D. Science Investigation

The accretion of the terrestrial planets should have endowed both Earth and Venus with similar amounts of water, but today Venus is quite dry with a few cm equivalent of water in the atmosphere compared to the Earth's several kilometers of water. Current observations show a D/H ratio in the Venus atmosphere that is about 150 times terrestrial, suggesting the preferential escape of H derived from at least 10's of meters of water. If early Venus did have an abundance of water, it would have greatly affected the evolution of the planet. Oceans would have left characteristic geological features and compositional evidence in the crust, as well as provided potential biological harbors. Thus the history of water on Venus is a subject with far-reaching consequences. The processes that led to the observed D/H ratio are still a matter of speculation. They may have been "exotic" by present day standards (e.g. "blowoff" or hydrodynamic escape), or they may have been enhanced versions of contemporary escape processes that can be studied today.

This proposal seeks to **investigate the plasma environment and atmospheric escape processes of Venus** by analyzing data from the Energetic Neutral Atom (ENA) detectors, ion and electron spectrometers on the ASPERA-4 experiment on board the European mission Venus Express. Included within the United States portion of the ASPERA-4 experiment is support for 1) theoretical, science, and analysis of ASPERA-4 data from the Venus Express mission, 2) the electron spectrometer instrumentation, 3) calibration and testing of the neutral particle detection instruments, 4) ASPERA-4 telemetry ground system development and operation.

This proposal is complementary to the one submitted by Jet Propulsion Laboratory (JPL). It is our understanding that the JPL proposal covers the non-ASPERA aspects of the mission and focuses on the science of lower and upper atmosphere of Venus. Both proposals would benefit greatly from eachother results, due to the intimate linking between atmospheric chemistry and processes that lead to the ultimate escape to space. Dr. C. T. Russell has agreed to lead the science coordination between these two proposals if both are being selected.

D.1 *Science Goals and Objectives*

The central question of the ASPERA-4 investigation is:

How does the solar wind interaction affect the global atmospheric escape and distribution?

The objectives of the ASPERA-4 experiment are to:

- Determine the instantaneous global distribution of plasma and neutral gas near the planet
- Study the plasma induced atmospheric escape
- Investigate the modification of the atmosphere through particle precipitation
- Investigate the energy deposition from the solar wind to the ionosphere
- Define the local characteristics of the main plasma regions

These objectives and questions will be answered by measuring the *in-situ* ion and electron fluxes with high angular, mass and energy resolution in the 10 eV – 40 keV range, and obtain remote ENA images with mass and energy resolution of the solar wind – atmosphere interaction in the 100 eV – 60 keV range. Model simulations will be intimately tied to data analysis and will be used to combine the measurements from the different instruments to extract the physical parameters. The basic science analysis approach is almost identical to the one applied to the ASPERA-3 experiment on board the Mars Express satellite orbiting Mars since December 2003.

There are two main reasons why we need to understand the solar wind interaction with the Venusian atmosphere: First, it is needed to fulfill the objective of the entire VEX mission. Second, atmospheric escape into space is the ultimate atmospheric loss process. A quantitative specification of the processes at work is required to understand the climatic evolution and to put constraints on atmospheric processes and transport. Furthermore, comparing the atmospheric loss rates from Venus with the ones from Mars and Earth will enable a deeper understanding of their different fates. There are theories that rely on the fact that the young Sun had such an enhanced Extreme Ultra Violet (EUV) output that it caused a "catastrophic" escape of hydrogen through photodissociation of the water molecules. However, it is unclear if such a scenario could actually lead to the high D/H ratios observed. It is probably safe to assume that at around the solar system age of 3.5-4.0 Gyr, escape processes, that can be observed today, became dominant.

A serious problem of the evolution of Venus is how all the oxygen, left behind by the hydrogen escape, is lost [Donahue and Hodges, 1992]. Magellan results imply that the surface can accommodate a significant oxidation rate, but to dispose of the left over oxygen would require an oxidation of 200 km of crust, which is considered to be unreasonable. Furthermore, Prinn and Fegley (1987) considered that the presence of the sulfur in the atmosphere requires a low oxidation state of the surface/crust. Thus, the oxygen created by the implied loss of so much water-derived hydrogen presents a major unresolved problem.

An estimate of the fraction of an Earth ocean lost from Venus by contemporary processes requires measurements that allow us to build a physical model for the escape of hydrogen and oxygen as a function of solar EUV and solar wind conditions. Initial approximations to such a model have already been derived from Pioneer Venus Orbiter (PVO) observations, but crucial gaps are left due to the limitations of its instruments. Moreover, the PVO mission took place during solar maximum, while the orbit insertion for VEX is scheduled for April 2006, during solar minimum, during which the average EUV flux is lower and solar wind dynamic pressure is higher. Thus, the decreased ionization on the dayside will reduce the O^+ density, which in turn will affect the rate of pick-up ions and their precipitation in to the atmosphere [Knudsen et al., 1987]. Although remote radio occultation experiments exist for the solar-minimum Venus ionosphere, no in-situ or more detailed measurements exist during solar minimum. The VEX mission will therefore provide answers to what happens during solar minimum conditions, which, together with the results from the PVO mission, will enhance the understanding of the full range of dynamic conditions of the solar wind interaction.

The inferred escaping O^+ results from PVO were intriguing from the standpoint of water evolution. In spite of the 8 keV limitation which prohibited detection of any O^+ moving at speeds in excess of ~310 km/s (the average solar wind speed is ~350-400 km/s in the ecliptic), the escaping fluxes could be estimated and compared with models for the dominant oxygen escape process. In contrast to hydrogen, the proposed physics of the oxygen loss involves a chain of processes starting with the ionization of the upper atmospheric particles present above the Venus ionopause (at about 300 km altitude at the subsolar point, increasing to ~800 km near the terminator). Following pickup by the solar wind electric field, these atmospheric ions can escape directly, or they may charge exchange in the oxygen or hydrogen exosphere to become fast atmospheric neutrals (leaving behind a new slow exospheric ion to be picked up), or avoid escaping but reimpact the exobase where they effectively sputter oxygen atoms away. Although we do not know the details of the escaping O^+ flux above 8 keV energy from PVO, the existing results hint that this picture of oxygen loss is correct. The measurements also provided information on the detectability of the escaping O^+, which can have fluxes comparable to or greater than the local solar wind proton fluxes in the wake [Moore et al., 1990]. However, the overall oxygen escape rate, including the contribution from oxygen energetic neutral atoms and sputtered oxygen (which according to Luhmann and Kozyra (1991) may exceed the O^+ loss) remains undetermined.

With ASPERA-4 we propose to carry out the measurements pertinent to the current escape of the constituents of water from Venus, with the additional goal of using them to infer the time-integrated impact of the contemporary loss mechanisms of both neutral and ionized hydrogen and oxygen. The required experiments for this study consist of the ASPERA-4 ENA and ion/electron spectrometers and supporting magnetometer data. The ASPERA-4 ion spectrometer is capable of both detecting the planetary hydrogen ion component in the solar wind background through a combination of sensitivity and angular response, and of evaluating the escaping O^+ ion fluxes missed on PVO due to their greater than 8 keV energies. This instrument will also detect other escaping constituents whose energies are below the maximum instrumental energy limit of ~40 keV, including the molecular ions occasionally detected on PVO using special ion neutral mass spectrometer instrument modes [Intriligator et al., 1980]. The VEX magnetic field measurements will be used to produce particle phase space distributions that will help us to distinguish between convecting ions that have bulk velocities in excess of their (random) thermal velocities (like the solar wind populations), and pickup ions which are not expected to be fully assimilated into the solar wind flow at the distance of the VEX orbit in the wake. Similar instrumentation has been used with great success at both comets and at Mars [Lundin and Dubinin, 1992]. The electron measurements will help to establish the importance of electron impact as an ionization mechanism, as well as provide a diagnostic of other ionization processes. The ENA measurements will for the first time confirm the existence of and importance of the sputtering process, as well as the contribution to losses of escaping ENA hydrogen and oxygen. The MEX mission is now carrying out similar measurements of atmospheric escape from Mars, providing an unusual opportunity to conduct comparative planetology studies with an evolutionary twist.

D.2 *PLASMA ENVIRONMENT AND ESCAPE PROCESSES*

The absence of a planetary magnetic field leads to important differences between Venus' and Earth's atmospheric escape and energy deposition processes. The upper atmosphere of Venus is not protected by its weak intrinsic magnetic field from direct interaction with the solar wind. As a result, the solar wind flow affects the ionosphere and the upper atmosphere. Figure 1 shows an overview of the known plasma environment of Venus. PVO observations showed a robust magnetic barrier and an almost complete solar wind deflection around the exobase. The deflection of the supersonic solar wind forms a bow-shock. At Venus, unlike at Earth, it is the thermal pressure of the ionosphere that stands-off the solar wind. The region where the solar wind and the ionospheric thermal pressures balance is called the ionopause, which is located at a few 100 km's altitude. The abrupt drop in ionospheric density at the ionopause is perhaps the most striking evidence that the solar wind is scavenging the upper ionosphere. Just above the ionopause is region called the mantle, and between the mantle and the bow-shock is a region called the ionosheath, whose properties are highly affected by the presence of the neutral atoms extending above the ionopause. It was realized from early PVO measurements that there was a significant outflow of ionospheric material [Mihalov and Barnes, 1981]. Observations of wavy structures of the ionopause and possibly related plasma clouds have been reported [Russell et al., 1981], as well as filamentary structures in the tail region [Brace et al., 1987]. These early observations indicate that there is a high potential for discovery with instrumentation of higher resolution, such as on ASPERA-4.

Escape processes at Venus, as at Mars, include mechanisms affecting both neutral and ionized constituents. They can be divided up into thermal and non-thermal processes. The thermal escape process is also known as “Jeans” escape and acts on atmospheric neutral. Solar EUV flux heats the atmosphere until the atmospheric particles energy is higher than the gravitational escape energy (a couple of eV’s).

