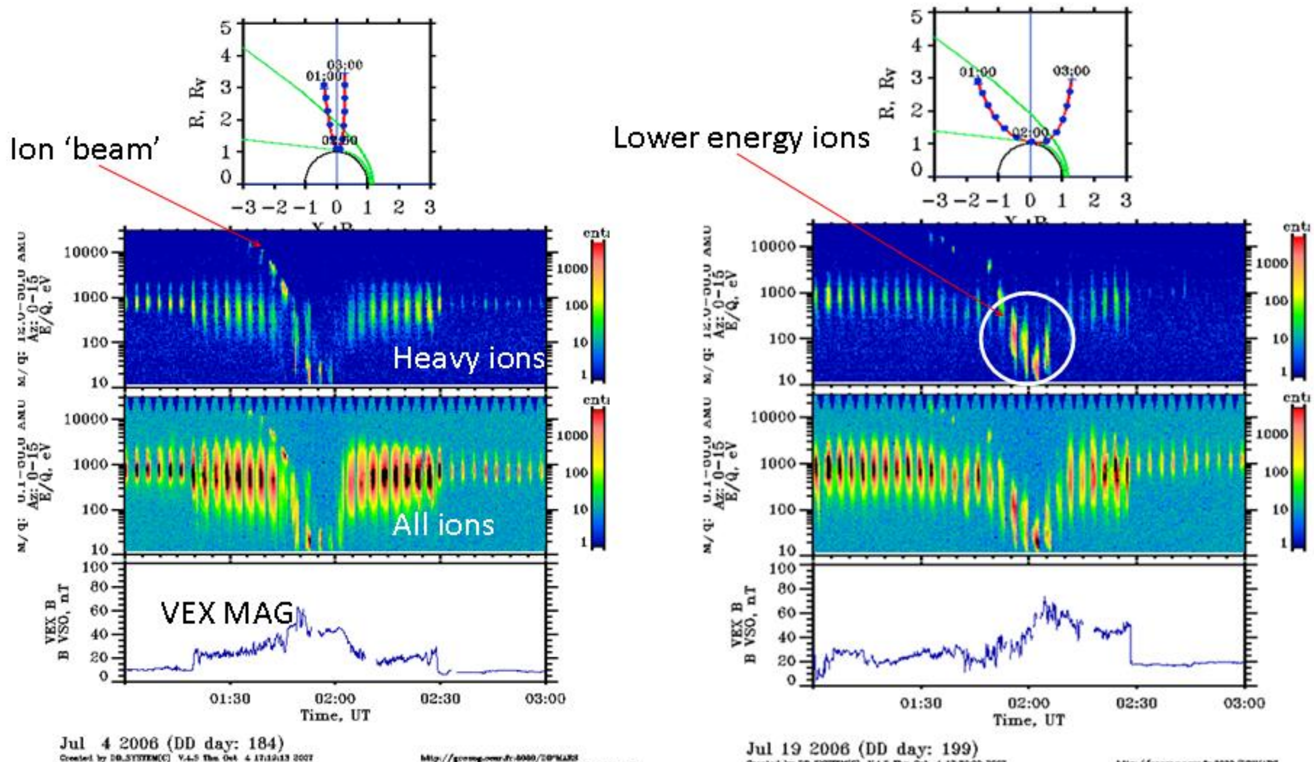


Different O+ pickup ion samplings on PVO and VEX illustrated with a model

Although orbital sampling and instrumentation differ, PVO also saw the Venus ion 'beams', and inferred they were O+

