ULF Waves in Venus's Magnetosheath

and how do they compare with Mars?[1,2]

1 Introduction

All planets in our solar system, as well as exoplanets (i.e. planets circling around other stars than our Sun), have interactions with the solar/stellar wind coming from their host star. The solar wind is comprised of plasma moving away from the Sun at velocities around 400 km/s and densities around a few per cubic cm around 1 Astronomical Unit (AU, distance Sun-Earth). Embedded and moving along with the plasma is the Sun's magnetic field with a strength of several nT, also called the interplanetary magnetic field (IMF). These values can strongly vary when eruptions on the Sun, so-called solar flares and coronal mass ejections (CMEs) occur.

Naturally, for each planet the interaction with the solar wind and the IMF is different, caused e.g. by the presence of a planet-internally generated magnetic field and/or by the distance of the planet from the Sun. However, the regions around the planet are basically similar for all planets: the super-sonic solar wind gets braked at the bow shock to sub-sonic speeds. The slowed down magnetoplasma flows in the so-called magnetosheath, where it interacts with the (magnetized) planet. It forms a boundary at the location where the magnetic pressure becomes equal to the ram pressure of the solar wind. This boundary is called the magnetopause/ionopause/pile-up boundary, depending on the magnetization of the planet. In the region between the bow shock and the magnetopause, the magnetosheath, many plasma phenomena take place, see e.g. Song and Russell [1997].

Figure 1: On scale images of Mars and Venus.

In this project the magnetosheaths of two terrestrial planets, Venus and Mars, will be investigated and compared. Questions whether the size of the planet, with Mars approximately half the size of Venus, see Fig. 1, has an influence on the activity in the magnetosheath, or if the distance from the Sun, with Mars approximately twice as far as Venus, makes any significant difference are addressed in this project. Naturally, the fact that there are no upstream solar wind monitors

[1] *Short title: ULF Waves in Venus's and Mars's Magnetosheath*

[2] 2nd submission, textual changes in green.

at these two planets makes interpreting the results obtained in the magnetosheath more difficult. There are methods in order to overcome this, which will be addressed in the project.

The overall scope of this project is ambitious, however the requested postdoc and student assistants (possibly resulting in master's thesi) will be able to perform this task, in collaboration with the people in the teams of the international collaborators.

2 Induced Magnetosphere

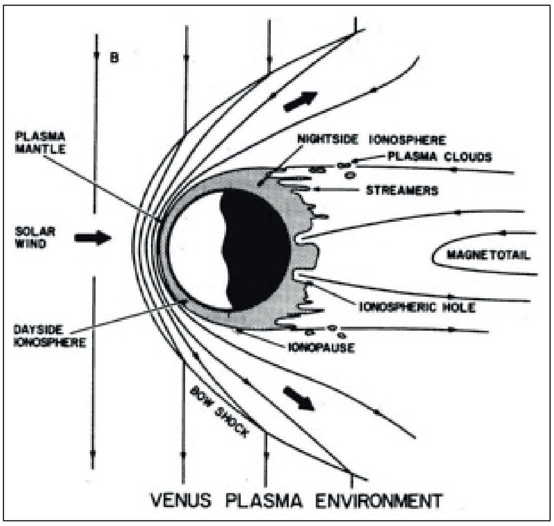

Figure 2: The interaction of Venus with the solar wind creating an induced magnetosphere. The mass loaded solar wind, by pick-up ions from Venus's exosphere, slows down the solar wind and its IMF, creating a bow shock, magnetosheath with increased magnetic field strength, and a magnetotail. A similar process also occurs at Mars.

Although Venus does not have an intrinsic magnetic field, through its interaction with the magnetoplasma of the solar wind, a so-called induced magnetosphere is created [Zhang et al., 2008*b*]. Ionization of neutrals in Venus's exosphere lead to mass-loading of the solar wind, as the newly created ions are picked-up by the Interplanetary Magnetic Field (IMF). Conservation of momentum leads to a slowing down of the mass-loaded solar wind in the region where pick-up is taking place, whereas further away from the planet the solar wind remains unperturbed. This leads to a bending and stretching of the IMF, with the field lines draped around the planet, see Fig. 2, thereby creating an induced magnetosphere. This process is similar to that proposed by Alfvén [1957] for the creation of cometary tails.

The obstacle, planet Venus, in the flow of the solar wind also creates a bow shock upstream of the planet [Zhang et al., 2008*a*], where the solar wind is decelerated from supersonic to subsonic velocities.

This same mechanism is working at Mars, also creating an induced magnetosphere around this planet. The major differences here are generated by the smaller size of Mars (radius $R_\mathrm{M} \approx 3390$ km vs. $R_V \approx 6052$ km), the lower plasma density and magnetic field strength of the solar wind/IMF: $N_\mathrm{M} \approx 2\,\mathrm{cm}^3$, $B_\mathrm{M} \approx 3$ nT, $v_\mathrm{M} \approx 450$ km/s [see e.g. Sauer and Dubinin, 2000], where at Venus $N_\mathrm{V} \approx 10\,\mathrm{cm}^3$, $B_\mathrm{V} \approx 9$ nT, $v_\mathrm{V} \approx 400$ km/s [see e.g. Neugebauer and Snyder, 1965; Delva et al., 2015].

The boundary where the plasma pressure of Venus's ionosphere and the magnetic pressure equal each other is called the magnetopause/ionopause/pile-up boundary[3] and the region between the bow shock and the magnetopause is the magnetosheath. In the magnetosheath the slowed-down, mass-loaded solar wind is transported past the planet towards the tail region. The magnetosheath is characterized by the presence of strong Ultra-Low-Frequency (ULF) wave activity, as shown e.g. in Guicking et al. [2010], Du et al. [2010], Volwerk et al. [2016] and Fränz et al. [2017].