D.2.a Pick-up ion process

Non-thermal escape processes (10 eV – 1 keV) act on both ions and neutrals. Ions picked up by the solar wind, so-called pick-up ions, were at first believed to be the primary escape process of atmospheric ions. A pick-up ion is formed when a thermal ion from the ionosphere is gradually accelerated by the convective electric field from the solar wind. The pick-up ion can reach energies greater than the escape energy and thus be lost from the ionospheric and atmospheric system and be carried away by the solar wind (mass loading). Due to the large gyroradii of the ion the pick-up ion process is expected to be highly asymmetric. Depending on the direction of the solar wind magnetic field (and therefore the direction of the convective electric field) an ion picked up in one hemisphere will be accelerated towards the surface and thus have no room to make even one gyration before it hits the planetary atmosphere again and is lost to the atmosphere. An ion picked up in the opposite hemisphere will more easily be accelerated away from the planet. The presence of such an asymmetry in energetic ion outflow is therefore a clear indicator that a pick-up process is at work. This process should be effective for H^+ through O^+ and even molecular ions such as O_2^+, CO_2^+, N_2^+, CO^+, and NO^+ [Luhmann et al., 1995]. O^+ escape rates have been estimated to a few times 10^{24} s^{-1} [Moore et al., 1991].

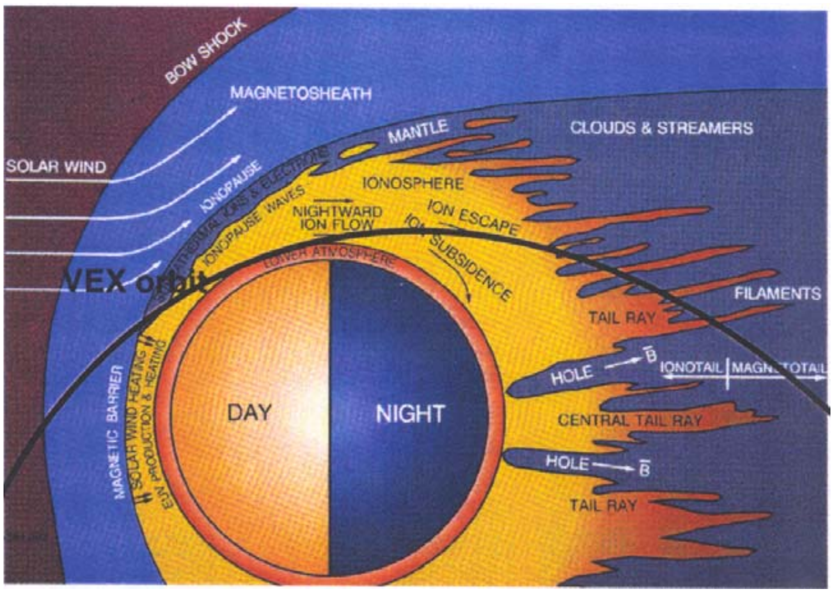
D.2.b Sputtering

Atmospheric neutrals can escape by energy deposited in the atmosphere. Energy is deposited by precipitating particles or photochemical reactions (e.g. O2+ dissociative recombination). Luhmann and Kozyra [1991] found that 90% of the O+ pick-up ion flux reimpacts the exobase region, which sputters a larger flux of neutral oxygen atoms. The atmospheric loss through sputtered oxygen escape exceeds the loss through pick-up O+ by about two orders of magnitude and far exceeds that of Jeans and photochemically induced escape. In the case of Mars, it was shown by Kallio et al. [1997] that the energy deposition of precipitating solar-wind neutrals can be an order of magnitude higher than that of precipitating pick-up O+ ions, and thereby be dominated only by the energy deposition of solar EUV. Those sputtered particles with energies less than the escape velocity become part of the extended neutral exosphere corona, increasing its density and extent, which in turn affects the efficiency of the pick-up ion process. It is easy to see from these examples how intimately coupled the loss processes are at Venus and that modeling will play an essential role in the data analysis.

D.2.c Tail-ion wind

For some time it was considered that non-thermal escape of a "hot" hydrogen exosphere component, produced by charge exchange between the solar wind protons and the thermal hydrogen exosphere, was the primary contemporary process for hydrogen loss from Venus. This deduction was based on analyses of Mariner 5 Lyman alpha altitude profiles [Paxton and Anderson, 1992]. More recently, Hartle and Grebowsky (1993;1995) used altitude profiles of ionospheric hydrogen obtained from the PVO thermal ion mass spectrometer to infer the greater importance of a tail ion "wind" emanating from the region of the nightside hydrogen concentration or "bulge". This upward wind (projected to move at ~1 km/s near the ion exobase at ~500 km altitude in this region) is thought to be initiated by polarization electric fields in the ionosphere. Once the ions reach the ion exobase, their velocities are believed to increase to values in excess of the ~10 km/s escape velocity with the help of the solar wind electric field. Charge exchange between the accelerated ionospheric hydrogen ions and hydrogen atoms in the bulge region add a neutral component to the escaping population. The escape of the planetary hydrogen ions and neutrals, however, could only be inferred. The solar wind proton flux at Venus is about 5 10^9 $cm^{-2}s^{-1}$, while Hartle and Grebowsky (1995) inferred escaping planetary hydrogen ion fluxes of ~2 10^7 cm^{-2} s^{-1} and deuterium fluxes several orders less. (This amounts to a planetary source rate of ~8 10^{25} s^{-1}) Detection of this small flux was potentially possible in the high energy ion mode in the Venus wake, but the limit of sensitivity of the instrument was near the expected planetary H^+ flux level. Other hydrogen escape as ENAs and pickup ions could also not be deduced for comparison.

Figure 1. The Near Planet Structure Around Venus. Shown is an artist conception of the structure of the Venus ionosphere induced by the solar wind interactions. The black line shows the Venus Express orbit. ASPERA-4 operations occur through out the solar wind interaction region.



A key aspect of the interaction of precipitating ions with the planetary atmosphere, underlying atmospheric loss, concerns the manner in which energy is distributed to the other atmospheric particles. For example, after precipitating O^+ ions exchange charge, the resulting fast O atoms undergo a series of elastic collisions with cold O atoms in the background gas near and above the exobase. The directions of the atoms, which gain energy from these collisions, are such that a certain fraction will be scattered back out of the atmosphere. The energy spectra of these backscattered or "sputtered" oxygen atoms calculated in Luhmann and Kozyra [1991], are shown in Figure 2 in comparison with the upgoing particle spectrum in the hot atomic oxygen corona as modeled by Nagy and Cravens [1988]. It is particularly notable that many of these sputtered oxygen atoms have velocities exceeding the escape velocity (~10 km/s or an energy of ~ 9 eV on Venus). In fact, this source produces the only neutral O escape flux on Venus, where gravity makes the velocity threshold higher than that on Mars. Moreover, a comparison of the integrated precipitating and escaping number fluxes in Figure 2 demonstrates that each incoming energetic oxygen ion is in effect converted to a larger number of upgoing less energetic oxygen atoms on Venus. Of course, these gain or "yield" factors are a function of the energy spectra of the precipitating ions. The gain increases significantly as the energy of the precipitating oxygen atoms increases from 500 eV to 6 keV. In addition, one might expect significant backscattered fluxes of other neutral species (such as helium).

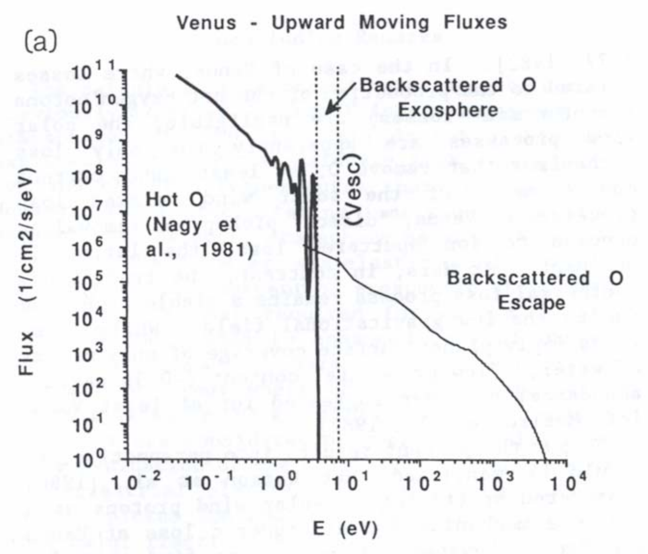


Figure 2: Calculated energy spectrum from backscattered Oxygen atoms. Taken from Luhmann and Kozyra [1991].

Hence, a feedback exists between the gases of the cold neutral exosphere, serving as the target for precipitating O^+ ions and ENAs, and the resulting escaping "sputtered" atoms themselves (mostly atomic oxygen). As the target cold atmosphere is being eroded by sputtering, the yield of outgoing escaping atoms (or molecules) is reduced. Furthermore, the upward traveling energetic oxygen atoms with insufficient energy to escape populate the hot oxygen corona, yielding new atoms for ionization in the solar wind, which also contribute to the source of pick-up ions available for precipitation. These processes constitute a feedback loop that serves to regulate the total "sputtered" escape rates. A realistic estimate of the total escape rates due to sputtering must take this feedback into consideration.

D.2.d Bulk outflow

There have been observations of a wavy structure of the ionopause at altitudes which is far from the nominal ionopause altitude [Brace et al., 1981]. Magnetic field and plasma wave measurements indicated that plasma clouds could form and perhaps detach from the ionosphere and thereby representing an important outflow mechanism of up to 10^{25} s^{-1} [Russell et al., 1981]. This is a complicated process, probably involving Kelvin-Helmholtz instabilities. ASPERA-4 should provide essential information here with a combination of in-situ and global ENA measurements.

D.3 *MODELING*

The complex nature of the solar wind interaction with Venus necessitates the use of models. The Science Team will use four models: (1) A semi-empirical 10-parameter solar-wind flow model based on the Mars model Kallio et al. [1996], to extract basic physical parameters from the ENA images. (2) A 3D MHD model to reproduce the observed magnetic features [Kallio et al., 1998], in which detailed modeling of pick-up and atmospheric sputtering will be performed by coupling (3) The Venus Thermospheric General Circulation Model (VTGCM) developed by Bougher et al. [1999]. (4) A recently developed quasi-neutral hybrid model by Dr. Kallio.

D.3.a The Solar-wind flow model

The parameterized model is a development of the previous Mars model by Kallio [1996] and uses ten parameters to describe the flow geometry, shape and position of the bowshock and magnetopause. Dr. Kallio has worked in close collaboration with the Science Team (especially with Dr. Luhmann and Kozyra) in past efforts (Venus modeling, Mars Express/ASPERA-3). The model will be used to extract basic physical parameters from the observed ENA images, such as basic flow geometry, exospheric temperature and density. Figure 3 shows an example of the streamlines from this model. The parametrized streamlines and velocity field are then used to derive the density by assuming continuity, temperature from a gas dynamical approximation, and the magnetic field by assuming the frozen-in-condition.