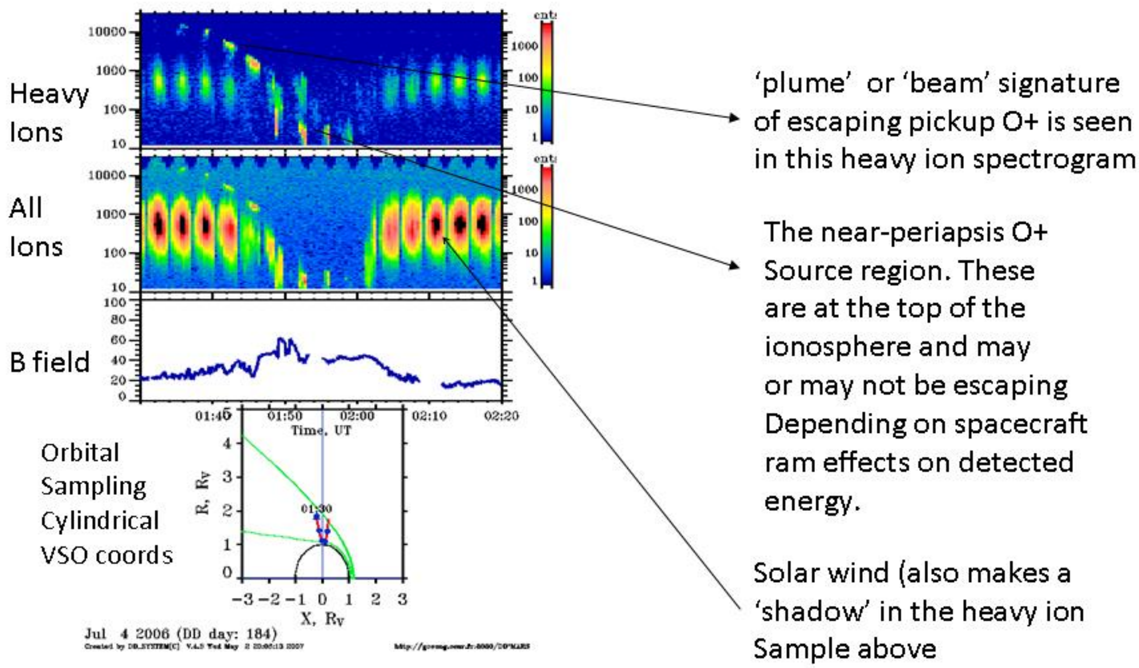


Accelerating O^+ ion ('beams') seen in VEX IMA spectrograms can be attributed to classical ion pickup and assumed to represent escape. The lower energy ions seen around periapsis are harder to interpret because their energies are affected by spacecraft motion and potential.



DD images

VEX ASPERA-4 IMA signatures of escaping ions at Venus (10 eV-36 keV) include both energetic 'beams' and low energy or suprathermal ions near periapsis ('outflows')



Solar Wind Interaction Related Ion Escape at Venus

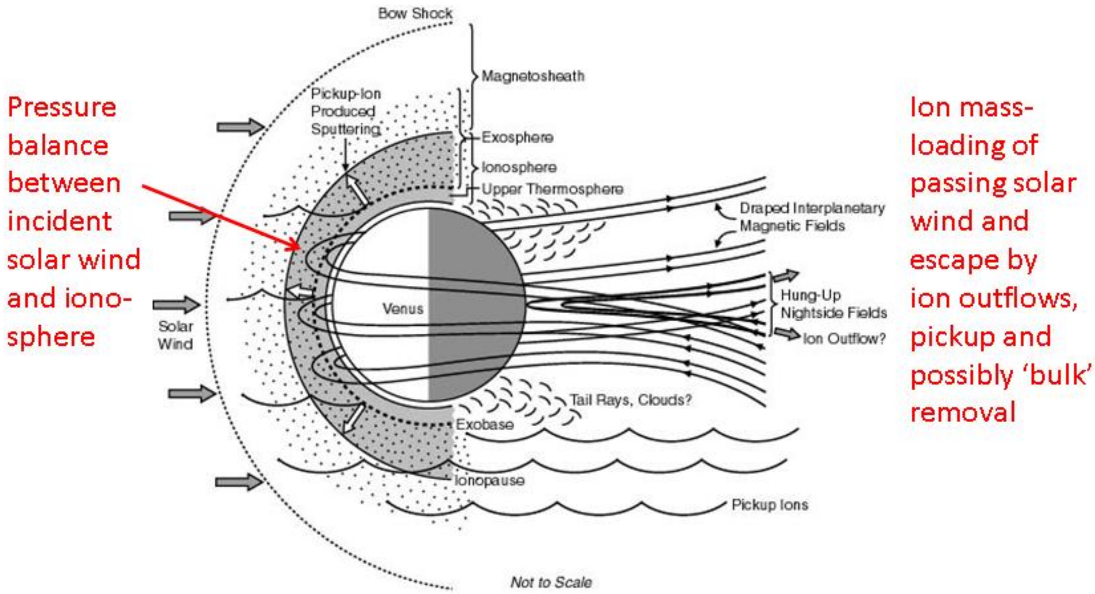


Illustration of the basic Venus-solar wind interaction and related atmosphere escape. Escaping oxygen and other ions have been observed on Venera, Pioneer Venus Orbiter and VEX. Ion escape is an integral part of these comet-like interactions.

Summary

- Proton cyclotron waves are found at Venus due to the pickup of newly created protons from exospheric hydrogen.
- The VEX observations of waves below the proton gyro-frequency are likely to be generated from the bow shock rather than due to pickup. Thus the pickup region for Venus is possibly restricted to the magnetosheath based on previous PVO observations.
- At Venus ion cyclotron waves are seen with frequency much higher than the local gyro-frequency. These appear not to depend on the presence of Venus. They are likely to have been produced close to the Sun and convected outward to 0.73 AU.
- Foreshock waves can be convected into the Venus sheath. These are produced by physics related to shock formation and not to ion pickup. (note: interplanetary current sheet related 'hot flow anomalies' also occur upstream due to the shock presence.)

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