The ULF frequency range is based on the different (both continuous, Pc, and irregular, Pi) pulsations that are observed in the Earth's magnetosphere, and is usually set to periods $1 \leq T_{\mathrm{ULF}} \leq 1000$ seconds. However, just setting a frequency range does not suffice. The wave frequency must be "low" compared to a natural frequency of the plasma, e.g. the plasma frequency $f_{\mathrm{p,i}} = (n_i e^2/2\pi\epsilon_0 mi)^{1/2}$ and the proton gyro frequency $f_{c,p} = eB/2\pi m_p$ [see e.g. Kivelson and Russell, 1995, Chapter 11]. The categorization of ULF waves in the Earth's magnetosphere are given in Kivelson and Russell [1995, Table 11.1] and these different categories are mainly caused by the internal magnetic field of the Earth. Such a categorization will not be found at unmagnetized planets, because of the lack of closed field lines. Specific wave modes, though, such as mirror mode waves or ion cyclotron waves, will be able to be identified in the data, which will be addressed in this proposal.

ULF wave power is not only present behind the bow shock, but is also generated in front of it. Because of ionization of neutrals from the part of the exosphere that is outside of the bow shock, proton cyclotron waves are generated [see e.g., Delva et al., 2008, 2015]. Also solar wind ions reflected off the Venusian bow shock will create foreshock waves, [see e.g., Shan et al., 2016; Dubinin and Fraenz, 2016]. As an introduction, some of the ULF wave mode studies at Venus will be discussed below and some comments about their occurrence at Mars.

The lack of an upstream solar wind monitor, like at Earth, makes analysing the data slightly more involved. It is best to study "steady" conditions of the magnetosheath, i.e. the solar wind IMF direction before crossing the bow shock ingress, and after crossing it egress, should not differ more than a certain pre-determined angle [e.g. Delva et al., 2017]. This decreases the amount of orbits available for analysis, but it increases the accuracy of the results.

[3] The correct term to be used is highly debated in the field

3 Mirror-Mode Waves

One characteristic wave behind the quasi-perpendicular bow shock is the mirror-mode wave [Gary, 1992; Gary et al., 1993]. This kind of bow shock, with its normal almost (quasi) perpendicular to the IMF, will heat ions mainly in the perpendicular direction of the magnetic field. This creates a ion-temperature asymmetry with $T_\perp > T_\parallel$, which can generate ion-cyclotron waves (for low plasma-β, which is defined as the ratio of plasma pressure $P_\mathrm{p} = nk_\mathrm{B}T$ and magnetic pressure $P_\mathrm{B} = B^2/2\mu_0$) and mirror-mode waves (for high plasma-β). The instability criterion is given by Hasegawa [1969]:

$$1 + \beta_\perp \left(1 - \frac{T_\perp}{T_\parallel}\right) < 0, \qquad (1)$$

where $\beta_\perp$ is the "perpendicular" plasma-β, in which only the temperature component perpendicular to the magnetic field is taken into account.

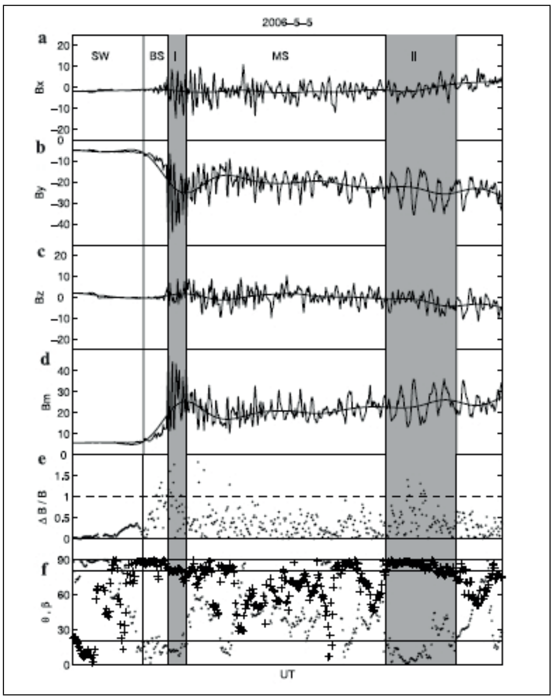

Figure 3: Mirror mode waves behind the quasi-perpendicular bow shock, observed by the Venus Express magnetometer. The top four panels show the magnetic field components and magnitude. The bottom two panes show $\delta B/B$ of the waves and the angles of the minimum ($*$) and maximum ($+$) variance direction with respect to the low-pass filtered magnetic field [Volwerk et al., 2008*a*].

Using the Venus Express (VEX) magnetometer [Svedhem et al., 2007], these waves were first identified at Venus by Volwerk et al. [2008*a*], behind the quasi-perpendicular bow shock.