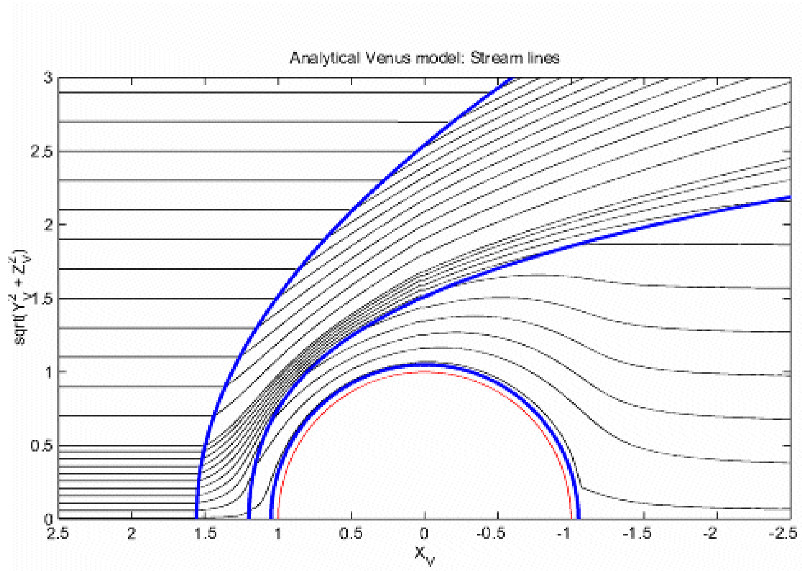


Figure 3: Streamlines of the parameterized Venus model. The blue lines represent the bowshock (outer), magnetic pile-up boundary (middle) and the obstacle boundary (inner). The red line represents the surface of Venus.

D.3.b Modeling pick-up ions and atmospheric sputtering

The 3D MHD model reproduced the shock position and shape consistent with PVO observations during solar maximum [Kallio et al., 1998], by introducing mass-loading by photoionization of the atomic oxygen upper atmosphere. We expect less mass loading during the VEX mission lifetime (solar minimum). The model will be used to improve on the calculations of pick-up ion distributions and their precipitation in the atmosphere [Luhmann and Kozyra, 1991]. Applying photoionization rates to a realistic atmospheric model will provide a source ion distribution for pick-up ion calculation. The modeled velocity field and the magnetic field of the solar wind flow around Venus will be used to obtain the electric field in which the pick-up ions will then be traced. By monitoring outgoing ENA and ion fluxes, and magnetic fields, this type of modeling will allow us to estimate the global escape rates. With additional solar wind and solar EUV measurements (and ancient Sun estimates), we would be able to make extrapolations of the impact of atmospheric escape over the history of Venus.

The complex feedback loop of precipitating pick-up O^+ ions, sputtered O-atoms and the effects on atmospheric temperature and distribution, will require careful atmospheric modeling. The “static” cold neutral exobase region has been simulated for these conditions using the VTGCM [Bougher et al., 1999]. These solar minimum VTGCM target neutral densities (CO2, CO, O, N2, etc.) and temperatures will be modified in response to new sputtered inputs gleaned from ASPERA-4 measurements and the corresponding O^+ and ENA precipitation fluxes calculated from a 1-D ion/neutral transport model. The

VTGCM will require inputs for precipitation neutral heating rates, ionization rates, oxygen atom (and other specie) loss rates, and production rates for excited chemical species. These inputs will drive a modified VTGCM simulation of cold neutral densities and temperatures, ready for the next generation of “sputtered” inputs. Convergence of these sputtering processes and the cold neutral atmosphere will require a few iterations of the VTGCM code and the 1 D ion/neutral transport code [Luhmann and Kozyra [1991]. The resulting sputtered escape rates for atomic oxygen (and other species) will be refined and consistent with the feedbacks outlined above. These sputtering loss rates can then be combined with the direct pick-up ion loss rates, yielding the total non-thermal loss rates for atomic oxygen (and other species) at Venus.

D.3.c Quasi-neutral hybrid model

Dr. Kallio and co-workers has now completed their development of a quasi-neutral hybrid model similar in structure to the one developed for Mars [Kallio et al., 2002]. The model treats electrons in an MHD-fluid approximation, the ions as test particles and it includes solar wind ions and pick-up ions. It is therefore possible to study these two populations (and their corresponding ENA signatures) in a self-consistent manner.

D.4 *ENA ENVIRONMENT*

Since, the analysis of ENA images will constitute a core part of the science analysis, it requires an introduction here. ENAs are produced when energetic, singly charged ions charge exchange with atoms or molecules [*Roelof et al.*, 1985]. We define ENAs as neutral atoms with energies much greater than the escape energy of the particular species. For Venus, the escape energy for hydrogen is about 0.6 eV and for oxygen it is about 8.9 eV. At energies large than 50 eV it is safe to assume that the scattering angle in the charge exchange process and that the cross sections of elastic collisions are negligible. While ENA imaging has proven useful to image the Earth’s ring current [Roelof et al., 1987], plasma sheet and ionospheric outflow, the Aspera-3 experiment on board the MEX mission will enable the first utilization of this technique at a non-magnetized planet.

There are three main sources of ENAs at non-magnetized planets:

1. **Solar-wind ENAs**, produced by the direct interaction of mainly solar wind protons with the upper atmosphere and exosphere. Energy range: 100’s eV – 10 keV.
2. **Pick-up ENAs**, produced by charge exchange between the pick-up ions and the upper atmosphere and exosphere. Energy range: 100’s eV – 10 keV.
3. **Sputtered ENAs**, produced directly by the precipitation of pick-up ions onto the atmosphere. Energy range: 10’ eV – 1 keV.

Solar wind ENAs will be produced primarily in the direction of the deflected solar wind flow around the planet and so, ENA flux will be highly dependent on the vantage point. Their energy spectrum will be characteristic of the solar wind ion energy spectrum (peak at ~9 keV) convoluted with the energy dependent charge exchange cross section. Figure 4 shows a simulated ENA spectrum from different vantage points computed by Lichtengger et al. [2002]. The upper panel represents the spectra of ENAs produced by solar wind ions. The lower panel shows the spectra of ENAs produced by charge exchange between pick-up ions and the neutral upper atmosphere. The spectra were obtained from two different vantage points as indicated by the middle panel. The spectral signatures will be of vital importance when separating the different origins of the observed ENAs.

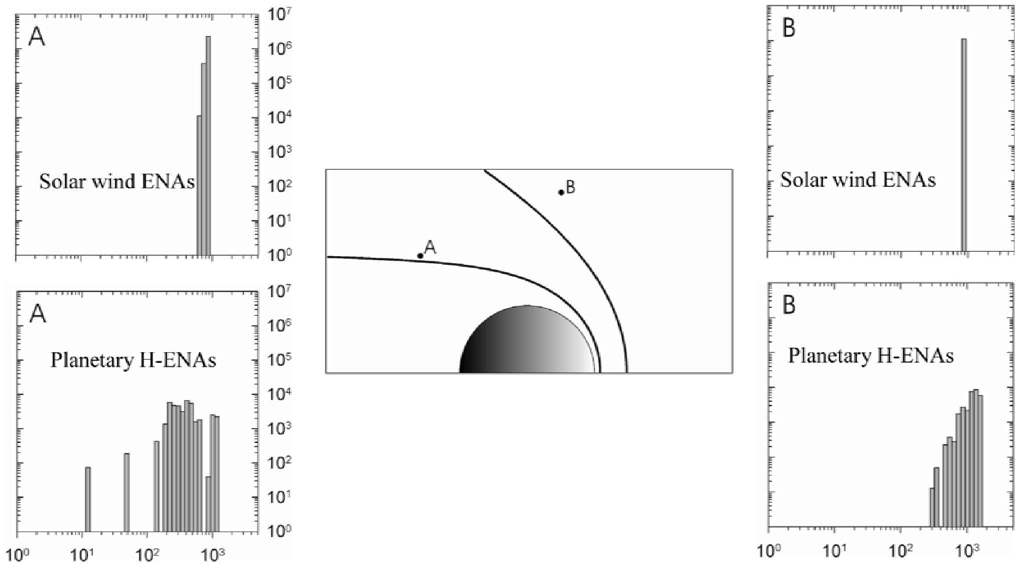


Figure 4: Upper panel: Position in the simulation box where the ENA energy spectra are calculated. Middle and lower panel: Energy spectra of ENAs coming from the solar wind and from the planetary atmosphere, respectively. Taken from Lichtengger et al., [2002].

Figure 5 shows a simulated ENA image of the solar wind ENAs, using the ten-parameter model developed by Kallio [1996]. The imaging vantage point in this example is at {0.41, 0.0, 1.59} R_M. The exospheric distribution of H and O was taken from Gunnel et al. [2004]. A solar wind density of 14 cm^{-3} and a solar wind velocity of 400 km/s were assumed. By simulating ENA images with different sets of parameters and compare them to observed ENA images we will extract physical parameters from the ENA images.

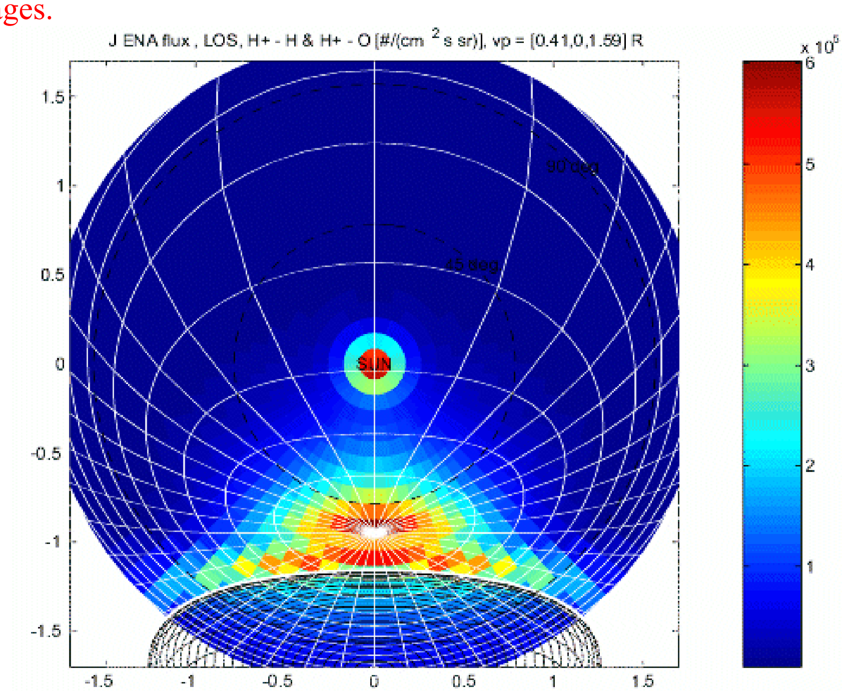


Figure 5: Simulated ENA flux (cm^{-2} sr^{-1} s^{-1}) using the parameterized solar-wind flow model by Kallio [1996] applied to Venus. The vantage point is 0.41, 0, 1.59 R_M and the exospheric H and O distribution was taken from Gunnel et al. [2004].

The second source of ENAs is the charge exchange of **pick-up** ions with the neutral exosphere and upper atmosphere. The third source of ENAs is the **sputtered neutrals** produced by precipitating particles into the atmosphere as described above. Both the pick-up ions [Luhmann and Kozyra 1991] as well as ENAs produced by pick-up ions and solar wind ions [Kallio and Barabash, 2001] can precipitate into the atmosphere and sputter neutrals that in turn may be detected as an additional faint ENA flux from the surface of the planet [Holmstrom et al., 2002]. It is possible that there are other signatures in the ENA images revealing the presence of tail-ion winds and detached plasma clouds. To investigate such features we will turn to the more advance quasi-neutral hybrid model.

D.5 *MEASUREMENT REQUIREMENTS*

In this section we will discuss what measurements are required to address the scientific objectives. Each escape process has specific observable signatures that can be used to sort our their contributions: sputtering and charge exchange produce distinctive ENA populations, pickup ion distributions can be identified using an ion spectrometer and a magnetometer to determine the particle pitch angles, and bulk ion removal can be diagnosed at the terminator and in the low altitude wake with an ion spectrometer and magnetometer data. Table 1 below describes the required measurements for each scientific objective.

In order to **determine the instantaneous global distribution of plasma and neutral gas near the planet** measurements of the ENA flux produced by the charge exchange between the solar wind protons and the exosphere are required. Solar wind ENAs are produced primarily up to the solar wind energy (~1 keV), with fluxes as high as 10^5 $(cm^2\ sr\ s\ keV)^{-1}$ and consists of hydrogen. Reasonable changes in exospheric and solar wind parameters can be resolved in ENA images with about 5 deg resolution [Holmstrom et al., 2002]. To specify upstream solar wind parameters, energy resolved measurements of ions and electrons around solar wind energies are required.

In order to study the **plasma induced atmospheric escape** we have to measure the ENAs and ions produced from planetary escape processes. The ENA imager must be able to separate planetary ENAs from solar wind ENAs, since almost all Oxygen ENAs are planetary in origin, but Hydrogen ENAs could originate from the atmosphere (pick-up ions) or the direct charge exchange between the solar wind protons and the neutral exosphere. According to the simulated spectra in Figure 4, solar wind Hydrogen ENAs have a spectrum that peaks around around ~1 keV, whereas the planetary Hydrogen ENAs display a continuum from 10-100 eV to 10's keV. The requirement on angular resolution may be relaxed here due to the global nature of the pick-up ion process.

To **investigate the modification of the atmosphere through particle precipitation** we have to measure the sputtered oxygen atoms that are produced from the precipitating O^+ pick-up ions. As Luhmann and Kozyra [1991] showed, the sputtered oxygen atom flux may exceed the flux from that of pick-up O^+ ions, but extends to much lower energies (10's eV). Simulations for Mars show that the ENA flux from pick-ions and sputtered ENAs are 10^3 $(cm^2\ sr\ s\ keV)^{-1}$ and 10^6 $(cm^2\ sr\ s\ keV)^{-1}$ (at 100 eV), respectively [Holmstrom et al., 2002; Barabash et al., 2002].

The **energy deposition from the solar wind to the ionosphere** can be investigated by imaging the proton solar wind flow and puts essentially the same requirements as the first objective.

To **define the local characteristics of the main plasma regions** both ion, electron and magnetic field measurements are required.

Table 1. Measurement Requirements

SCIENTIFIC OBJECTIVE	ASSOCIATED MEASUREMENT	MEASUREMENT REQUIREMENTS
Determine the instantaneous global distribution of plasma and neutral gas near the planet	ENAs originated from the shocked solar wind	• Measure the ENA flux in the energy range 10's eV - ~1 keV with 4 pi coverage. • ENA flux > 10^4 (cm^2 sr s keV)$^{-1}$ • Measure the upstream solar wind parameters.
Study the plasma induced atmospheric escape	ENAs originating inside the magnetosphere	• Mass resolved (H, O) ENA measurements in the energy range up to ~10's keV. • ENA flux > 10^3 (cm^2 sr s keV)$^{-1}$
Investigate the modification of the atmosphere through particle precipitation	ENA albedo	• Mass resolved (H, O) ENA measurements down to ~10's eV. • ENA flux > 10^6 (cm^2 sr s keV)$^{-1}$ (at 100 eV).
Investigate the energy deposition from the solar wind to the ionosphere	Precipitating ENAs	• ENA measurements in the ~10 eV - ~1 keV. • ENA flux > 10^4 (cm^2 sr s keV)$^{-1}$
Define the local characteristics of the main plasma regions	Ion and electron measurements of hot plasma	• Ion and electron measurements in the energy range ~1 eV - ~10 keV with 4 pi coverage.

The ASPERA-4 experiment comprises the Neutral Particle Imager (NPI), the Neutral Particle Detector (NPD), the Ion Mass Analyzer (IMA), and the ELectron Spectrometer (ELS), which is a standard top-hat electrostatic analyzer in a very compact design with high energy resolution. The characteristics of these instruments are given in Table 2.

Table 2. ASPERA-4 Instrument Characteristics

ASPERA-4 Instrument	**NPI**	**NPD**	**IMA**	**ELS**
Particles to be measured	ENA	ENA	Ions	Electrons
Energy range, keV	0.1-60	0.1-60	0.01-40	0.0º 1-20
Energy resolution, ΔE/E	No	80 %	10 %	8 %
Mass resolution	No	H, O	M/Δ M=5	No
Intrinsic field of view	9° x 344°	9° x 180°	90° x 360°	10° x 360°
Angular resolution (FWHM)	4.6° x 11.5°	5° x 30°	5° x 22.5°	5° x 22.5°
G-factor / pixel, cm^2 sr	2.5 x 10^{-3} (no ϵ)	6.2 x 10^{-3} (no ϵ)	3.5 x 10^{-4} (ϵ included)	6 x 10^{-4} (ϵ included)
Efficiency, epsilon (ϵ), %	1 %	1 – 25 %	N/A	N/A
Time resolution for full 3D	32 sec	32 sec	32 sec	32 sec
Instrument Temporal Resolution	32 msec	32 msec	32 msec	32 msec

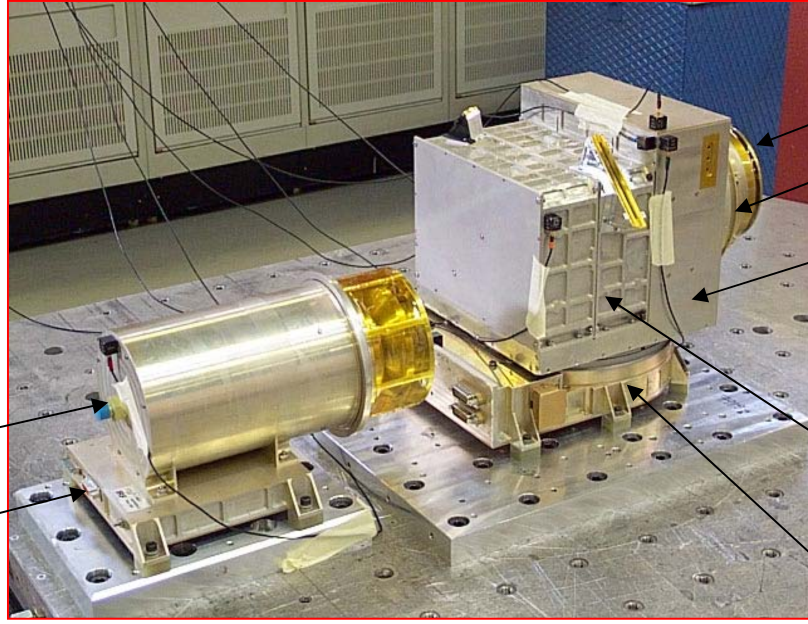


Figure 6. Shown here is the ASPERA-3 experiment undergoing vibration testing. The main unit (right) is mounted on the top of the Mars Express spacecraft and contains the ELS, NPI, and NPD instruments mounted on a scanner. The IMA unit (left) is mounted on the bottom of the spacecraft. The ASPERA-4 experiment on Venus Express spacecraft uses mostly modified Flight Spare units from Mars Express instrumentation and will be flown is the same configuration.

The ESA Venus Express launch date is November, 2005. ASPERA-4 will be in elliptical orbit between 250 km to 10,000 km altitude. Data measurements will be accomplished about the pericenter and stored in memory. On the apocenter of the orbit, telemetry will be transmitted to the Earth. ASPERA-4 instruments will be controlled by IRF. The instrument data generation modes will be assigned in accordance with ASPERA-4 telemetry resources anticipated to be at most 500 Mbits/day. ASPERA-4 data should reveal charged particle and ENA flows around the planet. Spacecraft orientation is used to determine plasma flow directions and relate them to planet orientation.

D.6 *SCIENCE IMPLEMENTATION*

The Analyzer of Space Plasmas and Energetic Atoms has been selected as a part of the ESA Venus Express core payload. The launch date is November, 2005. The ASPERA-4 instrument is a copy of the ASPERA-3 on board the ESA Mars Express satellite now orbiting Mars. Thus, this will add the benefit that both planets (Mars and Venus) will be studied with identical instrumentation.

D.6.a Data Analysis

Data analysis will be the prime responsibility of the Science Team (see below). In order to provide estimates of the global atmospheric escape rates, we need to relate the global ENA fluxes to total escape rates. This has to be done in close synthesis with models and measurements. A significant heritage of the data analysis and modeling for the ASPERA-3 experiment, now taking place for Mars, is expected to be used for ASPERA-4.