It was found that there are two regions where the MM waves occur, see Fig. 3: I. Just behind the bow shock with freshly shocked ions; and II. close to the magnetopause, where the magnetic field is compressed and ions are re-heated perpendicularly by conservation of the first adiabatic invariant:

$$\mu = \frac{mv_\perp^2}{2B}. \qquad (2)$$

The MMs have a period between 5 and 15 seconds depending on the location in the magnetosheath. Unfortunately, the cadence of the VEX plasma instrument ASPERA-4 [Barabash et al., 2007] is much too low (> 3 min) to resolve the characteristic anti-phase behaviour of the plasma ion density and the magnetic field strength of MMs. Therefore, the MMs are searched for using a

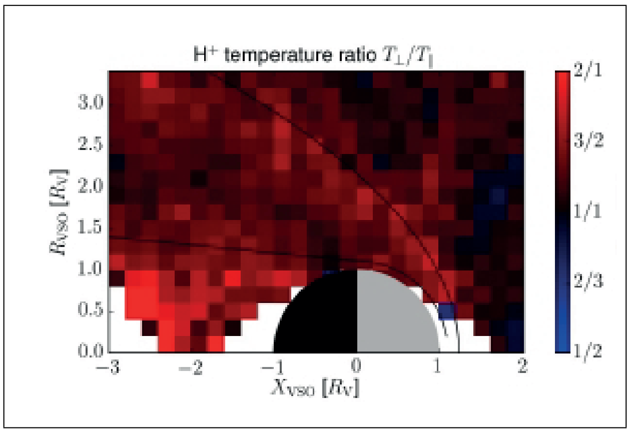

Figure 4: The temperature asymmetry $T_\perp/T_\parallel$ for protons at Venus. [Bader, 2017].

magnetic-field-only method described by Lucek et al. [1999].

Recently, Bader [2017] performed a study of the ion temperature asymmetry as measured by the ASPERA-4 instrument. In Fig. 4 the ratio of $T_\perp/T_\parallel$ for H^+ ions is shown, for all measurements between 14 May 2006 and 28 December 2009. The red colour along the nominal bow shock (black line) shows clearly the perpendicular heating of the ions, both in the magnetosheath (heating of crossing ions) as well as in the solar wind (heated reflected ions).

A statistical study [Volwerk et al., 2008*b*] showed that the MMs indeed have the "correct" characteristics with respect to their observational location and the direction if the IMF, always on the side where the IMF creates the quasi-perpendicular bow shock and close to the magnetopause.

Solar Minimum and Maximum

Thanks to the long life-time of the VEX mission, orbit insertion 2005 and end of mission 2014, it is possible to compare the MMs during the period of solar minimum and solar maximum. Delva et al. [2015] showed that there was a significant difference in the proton cyclotron waves upstream of the bow shock, between solar minimum and maximum. Similarly, Volwerk et al. [2016] compared the statistical behaviour of MMs for solar minimum, as presented in Volwerk et al. [2008*b*], with their statistical behaviour during solar maximum.

In order to statistically study the MMs the observational rate is calculated over one Venus-year, i.e. 223 days. The space around Venus was projected on the XR-plane, where $R = \sqrt{Y^2 + Z^2}$, and split up into $0.25 \times 0.25 R_V$ boxes. The MM events in each box were counted and divided by the time that VEX spent in that box. In Fig. 5 the logarithm of the observational rate is colour coded.

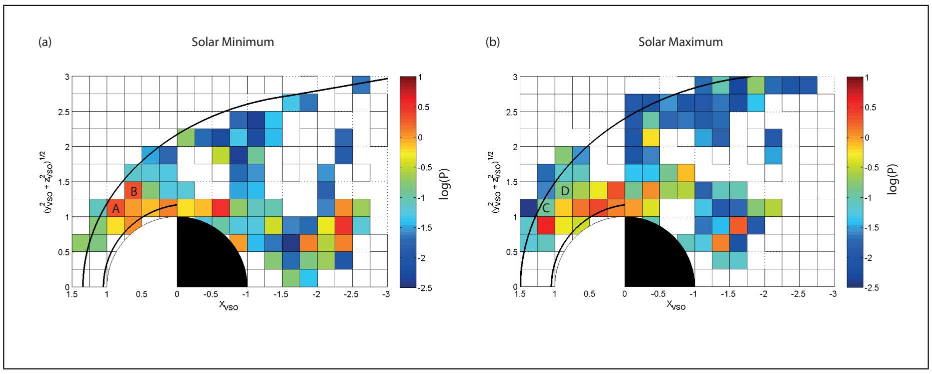

Figure 5: Observational rate of MMs for (a) solar minimum and (b) maximum. Rows A/B and C/D for show a different behaviour in growth and decay of the waves [Volwerk et al., 2016].

A comparison of the observational rate of MMs in Venus's magnetosheath is shown in Fig. 5. In all, over one venus-year the total number of MM events was only $\sim 14\%$ higher for solar maximum, however, the distribution over the magnetosheath was different, as can be seen by comparing panels (a) and (b) in Fig. 5.

It can be noticed that the maximum observational rate of the MMs for solar minimum is directly behind the model bow shock, which then decreases along the X-axis (see the horizontal rows labeled A and B). For the same rows during solar maximum (labeled C and D) it can be seen that there is a low rate which first increases along the X-axis and then decreases. This indicates that the magnetosheath is somehow different for the two solar extremes, for which, as yet, no explanation has been found.

Wave Mode Identification

Recently, Fränz et al. [2017] revisited the data for one event by Volwerk et al. [2008*a*] in order to study the presence of MM and fast-mode waves, shown in Fig. 6. Using also the ASPERA4 electron data from ELS, which has a much higher cadence of 4 seconds, they found that using only magnetic field data can lead sometimes to misinterpretation between MM- and fast-mode waves, both of which are compressional waves in the magnetic field, however, their phase with respect to plasma density is different, in anti-phase and in-phase, respectively.