The first step in the data analysis is the internal data validation, which includes consistency checks of ENA images from NPI and NPD. The second step is to extract physical parameters from the data. Here we will use the analytical solar wind flow model developed by Kallio et al. [1996] to extract features of the solar wind interaction such as the basic flow geometry and exospheric temperature and density. In the approximation used by Kallio et al. [1997], the solar wind flux can be written as a convected thermal phase space density characterized by a local density, temperature, and velocity. The temperature itself is calculated from the local velocity and the properties of the upstream solar wind using a gas dynamic law. If the streamline function is known, the local density of the solar wind flow may be calculated from the conservation equation by integrating along the streamline. Kallio [1996] has parametrized the streamline function, so that all quantities are implicit functions of the solar wind input parameters. If the solar wind density and velocity functions were available as explicit functions of the parameters it is computationally feasible to pick a set of input parameters for the solar wind stream function and the exospheric distribution and then compute ENA flux. This would provide a ENA images of the expected solar wind ENAs through a parameterized model.

Since the energy spectrum for solar wind ENAs is peaked around the incident solar wind energy, we can compare the observed NPD (and higher resolution distributions inferred from NPI images) images around the solar wind energy with the simulated images. The selected set of parameters would then be modified until a close match could be found between simulated and observed ENA images. With in-situ measurements of solar wind parameters, this approach would provide information on the flow geometry and exospheric temperatures and densities. Figure 5 shows a simulated ENA images based on an analytical flow model applied to Venus.

In order to investigate and estimate the global escape rates, we will use the flow geometry obtained from the approach above and perform test particle modeling. If the velocity and density of the solar-wind flow lines are specified one can use this information to compute the electric and magnetic field by assuming a frozen-in condition. With an appropriate source model for ions, one can trace the ions in the computed electric and magnetic field and in such a way obtain the pick-up ion distributions. This approach has been tested by several [Luhmann and Kozyra, 1991; Lichtenegger et al. 2002, Barabash et al., 2002, Moore et al., ????]. Since almost all O^+ pick-up ions originates from the atmosphere, Oxygen ENA images from NPD (and higher resolution distributions inferred from NPI images) would represent the O^+ pick-up ion distribution. By modeling the O^+ pick-up ion distribution with the above approach and use constraining in-situ O+ measurements by IMA, we will be able to estimate the global escape rate of the O^+ in that particular energy range. Any inconsistencies in the results could be an indication of other escape processes at work. The more advanced, but computationally expensive, hybrid model developed by Dr. Kallio, could be used to investigate other escape processes. This model would also be used to specify the spectral differences between solar-wind ENAs and ENAs produced by pick-up ions.

D.6.b Data Processing and Archiving

Data processing and archiving will be the primary responsibility of SwRI (Drs. Winningham, Sharber, and Frahm). ASPERA-4 data from the Venus Express spacecraft will be telemetered through the ESA ESTEC data collection system. This data will be transmitted to the PI institution, IRF, which will send it to SwRI. SwRI will process the Venus Express telemetry into IDFS files. SwRI will archive this processed data, transmit it to IRF and the remainder of the ASPERA-4 team, and update public web sites. The goal is to complete all data processing and archiving within 24 hours of its arrival. ESA requires a 6 month proprietary data use period. After this time, ASPERA-4 data will be transmitted to the Planetary Data Systems (PDS) node for long-term NASA archival.

ASPERA-4 data will have mirror archive web sites in Europe (IRF) and the USA (SwRI). The mirror site configuration allows data to be accessed from either system at any time and provides redundancy and a back-up should one archive site encounter difficulties.

IDFS is a standard file format for storing raw data and analysis procedures. Conversions to science data occur on the fly. IDFS files can be viewed using the SwRI SDDAS system. SDDAS will be used to construct a password protected web site which will have public and private areas. The public areas will show displays of uncalibrated data directly from telemetry. Private areas will be accessible to ASPERA-4 CoIs only. The web site for ASPERA-4 Venus Express data will be modeled after the Cluster/PEACE high resolution data system, which can be found at http://cluster2.space.swri.edu/.

After the 6 month proprietary data use period required by ESA, SDDAS will be executed to create stand-alone ASPERA-4 data files to be archived in the PDS system of the USA. The latest calibration factors will be used to generate static data for PDS. Data files are expected to be transmitted to PDS each day after the 6 month delay. SDDAS is written generically so that any data in IDFS format may take advantage of any tools within SDDAS. Once data is placed within the IDFS format, all SDDAS functions become immediately available. This saves time and cost of re-developing analysis tools for each spacecraft mission. The ASPERA-4 data delivery schedule is shown in Table 4:

Table 4. ASPERA-4 Data Delivery

	Launch ↓			Encounter ↓			2006												2007				End Normal ↓	
Task Description	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
ASPERA-4 Data Acquired																								
ASPERA-4 Data Delivered to NASA PDS node																								

					End Normal Delivery ↓	2008					End Reprocessing Delivery ↓							2009					End Extended Mission ↓	
Task Description	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
ASPERA-4 Data Acquired																								
ASPERA-4 Data Delivered to NASA PDS node																								
ASPERA-4 Data Reprocessed																								

					End Extended Delivery ↓	2010					End Reprocessing Delivery ↓	
Task Description	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
ASPERA-4 Data Delivered to NASA PDS node												
ASPERA-4 Data Reprocessed												

*Preflight calibration data delivered at the end of the mission

Data processing software will be verified using simulated data sets, laboratory calibration data, data from Mars Express where appropriate, and data from instrument level tests of ASPERA-4 on the Venus Express spacecraft. Preliminary analysis, comparison, and validation of data will occur during the orbital transfer phase of Venus Express. Scaling laws will often allow comparison of Venus Express data to comparable data at Mars.

D.6.c. Instrumentation

The Electron Spectrometer (ELS) instrument represents a new generation of ultra-light (300 g), low-power (650 mW), electron sensors flight-proven on Astrid-2 and Munin (see Figure 7). It is a spherical electrostatic analyzer in a top hat configuration with a single collimator system. Particles enter the aperture at any angle in the plane of incidence. Electrons are deflected into the top hat spectrometer by applying a positive voltage to the inner spherical electron deflection plate. The electrons hit a microchannel plate (MCP) detector after being filtered in energy by the analyzer plates. The plates are stepped in voltage to achieve an energy spectrum.

Electrons with energies up to 20 keV/q will be measured, with a maximum time resolution of one energy sweep (128 values) per four seconds. There are 16 anodes, each defining a 22.5° sector, which provide simultaneous measurement. The ELS energy resolution is 8% and its geometric factor is 5.7×10^{-4} cm^2 sr. ELS was designed to resolve the major photoelectron peaks from Mars measurements (see Figure 8). Identification of these major peaks aids in identification of major atmospheric species which have been ionized. Its capabilities will be an important diagnostic tool used at Venus to identify atmospheric escape.

SwRI will provide the ELS Flight Spare from the Mars Express program. It will be modified and calibrated by MSSL, and become the Flight Unit for Venus Express. SwRI will upgrade, modify, and calibrate the Mars Express ELS engineering unit so that it becomes a space qualified Flight Spare for Venus Express.

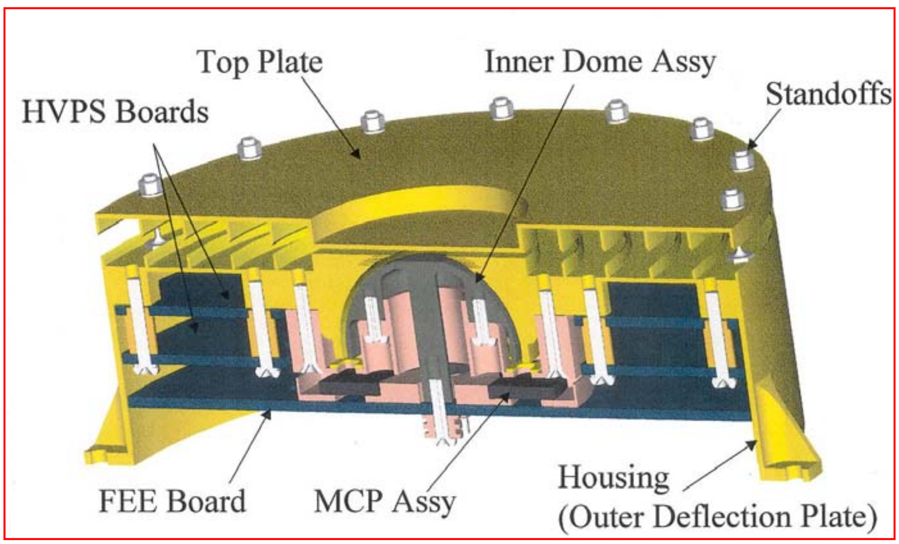


Figure 7. Internal View of the ASPERA-4 ELS. View of the ELS cut in half to reveal its major internal parts. ELS is a standard top hat sensor constructed with high precision.

The Neutral Particle detector (NPD) instrument consists of two identical detectors, each of which is a pinhole camera (see Figure 9). NPD provides measurements of the ENA flux, resolving velocity and mass (H and O) with a coarse angular resolution. Within each detector near the entrance, charged particles with energies up to 70 keV (electrons and ions) are removed by the deflection system. The deflection system consists of two 90° sectors separated by a 4.5 mm gap. Apart from being ON or OFF, the deflection system can be operated in an alternating mode. Entering particles not swept away by the deflection plates are ENA particles. The ENA beam emerging from the 4.5 x 4.5-mm pin-hole hits the START surface at a grazing angle 15° and causes secondary electron emission. Using a system of collecting grids, the secondary electrons are transported to one of two MCP assemblies giving the START signal for the time-of-flight (TOF) electronics.

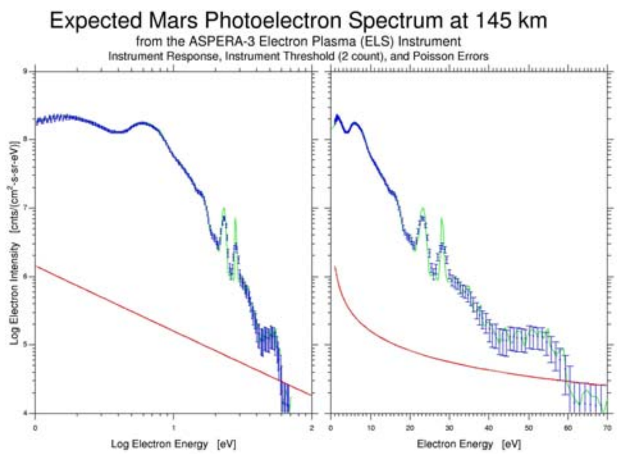


Figure 8. Mars Photoelectron Spectrum Comparison. Presented in this figure is a simulated measurement of ELS to a theoretical Martian electron spectrum (log presentation on the left; semilog presentation on the right). The energy resolution is such that the major photoelectron spectrum peaks can be resolved.

Depending on the azimuth angle, the collection efficiency varies from 80% to 95%. The incident ENAs are reflected from the START surface near-specularly. Since the charge state equilibrium is established during the interaction with the surface, the emerging beam contains both the neutral and ionized (positive and negative) components. To increase the total efficiency, no further separation by the charge is made. As proven by the ion tracing, the START electron optics introduce very little disturbance to the reflected atomic ions leaving the START surface with an energy above 80 eV. Therefore particles of all charge states - negative, neutral, and positive - will impact the STOP surface, and again produce secondary electrons which are detected by one of the three MCP assemblies, generating the STOP signal for the TOF electronics.

The TOF over the fixed flight distance of 8 cm determines the particle velocity. The STOP MCPs give the azimuthal direction. Since the secondary electron yield from the START surface for an ENA of given velocity depends on the ENA mass, pulse height distribution analysis of the START signals and independent analysis of the STOP signals provide an estimation of the ENA mass. Each event is stored in the array START MCP charge x STOP MCP charge x time-of-flight x direction.

UV suppression in NPD is based on coincidence of START/STOP signals. To increase the particle reflectivity, the START surface is a very smooth (roughness <100 A) metal surface. The STOP surface is graphite (~100 nm roughness) covered by MgO. This combination has a very high secondary electron yield, low photoelectron yield and high UV absorption. Both surfaces are stable and do not require special maintenance.

Two separate NPD detector heads comprise a complete NPD instrument. One spare head is available from Mars Express ASPERA-3. IRF is producing a second NPD head and an additional flight spare. The University of Arizona is coating the START surfaces for the 2 units produced by IRF.

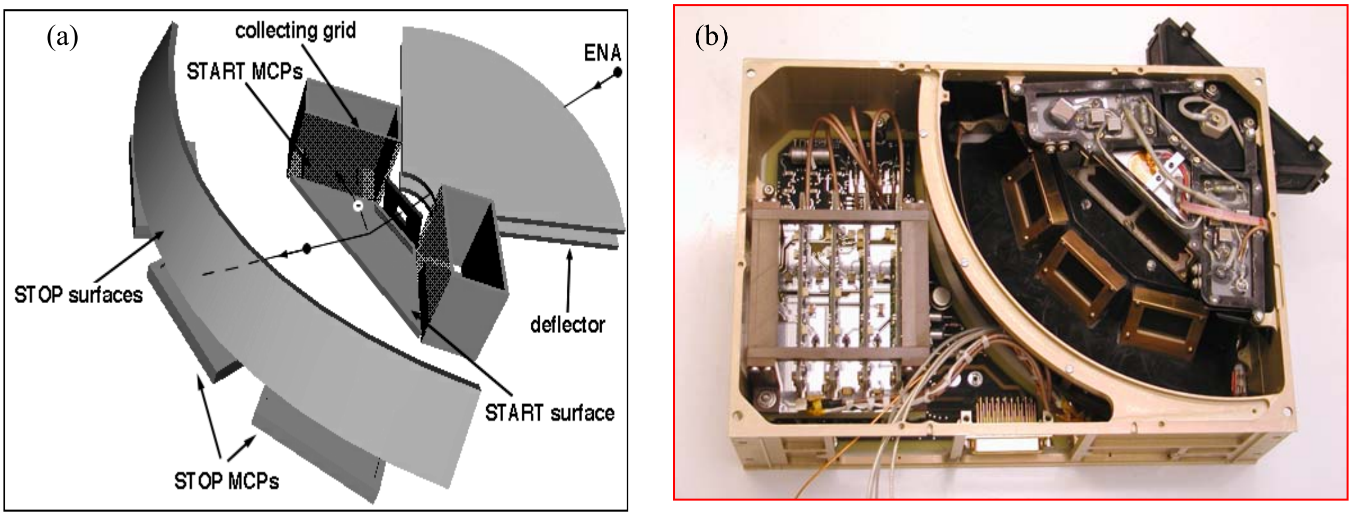


Figure 9. NPD schematic and hardware. The design of the NPD is shown in (a). This design was implemented to produce an NPD flight unit shown in (b).

The Neutral Particle Imager (NPI) head is a copy of the NPI-MCP sensor developed for the ASPERA-C experiment on the Mars-96 mission and successfully, flown on the Swedish micro-satellite Astrid-1 launched in 1995 (see Figure 10). NPI provides measurements of the integral ENA flux with no mass and energy resolution, but comparatively high angular resolution. In the NPI the charged particles (electrons and ions) are removed by the electrostatic deflection system which consists of two disks separated by a 3 mm gap. The 5 kV potential sweeps away all charged particles with energies up to 60 keV. The disks also collimate the incoming beam in the elevation angle. In addition to being on or off, the deflection system can be operated in an alternating mode. The deflection system also collimates the beam into 32 sectors.

Neutrals passing through the deflection system hit a 32 sided cone target with a grazing (20°) angle of incidence. A MCP stack in the chevron configuration detects the particles leaving the target block with 32 anodes. The signal from the MCP gives the direction of the primary incoming neutral. The MCP operates in an ion mode with a negative bias of -2.4 kV and thus detects (a) sputtered ions of the target material, (b) ions resulting from stripping of the primary neutrals, and (c) neutrals reflected from the target surface. In order to improve the angular resolution and collimate the particles leaving the interaction surface, 32 separating walls are attached to the target forming a star-like structure. NPI covers 4 pi in one instrument scan and produces an image of the ENA distribution in the form of an azimuth x elevation matrix. To suppress the UV flux, the NPI target uses the same coating as in the PIPPI and ASPERA-C experiments, namely, DAG 213, a resin-based graphite dispersion.

The flight spare units of NPI from the Mars Express mission are provided by Instituto de Fisica dello Spazio Interplanetari (IFSI) and IRF, and will be the flight units for Venus Express. IRF will modify the NPI units for the higher radiation environment experienced by the ASPERA-4 at Venus.

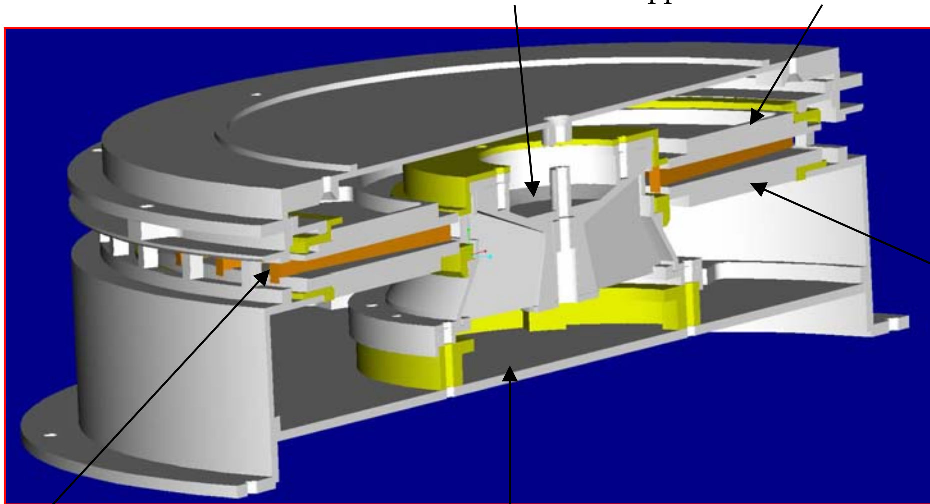


Figure 10. Cut away view of the ASPERA-4 NPI, showing major components.

The ELS, NPD, and NPI are mounted on a scanner which rotates the instruments so that they have a 4pi field of view. This occurs in 32, 64, or 128 seconds depending on the scanner operational mode. The scanner design is part of ASPERA-C and is flight proven to be robust and long lived. It contains a doubly redundant electronic and motor system which controls a worm screw. The flight spare scanner from the Mars Express mission will be provided by IRF.

The Ion Mass Analyzer (IMA) is an improved version of the ion mass spectrographs TICS (Freja, 1992), IMIS (part of ASPERA-C, Mars-96, 1996), and IMI (Planet-B, 1998). It is an exact copy of the ICA instrument to be flown on the ESA Rosetta mission. IMA is a mass resolving instrument providing ion measurements in the energy range 0.01 - 30 keV/q for the main ion components (1, 2, 4, 16 amu/q) and the group of molecular ions (20 - 80 amu/q) (See Figure 11).

Particles enter the analyzer through an outer grounded grid and pass through a deflection system which deflects particles arriving at from angles from 45° to 135° (wrt the symmetry axis) into an electrostatic analyzer. The electrostatic analyzer selects ions of a certain energy and directs them into a cylindrical magnetic field which deflects them radially outward from the center of the analyzer. The ions then strike a 10 cm diameter MCP and are detected by an anode system with digital position determination electronics. The anode system contains 32 concentric rings to measure the radial impact position (representing ion mass) and 16 sector anodes to measure the azimuthal impact position (representing ion entrance angle). The magnet assembly can be biased with respect to the electrostatic analyzer to post-accelerate ions and optimize the mass range and mass resolution.

The flight spare IMA sensor head from the Mars Express mission is provided by IRF. The IMA sensor head will be modified by Centre d'Etude Spatiale des Rayonnements (CESR)/Centre National de Recherche Scientifique (CNRS) and calibrated by CESR/CNRS. IRF will build a new set of IMA DPU electronics for Venus Express.

The ASPERA-4 data processing unit for ASPERA-4 will be constructed from Mars Express spare DPU components. Due to the higher radiation environment at Venus, additional hardware upgrades will need to be employed. Additional thermal controls are also needed. DPU hardware modifications will be performed by the Finnish Meteorological Institute.