Over a period of 8 years (2006 - 2014) Fränz et al. [2017] performed a statistical study of the waves in Venus's magnetosheath, where the main results were that Alfvénic fluctuations dominate all-over. Fast-mode waves are mainly seen near the bow-shock and MM waves are a "minor" wave

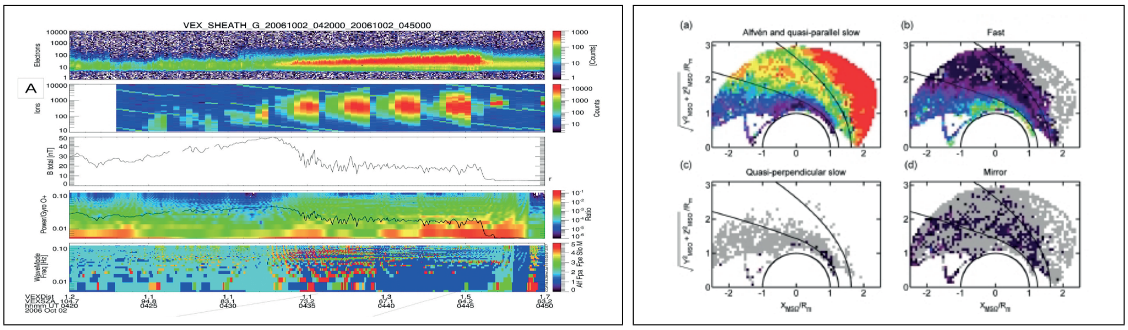

Figure 6: Left: VEX particle and fields observations on 03 June 2006: ASPERA4 ELS electron energy spectrum, IMA all ion spectrum, MAG total field strength $|B|$, Normalized Fourier spectrum of $|B|$ and gyro-frequency of O^+ ions overplotted in black, Wave mode identification after Song et al. [1994]: Alfvénic (blue), Fast (green), Slow (orange), Mirror (red). [Fränz et al., 2017]. Right: Wave occurrence ratios for the four low frequency wave modes. The occurrence rate of the "mirror mode" waves, bottom right panel, is rather different from that determined for Venus. [Ruhunusiri et al., 2015].

species, in agreement with other statistical studies at Venus and Mars that will be discussed in Section 4.

How About Mars?

There have not been specific MM wave studies at Mars, but they are included in some low-frequency wave studies such as Bertucci et al. [2004], Espley et al. [2004] and Ruhunusiri et al. [2015, 2017].

Fig. 6, right panel, shows the occurrence rate for four different ULF waves modes [Ruhunusiri et al., 2015] with MAVEN data from 28 November 2014 to 20 March 2015, i.e. solar maximum conditions. It is clear that the MM waves (panel d) only occur sporadically in Mars's magnetosheath, compared to the Alfvén/Slow (panel a) and the Fast mode (panel b) waves. Lately, however, Fränz et al. [2017] showed a new distribution of these waves in Venus's magnetosheath, and concluded that the occurrence rate for MMs is less then 20% compared to the full set of waves. This again is comparable with what is found at Mars. Indeed, the MMs seem to behave differently at Mars than at Venus as Bertucci et al. [2004] conclude: "*Interestingly, mirror mode waves at Mars occur whatever the shock's nature, and they always appear to be "attached" to the MPB*[4]*, as if they were convected down to it.*" This seems to indicate that the main generation of MMs in Mars's

[4]MPB: Magnetic Pile-up Boundary

magnetosheath is done by magnetic pumping and conservation of the first adiabatic invariant. A question that remains is why do MMs behave differently at Mars as compared to Venus, and do both planets show a different behaviour for solar minimum and maximum conditions?

4 Low-Frequency Magnetic Fluctuations

Statistical studies on ULF waves in Venus's magnetosheath have been performed by Du et al. [2010] and Guicking et al. [2010] using the Venus Express magnetometer data. In Fig. 7 the ULF wave characteristics for frequencies between 30 and 300 mHz are shown for April 2006 until December 2008, totalling 4.5 Venus years. The figure shows the results for solar wind cone angles $0^\circ \leq \theta_c \leq 30^\circ$ i.e. a quasi-parallel bow shock and $60^\circ \leq \theta_c \leq 90^\circ$ i.e. a quasi-perpendicular bow shock.

There seem to be some significant differences between the two types of bow shocks. Interestingly, the transverse and compressional ratio (top panel in Fig. 7), defined as $(P_\perp - P_\parallel)/P_T$ seems to be mainly between 0 and 1, which means that the transverse waves are dominant in Venus's magnetosheath. The propagation direction of the waves with respect to the magnetic field (bottom panel in Fig. 7), seems to be always greater than 30°.

The method used to determine the characteristics of the waves was to use the full 4.5 years of data, binned in 0.1×0.1 R_V bins, which resulted in 60(30) values per bin in the left(right) column, which were then averaged. A similar method was used by Guicking et al. [2010], but for a two-year period and with a bin size of 0.05×0.05 R_V and similar distributions were found as in Fig. 7. Additionally, the development of the wave power along stream lines in Venus's magnetosheath were studied.

Interestingly it was found by Guicking et al. [2010] that, depending on the streamline in the magnetosheath, the intensity of the waves decreased as a power law depending on the time since the crossing of the bow shock, as shown in Fig. 8. However, the intensity did not follow a decline as a function of distance from the bow shock, as predicted by the continuity equation $I(s)v(s)A(s) = \text{cst.}$, where I is the stream line, v is the plasma velocity and A the cross-section of the stream line. This was interpreted that the wave intensity is turbulently dissipated, $E \propto t^{-\lambda}$, with the coefficients given in Fig. 8. The values of λ are strongly varying for different streamlines.