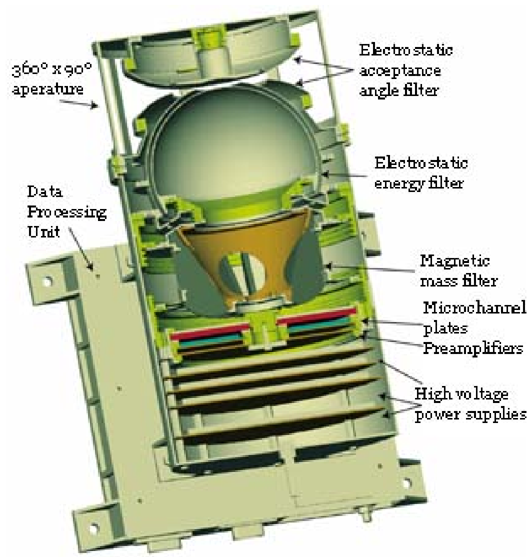


Figure 11. Internal view of the ASPERA-4 IMA. Shown is a slice through the IMA to reveal the internal IMA deflection. The electrical acceptance filter, electrostatic energy filter, and magnetic mass filter are arranged to analyze entering ions.

D.6.c Mission Concept

The Venus Express mission will be operated by ESA. The ESA Venus Express Mission Definition Report included in Appendix 9, Part B details the mission concept, observing strategy, spacecraft performance, and orbital requirements. A brief summary is given here, emphasizing ASPERA-4 operations. The Venus Express mission utilizes the Mars Express designed hardware, spacecraft, and launch vehicle, modified as required for Venus.

The Venus Express mission aims at exploring the Venusian atmosphere, the plasma environment, and the surface geology from orbit. The selected orbit is quasi-polar with a pericenter at ~250 km and apocenter in the range 30,000-45,000 km with a period of 9.6 to 16 hours. A high-inclination elliptical orbit provides complete latitudinal coverage and gives the best compromise for allowing both high-resolution observations near pericenter and global observations during the apogee part of the orbit, and for *in-situ* measurements of the Venusian environment and its interaction with the solar wind.

The "store and forward" concept of the orbital operations, implemented for the Mars Express mission, fits the Venus Express requirements. The ASPERA-4 experiment will collect the data in the vicinity of pericenter and store them in the mass memory. Data transmission periods will occur during the apocenter part of the orbit. ASPERA-4 will be observing when the orbital altitude becomes less than 10,000 km to obtain data on the solar wind interaction with the planet. All ASPERA-4 instrumentation works together and they are all activated simultaneously.

ASPERA-4 contains low, medium, and high data compression modes for ELS, NPI, NPD, and IMA independently. ELS, NPI, and NPD data compression modes are generally set by ground command and IMA data compression modes are dynamically set to maximize the use of ASPERA-4 telemetry. The ASPERA-4 PI at IRF and other instruments on Venus Express will negotiate with ESA for specific times when ASPERA-4 will operate in each of its data compression modes. Data compression modes are both lossy and lossless, and are used in combination to maximize the amount and accuracy of transmitted ASPERA-4 data.

Due to the heritage and the fact that most of the flight instrumentation has already been designed and built, it is proposed that this investigation start at Phase C/D. In order to start the process of refurbishment of the ELS flight spare unit for ASPERA-4 and the coating of spare NPD START surfaces, SwRI and UA are proposing that their hardware phases be funded as described in sections F on Management and Schedule and G on Cost and Cost Estimating Methodology.

D.6.d Science Team

The full international ASPERA-4 science team (listed in Appendix 9, Part C) will provide the ASPERA-4 science investigation. The ASPERA-4 Principal Investigator is Dr. Stas Barabash of the Swedish Institute of Space Physics (IRF), Kiruna, Sweden. ESA recognizes a Co-Principal Investigator, Dr. Jean-Andre Sauvaud of CESR/CNRS, France. The ASPERA-4 Experiment Manager is Mr. Herman Andersson, also from the Swedish Institute of Space Physics, Kiruna, Sweden.

For the ASPERA-4 experiment, the United States Co-Investigators are lead by Dr. J. David Winningham of Southwest Research Institute. He will serve as the Principal Investigator for this NASA Mission of Opportunity. The United States ASPERA-4 Co-Investigators are Dr. James R. Sharber and Dr. Rudy A. Frahm at Southwest Research Institute, Dr. Charles Curtis, Dr. Ke Chiang (Johnny) Hsieh, and Dr. Bill R. Sandel at the University of Arizona, Dr. Edmond C. Roelof and Dr. Pontus C:son Brandt at the Johns Hopkins University Applied Physics Laboratory, Dr. Janet G. Luhmann at the University of California at Berkley, and Dr. Janet U. Kozyra at the University of Michigan. For the United States part of the ASPERA-4 experiment, the Project Manager is Ms. Sandee J. Jeffers of Southwest Research Institute.

Dr. J. David Winningham will act as the United States Principal Investigator for all ASPERA-4 related activities and is an Institute Scientist at Southwest Research Institute. Dr. Winningham has been the PI/CoI of plasma instruments for NASA ISIS, DE-2/LAPI, UARS/PEM, TSS-1/ROPE, TSS-1R/ROPE, and Cluster/PEACE. He has been the United States PI for plasma instruments flown on Giotto/JPA, Mars Express/ASPERA-3, Astrid-2/MEDUSA, and Munin/MEDUSA-2. Every program included MO&DA phases and Dr. Winningham has been PI on several data analysis contracts including AFGL, Cluster-I through NASA, and Cluster-II through NASA. Dr. Winningham has been PI on several sounding rocket programs and CoI on numerous satellite and rocket programs.

Dr. Winningham will fulfill the role of Principal Investigator for NASA on this program. He will direct both hardware and software construction at SwRI, direct hardware construction of NPD to UA, and lead the United States science analysis effort on ASPERA-4. Dr. Winningham will communicate and coordinate with ASPERA-4 PI and PM at IRF, communicate and coordinate with CoI's at MSSL, and communicate with all CoI's in the United States. During the coarse of this contract, Dr. Winningham will be responsible to NASA for all reporting: scientific, technical, and budgetary.

Dr. James R. Sharber will be a Co-Investigator at Southwest Research Institute. He has an extensive background in instrument design and flight data analysis from his involvement in numerous NASA sponsored satellite programs. He is a CoI on UARS/PEM, Cluster-II/PEACE, and Mars Express/ASPERA-3 experiments. He has been Principal Investigator for the plasma instruments on the Polar ARCS, PULSAR-II, ARIA 1-4, and Svalbard Cusp campaign rocket investigations. Dr. Sharber recently spent 3 years at NASA Headquarters as Discipline Scientist in the Sun-Earth Connection Division of the Office of Space Science where he managed research SR&T programs of the division and was program scientist for the Polar, Wind, Geotail, Twins, and Cluster missions. Dr. Sharber will be responsible for and direct the EP/O portion of this proposal. He will also participate in analysis of ELS calibration data, data validation, and analysis of ASPERA-4 observations.

Dr. Rudy A. Frahm will be a Co-Investigator and is a Senior Research Scientist at Southwest Research Institute. Dr. Frahm participated in the calibration of the DE-1/HAPI, DE-2/LAPI, DMSP/SSJ4/Block5D, UARS/PEM/MEPS, TSS-1/ROPE/SPES, TSS-1R/ROPE/SPES, and Mars Express/ASPERA-3/ELS spacecraft experiment plasma instruments. Dr. Frahm is a CoI on UARS/PEM and Mars Express/ASPERA-3. He has assisted in and directed the development of some of the UARS/PEM, Cluster-II, and ASPERA-3 ground software data display and analysis system currently in use at SwRI.

Dr. Frahm will be responsible for directing and performing much of the ELS FS calibration at SwRI. He will participate in hardware related activities at MSSL and IRF. Dr. Frahm will conduct the initial analysis of instrument characteristics and reduce the ELS FS laboratory calibration data at SwRI and the ELS FU calibration at MSSL. Dr. Frahm will also be responsible for directing the design of the ASPERA-4 data analysis system, instrument descriptions, design of analysis system for spacecraft telemetry, and he will participate in the science analysis of ASPERA-4 data.

Dr. Charles C. Curtis will be a Co-Investigator and is a Research Associate Professor at the Department of Physics of the University of Arizona. Dr. Curtis is the designer of the FIS and EIS mass spectrometer sensors for the Soviet VEGA probes to Comet Halley. Dr. Curtis has also served as project manager for the development of the EUV Imager for the NASA IMAGE Mission. As a CoI, Dr. Curtis is involved with the NPD sensor on Mars Express/ASPERA-3 and aided in the design of START surfaces.

Dr. Curtis will be responsible for overseeing the hardware and data analysis activities at the University of Arizona. He will have overall responsibility for NPD testing and calibration activities performed at the University of Arizona, and will assist in the science analysis of ASPERA-4 data.

Dr. Ke Chiang (Johnny) Hsieh will be a Co-Investigator and is a Professor at the Department of Physics of the University of Arizona. Dr. Hsieh has served as PI for the neutral gas analyzers for the Soviet VEGA mission to Comet Hally and was the original instrument lead of the High Energy Neutral Atom imager for the NASA IMAGE Mission. Dr. Hsieh is a CoI on CELIAS/SOHO, MIMI/Cassini, HENA/IMAGE, and ASPERA-3/Mars Express.

Dr. Hsieh will participate in the science analysis of ASPERA-4 data.

Dr. Bill R. Sandel will be a Co-Investigator and is a Senior Research Scientist at the Lunar and Planetary Laboratory of the University of Arizona. Dr. Sandel served as PI for the UV intensifiers in the Auroral Imager for Viking and the EUV Imager on IMAGE. Dr Sandel is a CoI on UVS/Voyager, UVS/EUV/Galileo, and ASPERA-3/Mars Express. He has also developed advanced photon-counting array detectors for eight Shuttle experiments and an EUV-FUV telescope for study of the Jupiter system and stars.

Dr. Sandel will perform University of Arizona testing and calibration activities on the neutral particle detection instruments and supply necessary laboratory facilities.

Dr. Edmond C. Roelof will be a Co-Investigator and is Principal Professional Staff at Johns Hopkins University Applied Physics Laboratory. Dr. Roelof is a CoI on Pioneer 10/11 Cosmic Ray Energy Spectra experiment, Galileo/EPD, Ulysses/HI-SCALE, Geotail/EPIC, Cassini/INCA, the TWINS and Astrid energetic neutral atom imagers, and Mars Express/ASPERA-3. He is an expert on the theory and analysis of data on energetic charged particles and ENA imaging.