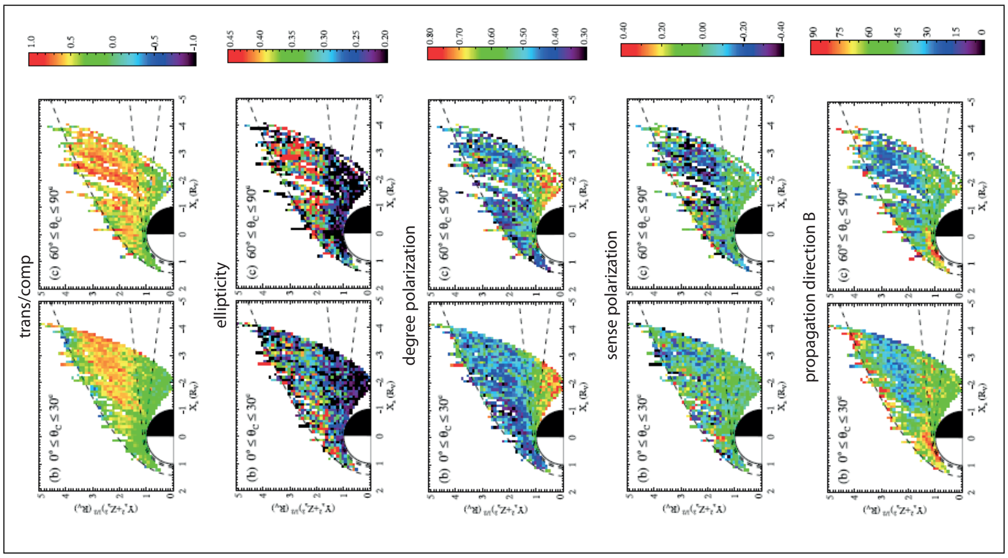

Figure 7: Characteristics of low frequency waves measured by the VEX magnetometer for solar wind cone-angles $0° \leq \theta_c \leq 30°$ (left column, quasi-parallel bow shock) and $60° \leq \theta_c \leq 90°$ (right column, quasi-perpendicular bow shock) [Du et al., 2010]. Three dashed lines indicate the positions of the bow shock and the upper and lower mantle boundaries, respectively. Differences in e.g. ellipticity or sense of polarization are clearly visible in the two columns.

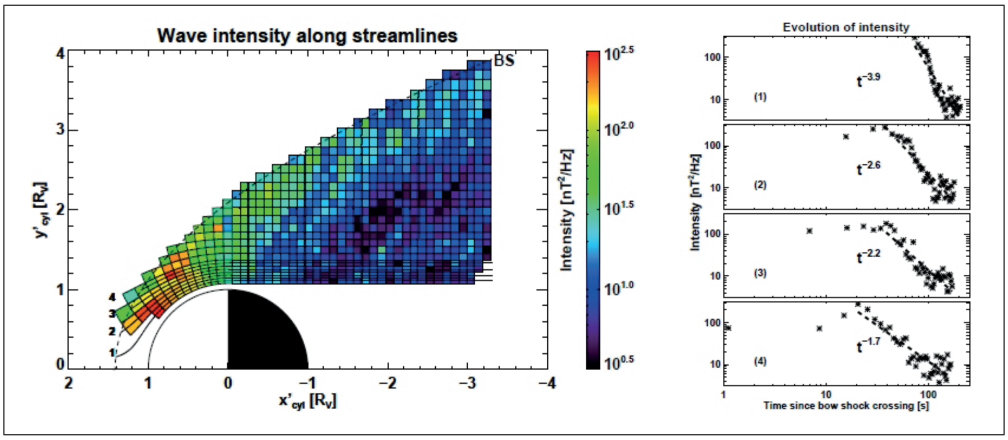

Figure 8: Left panel: The low frequency wave intensity in Venus's magnetosheath binned along stream lines and velocity potentials (see below Eqs. 6 and 8. 'Right panel: Wave intensity as a function of time since crossing the bow shock, along stream lines 1 through 4, fitted by a power law in time [Guicking et al., 2010]

A Look at Mars

Similar studies about the wave power in Mars' magnetosheath have been performed by Espley et al. [2004] with some of the results shown in Fig. 9, which can be directly compared with Fig. 7.

It is not explained in the paper by Espley et al. [2004] what time interval was chosen for the data analysis, only that the "*usable pre-mapping orbits*" (13 September 1997 - 8 Mach 1998) were used, i.e. 276 days, which means well less than one Mars year (687 days). Two case-studies are presented for 23 October 1997 and 31 January 1998. This means that the study was done for solar maximum conditions.

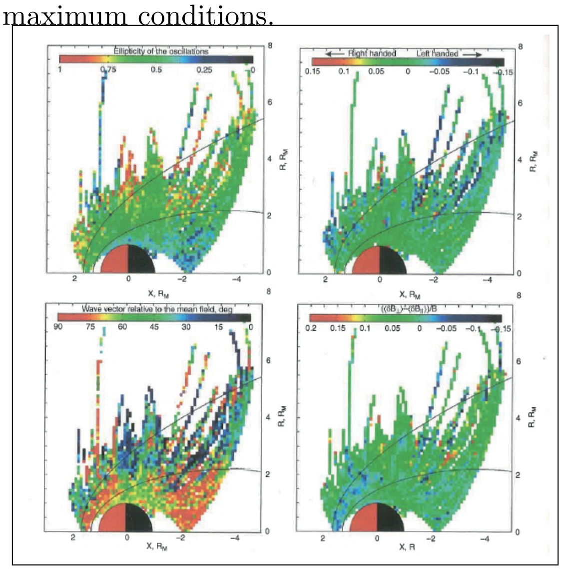

Figure 9: Characteristics of the low frequency waves in Mars' magnetosheath from Mars Global Surveyor magnetometer data. Top panels: Ellipticity and polarization; bottom panels: Propagation direction and compressibility, for solar maximum conditions during the pre-mapping phase of MGS [Espley et al., 2004].

Although some of the colour-bar scales are different in Figs. 7 and 9, the panels can easily be compared. The first great difference is between the transverse and compressional component, which for Venus is between 0 and 1, whereas for Mars it is more around 0. One should consider the different definitions, as in Espley et al. [2004] the compressional component is defined as $(\langle B_\perp \rangle - \langle B_\| \rangle)/B$, instead of magnetic pressure P.

The ellipticity and handedness of the waves seem to be rather similar for Venus and Mars, but the propagation direction with respect to the background field is again significantly different for the two planets. In order to do a real comparison, the data will have to be handled in the same way, for the same solar activity, i.e. solar mininum and maximum.

Turbulence in Mars' magnetosheath

Lately, Ruhunusiri et al. [2017] studied the turbulence in the plasma environment of Mars, using MAVEN data. For various regions in the induced magnetosphere, as well as upstream of the bow shock, the power spectral density (PSD) was determined with 32 Hz magnetometer data, using wavelet transform, as in Tao et al. [2015]:

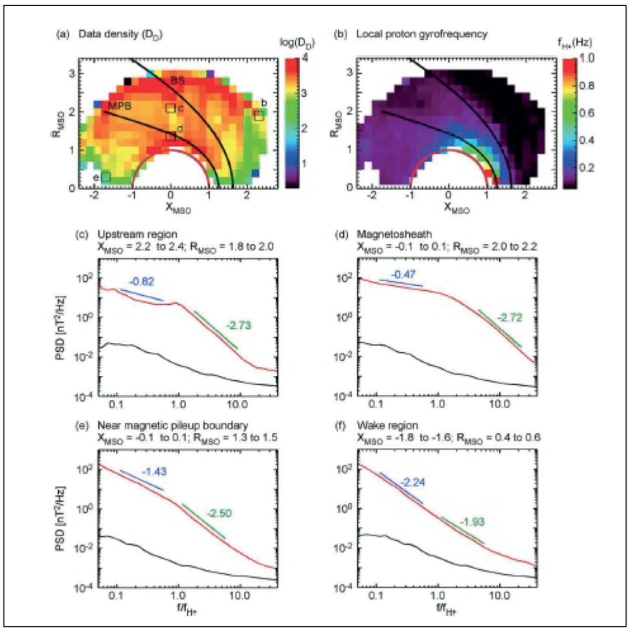

Figure 10: Turbulence in Mars' magnetosheath. Top two panes show the MAVEN data density (a) and the proton gyrofrequency (b). The bottom 4 panels show the median PSD for different regions around Mars, where the MHD (blue) and kinetic (green) intervals of the PSD are fitted by a power law. The black line is the PSD of the estimated noise level of the magnetometer [Ruhunusiri et al., 2017].

$$\mathcal{W}_{\mathrm{i}}(t,\tau) = \Sigma_{j=1}^{N} \delta B_{\mathrm{i}}(t_j) \tau^{-1/2} \psi^* \left[(t_j - t)/\tau \right] \Delta t, \tag{3}$$

from which the PSD is determined as:

$$\mathrm{PSD_i} = \frac{2}{N\Delta t} \Sigma_{j=1}^{N} \Delta \left| \mathcal{W}_{\mathrm{i}}(t_j,\tau) \right|^2, \tag{4}$$

where t is the time variable of N steps with interval Δt, τ is the time scale. ψ^* is the complex conjugate of the Morlet mother wavelet:

$$\psi(u) = \pi^{-1/4} e^{i\omega_0 u} e^{-u^2/2}. \tag{5}$$

Ruhunusiri et al. [2017] used 512 s windows with a time shift of 1 min. The median PSD is shown as a red curve in the bottom four panels in Fig. 10. For two different plasma regimes, MHD and kinetic, the PSD is fitted by a powerlaw $P(f) = P_0 f^{\alpha}$. The spectral index α is given in the panels. For the magnetosheath, in the kinetic regime, i.e. $f > f_{\mathrm{H+}}$ the slope for $-0.1 < X < 0.1$

and $2.0 < R < 2.2$ is shown to be $\alpha = -2.72$ and overall peaks around $\alpha = -3$, which is indicative of quasi-2D turbulence [Frisch, 1995]. It has been shown by Goldreich and Sridhar [1995] that the turbulence in a fast flow in a vertically limited flow channel, in the presence of a magnetic field, can develop hydrodynamically and be described by a spectral index $\alpha = 3$ [see also Volwerk et al., 2003]. Again, in order to compare the turbulence in the two magnetosheaths, the data needs to be handled in the same way, which has not been done so far.

Error bars and co.

Some of the uncertainties in the data used in this project have already been addressed. The lack of a solar wind monitor, for example, leads to a lack of knowledge of the IMF conditions. This can be partly resolved by demanding that the IMF does not change over more than a certain amount of degrees whilst the spacecraft is passing through the magnetosheath. Also, the determination of the MMs through only magnetic field data may lead to some misinterpretations of compressional waves as MMs, but for the longer period MMs this can be checked using the faster electron data. Spectral analysis can best be performed using a Welch algorithm [e.g. Erikson, 1998] which also gives error estimates to the spectral power. The magnetometer data are rather robust with an accuracy of 0.1 nT or better. The plasma data accuracy and time resolution differ for various instruments.