Dr. Roelof, together with Dr. Pontus C. Brandt, will be responsible for the in-depth analysis of the ENA data from NPI and NPD and extraction of physical parameters by the use of models.

Dr. Pontus C. Brandt will be a Co-Investigator and is a Senior Professional Staff at Johns Hopkins University Applied Physics Laboratory. Dr. Brandt analyzed the ENA data from the ENA imager PIPPI (almost identical to the NPI instrument) on board the Astrid-1 spacecraft. Dr. Brandt is currently analyzing the data from the HENA instrument onboard IMAGE.

Dr. Brandt will be responsible for the in-depth analysis of the ENA images from the NPI and NPD instruments as well as extraction of physical parameters from the ENA images by use of models. Both Dr. Roelof and Dr. Brandt will work closely with Dr. Luhmann, Dr. Kozyra, and the European investigators.

Dr. Janet G. Luhmann will be a Co-Investigator and is a Senior Fellow at the Space Sciences Laboratory of the University of California at Berkeley. Dr. Luhmann is the PI of an in-situ particles and fields experiment on the twin STEREO spacecraft, is a CoI on the ASPERA-3 experiment on Mars Express, and is a member of the ion-neutral mass spectrometer facility instrument team on the Cassini Orbiter mission to Saturn.

Dr. Luhmann together with associate research Stephen Ledvina, will be responsible for providing comparative modeling support for data interpretation in the form of models of the solar wind-Venus interaction. She will collaborate with other ASPERA-4 CoIs on calculations related to the generation of the ENA fluxes that will be imaged with ASPERA-4, and to evaluate the properties of the ENA fluxes incident on the upper atmosphere of Venus. Dr. Luhmann will also participate in the analysis of data on energetic charged particles and ENA imaging.

Dr. Janet U. Kozyra will be a Co-Investigator and is a Research Professor at the Space Physics Research Laboratory of the University of Michigan. Dr. Kozyra is an Interdisciplinary Scientist in the Thermosphere -Ionosphere - Mesosphere Energetics and Dynamics (TIMED) Mission, a CoI on Polar/TIDE and a CoI on the ASPERA-3 experiment on Mars Express. Dr. Kozyra has a long history in data analysis as PI of an interdisciplinary science investigation on DE and as a guest investigator on the AMPTE/CCE spacecraft. Her specific interest area is neutral atom and ion precipitation, and decay of the Earth's ring current. She is experienced in the theory and modeling of the ionosphere - magnetosphere coupling process.

Dr. Kozyra will be responsible for providing models of the Venusian atmospheric response to precipitating energetic neutrals and ions which originate from the solar wind and interact with Venus. For this effort, Dr. Kozyra will use an ion/neutral transport model and a Coulomb heating model. She will be collaborating with Dr. Stephen Bougher (also at University of Michigan) in this effort who will be modeling the evolution of the Venus atmosphere using neutral heating, ionization and production of excited chemistry from Dr. Kozyra's models as inputs to a Venus Thermosphere General Circulation Model (TGCM). The feedback between the two sets of models will also be included in understanding the time-dependent response to solar wind inputs. Dr. Kozyra will also participate in the science analysis of ASPERA-4 data.

Dr. C. T. Russell, Co-I on the VEX magnetic field investigation will work with the US ASPERA-4 TEAM to ensure access to the magnetometer data, assist with its interpretation, and to coordinate between the US ASPERA-4 team and any other US efforts that may be complementary, but is expecting that he will be funded through a separate proposal.

D.7 *SCIENCE DATA AND OTHER SCIENCE PRODUCTS*

Laboratory calibration data will be used to determine the characteristics of the instrument. Individual manipulations in laboratory data will be used to generate descriptions of the instruments and their specifics so that science data returned will be accurate.

SwRI will provide web access to all ASPERA-4 CoIs to analyze and down load data to their home institutions. ASPERA-4 will use the SDDAS system for its science investigation of coordinated studies with ASPERA-4 instrumentation. SDDAS offers a variety of analysis tools. These include sequential spectral plots, time oriented spectrograms, angle oriented spectrograms, correlograms, real time plotting capabilities, source integration methods, plasma moment calculations, 3D visualization and contouring. Since SDDAS is continually improving, the list of analysis tools will grow as needs for additional analysis tools arise. ASPERA-4 CoIs will immediately have all of the SDDAS tools for their use.

SDDAS also has the capability to include special computation formulation (SCF), a procedure description which is unique to the users science data. The procedure interfaces with some SDDAS routines so that results can be presented along with any IDFS data. The SCF contains some definitions but there are cases where the user may have a special analysis code. As long as the user can develop a user defined procedure for performing the calculations, that procedure may be included within a special computation formulation. An example from UARS/PEM data was to use the SCF to combine data from different plasma instruments having different energy and time base ranges, and then using a user defined routine, to determine the amount of ionization occurring at different altitudes in the Earth's atmosphere.

The SDDAS system will allow scientists to interrogate and investigate ASPERA-4 data to uncover the plasma-atmosphere interaction details. SDDAS can be configured to examine ASPERA-4 data to address the question of determining atmospheric escape in a coordinated fashion by examining the ion, electron, and ENA fluxes from the planet, simultaneously.

Data products will be delivered to the NASA Planetary Data System (PDS) Planetary Plasma Interactions node after an ESA requirement of a 6 month proprietary data use period. Data analysis and archiving will be the primary responsibility of SwRI (Dr. Winningham, Dr. Sharber, and Dr. Frahm). ASPERA-4 data from the Venus Express mission will be archived in calibrated flux values at PDS for the particle instruments, data matrix ENA flux values for the NPI data, and data matrix values from the TOF NPD based instrument.

Laboratory calibration data will be used as test sets of the PDS archival system when PDS is configuring to accept ASPERA-4 Venus Express data from SwRI. At the end of the science investigation, all US generated electronic documents in SwRI's document control archive will also be transferred to NASA's PDS. Plans for NASA PDS archive are similar to the arrangements for archiving data from ASPERA-3 on Mars Express.

The Venus Thermosphere General Circulation Model (VTGCM) simulates the physics of the Venus CO_2 dominated thermosphere and photochemical ionosphere, and has been documented in detail by Bougher et al. [1988; 1990; 1994; 1997]. The VTGCM will be used for theoretical studies of the interaction of the Venus atmosphere with the solar wind. Throughout the mission, VTGCM theoretical results will be compared with ASPERA-4 data.

Table 3 outlines the VTGCM input parameters, fields, and its computational domain. Also, O_2 visible (400-800 nm), IR (1.27-micron), and NO ultraviolet (198.0 nm) nightglow distributions can be explicitly calculated. Solar cycle variations of Venus upper atmosphere temperatures, neutral and ion densities, and airglow intensities have been monitored using Pioneer Venus Orbiter (PVO) and Magellan measurements taken over a fraction of two 11-year periods [e.g. Kasprzak et al., 1997; Fox and Bougher, 1991]. Many of the features of these observed solar cycle responses are captured by the VTGCM and in two empirical models: VIRA (Venus International Reference Atmosphere) [Keating et al., 1985; 1999] and VTS3 [Hedin et al., 1983]. A combination of collisionally enhanced CO_2 15-micron cooling, wave drag, and standard eddy diffusion formulations are incorporated into the VTGCM.

Table 3. VENUS TGCM Input Parameters, Fields, and Computation Domain

TGCM	Domain -Alt Range -Pres Range Resolution (LatxLon)	Major Species	Minor Species	Ions	Time-Step (secs)	Homopause Kzz (cm2/sec)	Heating Efficiences (EUV vs. UV)
VTGCM	94-200 km 11-4.6E-7 Pa 33-levels 5x5 degrees	CO_2 CO O N_2	O_2 He NO N(4S) N(2D)	CO_2+ O_2+ O+ NO+ (PCE)	180	1.0E+7 (at 136 km)	EUV = 20% UV + 22%

Where PCE refers to photochemical equilibrium: DYN refers to vertical diffusion and horizontal advection; Chem signifies neutral-neutral and ion-neutral chemical heating below 200 km; EUV refers to Extreme Ultraviolet heating efficiency; UV refers to Ultraviolet heating efficiency. In addition, 1E-7 is interpreted as $1x10^{-7}$.

D.8 *MINIMUM SCIENCE INVESTIGATION*

The minimum acceptable data and science will be determined by ESA. There are a variety of descoping options shown in Table 4. These options have consequences to other ASPERA-4 CoIs and other nations. A list of possible descope options are cited below along with the consequence to the descope option, phasing, schedule and cost savings for the US. In most cases, there is only savings on the US side as the tasks might be picked up by other ESA partners. However most of the ASPERA-4 for Venus Express is identical to ASPERA-3 from Mars Express and the rolls of the personnel involved in almost cases are identical. Therefore, the ASPERA-4 program for Venus Express is expected to be of low risk and the need to execute a descope option is expected to be low as well.

Table 4. Descope Plan

Descope Option	**Consequences**	**Phasing**	**Schedule Savings**	**Cost Savings**
A) SwRI does not produce an ELS Flight Spare	ELS Spare Unit not available to IRF. If the ELS Flight Unit becomes damaged beyond timely repair by IRF or MSSL, no electron data will be obtained from Venus Express. ASPERA-4 and Mission will be incomplete	At Selection	No ELS FS delivery	SwRI hardware budget
B) SwRI produces but does not calibrate the ELS Flight Spare	If IRF needs to use the spare unit, then electron data from Venus Express will be present, however, its interpretation will be difficult, instrument characteristics will be approximated, and the validity of Venus Express electron data will always be questioned.	In May of 2004	About a month	SwRI calibration budget
C) UA does not coat START surfaces for NPD	IRF will have to deal with an alternative method of producing coated NDP START surfaces. If successful, there will be no consequence to the science mission. If unsuccessful, NPD noise will be significant which could results in a total loss of useful data, and ASPERA-4 and Mission goal of determining atmospheric escape will become restricted without the knowledge of particle mass.	At Selection	No NPD part delivery	$107,000
D) EP/O Elimination	Public information	Any Time	No EP/O	$140,000.
E) Elimination of PDS archiving during last year	No PDS data available after November 2007	Before November 2007	No PDS after activity November 2007	Last year of PDS (ASK SANDEE)