Summing up

The interaction of Venus and Mars with the solar wind are very similar. A first paper comparing the induced magnetospheres with that of the Earth was performed by Gringauz [1981], who concluded that "*There are substantial arguments supporting the existence of a Martian intrinsic magnetic field, which is weak but sufficient to deflect the solar wind: the topology of the magnetic field in the day-side Martian magnetosphere is different compared to the Venus magnetosphere ...*"

One of the reasons why there are differences between Venus's and Mars's magnetosheath activity is the smaller size of Mars and the different solar wind and IMF at Mars. This causes e.g. the Larmor radii of solar wind protons to be on the same scale as the size of the Mars's bow shock [Bertucci et al., 2011], which means that kinetic effects are becoming important [Lambège and Savoini, 2002].

A full investigation of the ULF wave activity in both induced magnetospheres will give insight into how similar processes at two unmagnetized bodies of different size and different location in the solar system work. The results of this research will also have repercussions for plasma physics at comets and possibly exoplanets.

The Project

This project foresees the research being done by a postdoctoral researcher over a time period of three years, assisted by student assistants and the international collaboration teams. The goal is to obtain a full comparative magnetosheath physics study for Venus and Mars. The focus will be on comparing both the two magnetosheaths as well as the two extremes of the solar cycle (solar minimum and maximum). First a specific wave mode, mirror mode waves, will be investigated, after which concentration will be on the turbulence in the magnetosheaths.

Project 1: Bow Shock & Mirror-Mode Waves @ Venus & Mars

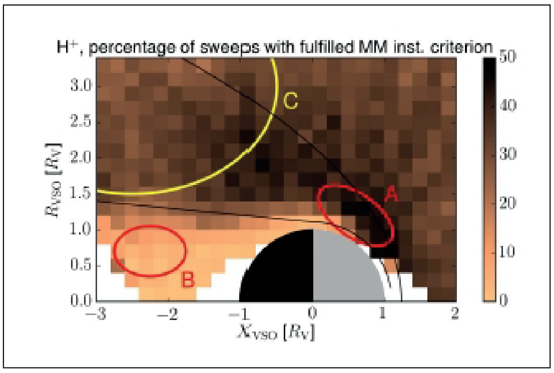

Figure 11: The percentage of sweeps fulfilling the MM instability criterion. Region A and B are the areas where Volwerk et al. [2008*b*] found the highest observational rates. Area C is where Delva et al. [2011] observed IC wave activity [Bader, 2017].

It has been shown that the behaviour of mirror-mode waves at Venus is different for solar minimum and solar maximum, however, no explanation for why was given. Lately, Bader [2017] investigated the ASPERA-4 data on temperature asymmetries, and for a period of 3.5 years determined the percentage of ASPERA-4 sweeps that fulfilled the MM instability criterion. The results are shown in Fig. 11. Clearly, the day side magnetosheath is most prone to fulfill the criterion, with up to 50% of the sweeps.

It would be necessary to expand on this investigation, where the data will be split into the different categories of bow shock and solar activity.

The reason for the different behaviour of the mirror-mode waves needs to be explained. Is the reason that the bow shock is different for solar minimum and solar maximum conditions? In order to do this, the upstream conditions of the solar wind must be investigated. Delva et al. [2015] already showed that observations from other spacecraft revealed that the southward tilt of the heliospheric current, the "bashful ballerina" sheet is responsible for a prevalence of the northern solar hemisphere with currently inward field during Solar Cycle 24. There is a significant asymmetry in the sector distribution of the IMF during each solar cycle [e.g., Smith et al., 2000; Mursula and

Hiltula, 2003; Mursula and Virtanen, 2012; McComas et al., 2013].

Putting together the different behaviour of the mirror-mode waves in Venus's magnetosheath and the asymmetries in the IMF during solar cycles, it stand to reason to investigate in detail the differences in the bow shock for solar minimum and maximum conditions. At the same time, this kind of behaviour should be compared with the other unmagnetized planet: Mars.

- **Determination of the quasi-perpendicular bow shock characteristics**
  Using both the Venus Express magnetometer and the ASPERA-4 plasma data, now with both ions and electrons, a statistical study will be made of the conditions upstream and downstream of the quasi-perpendicular bow shock for solar minimum and maximum conditions.

- **Solar minimum/maximum difference of the magnetosheath**
  After the characteristics of the bow shock are determined, a detailed analysis can be started of the question why the behaviour of mirror mode waves is different for both parts of the solar cycle. How does the structure, both magnetic and plasma, differ in both situations such that there is a strong difference in wave growth?

- **Comparison with Mars**
  A similar study of mirror-mode waves has not yet been performed, apart from what was shown in Fig. 6 right panel. Therefore, the same statistical study as performed by Volwerk et al. [2016] needs to be done. The Mars Global Surveyor (MGS) data, which cover the period of September 1997 to November 2006, which means that the solar minimum study can be performed on the same time interval as in Volwerk et al. [2008*b*]. Fortunately, the first part of the MGS mission was during the rising part of the solar cycle with maximum in 2001.

Project 2: Characterizing the ULF spectrum in the magnetosheath

In Project 1 only one specific wave mode is chosen to be investigated, but a whole slew of different wave modes are possible to exist in the magnetosheath as can be seen in Figs. 7 and 9 by Du et al. [2010] and Espley et al. [2004], respectively. In both studies, however, no differentiation by solar cycle was performed; in the first case four Venus-years of data (April 2006 to December 2008) were used, whereas in the second case less than one Mars-years (during the pre-mapping phase of MGS). Both studies find also evidence for ion cyclotron waves in the magnetosheath, mainly in the post-terminator region. The presence seems to be dependent on the upstream solar wind conditions, creating a quasi-perpendicular or quasi-parallel bow shock. This is in agreement with the results by Delva et al. [2015], where is was shown that the major occurrences of IC waves, outside the bow shock, happen in the post-terminator plane, as can be seen from the large clustering of points between $-2 \geq X \geq -3$ in Fig. 12.

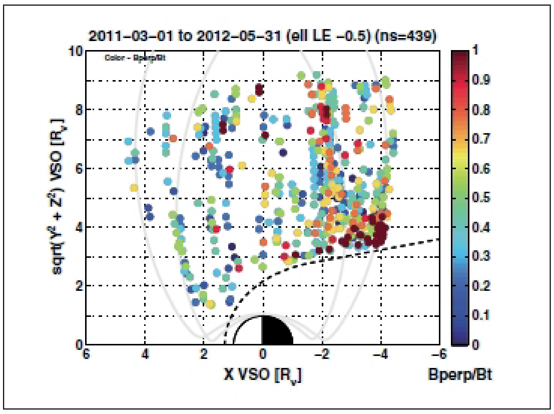

Figure 12: observed IC wave activity [Delva et al., 2015].

But not only specific wave modes are important, also wave turbulence, which distributes the energy to smaller scales is important [Vörös et al., 2008], but different regions in the magnetosheath scale differently in their turbulent spectrum.
Does the size of the obstacle in the solar wind (i.e. the radius of Venus and Mars) have any influence on the power input into the plasma of the magnetosheath, and how does this influence the turbulent cascade and its development along the streamlines [see e.g. Guicking et al., 2010]?
The magnetosheath streamlines can be modeled by the hydrodynamic flow around a cylinder [Valentine, 1967] for the day side magnetosheath, with flow along straight lines on the night side. This model has been shown to work successfully by Luhmann et al. [1983] for tracing back the stream lines to the quasi-parallel bow shock, and is also in agreement with the gas dynamical model of the interaction of the solar wind with Venus by Spreiter and Stahara [1994]. For the day side the stream line functions are described by [see e.g. Guicking et al., 2010]:

$$\Psi_{\rm d} = vy\left(1 - \frac{r^2}{x^2+y^2}\right), \qquad (6)$$

$$\Psi_{\rm n} = vy, \qquad (7)$$

for the dayside (d) and night side (n) respectively, with v the nominal velocity in the magnetosheath and r the radius of the planet and x and y are the (VSO) coordinates of a point in the magnetosheath. For the velocity of the plasma two potentials can be defined as:

$$\Phi_{\rm d} = vy\left(1 + \frac{r^2}{x^2+y^2}\right), \qquad (8)$$

$$\Phi_{\rm n} = vx, \qquad (9)$$

where spatial differentiation results in the velocity of the plasma in the direction of differentiation.

The potential lines of the velocity are perpendicular to the streamlines, which can be seen in the grid in Fig. 8.

- **Presence of ion cyclotron waves in the magnetosheath**
  The presence of ion cyclotron waves in the upstream regions of the bow shock are well studied and discussed [Mazelle et al., 2004; Delva et al., 2015], but their presence in the magnetosheath is not well studied. Therefore, a study shall be performed on these waves in Venus's and Mars's magnetosheath, with division into solar minimum and maximum conditions. Naturally, also the type of bow shock, quasi-parallel or -perpendicular, behind which the waves are observed, needs to be taken into account.

- **Characterization of the turbulence in the magnetosheath**
  The intensity $I(s)$ of the turbulent spectrum along the stream line s in Venus's magnetosheath was investigated by Guicking et al. [2010], under the assumption that a continuity equation in the form $I(s)v(s)A(s) = \text{cst.}$ holds, where $A(s)$ is the cross section of a flow line. This did not fit well, but a relationship between intensity and time since bow shock crossing could be found, as is clear in Fig. 8. This study needs to be expanded, not only the intensity $I(s)$ needs to be investigated along the stream lines, but also the spectral index α of the turbulence, i.e. $P(f) = P_0 f^{\alpha}$ (and possible higher order statistical moments), needs to be studied, as this indicates the character of the turbulence, which might change along the stream line. Using MAVEN data, Ruhunusiri et al. [2017] already investigated the spectral index in Mars' magnetosheath for two different scales (MHD and kinetic), but a comparison between Venus and Mars using the same methods has not been performed yet.

Dissemination of the project and milestones

This proposal contains two projects which split up into three main tasks for the candidate. This shall be roughly planned in the following way over the three years (Y) with the expected milestones (M). Naturally, some of the data analysis will be performed simultaneously, which makes this dissemination more a guide-plan than a working-plan.

Y1 – Data collection for both Venus (Venus Express) and Mars (Mars Global Surveyor, MAVEN), acquiring representative data sets for both solar minimum and solar maximum conditions.

- Characterization of the quasi-parallel and -perpendicular bow shock with comparison between Venus and Mars and also a possible dependency of solar activity.

M1
- Presentation of results at international meetings: EGU general assembly and e.g. EPSC;[5]
- Visit to collaborating institute IRF, Kiruna, Sweden;
- First paper on the characterization of the bow shock;

Y2
- Automatic search for mirror mode waves in the magnetosheaths of Venus and Mars.
- Automatic search for ion cyclotron waves in the magnetosheaths.
- Comparison of the behaviour of the MM and IC waves at both planets and for different solar activity.

M2
- Presentation of results at EGU general assembly and e.g. AGU fall meeting;
- Visit to collaborating institute IRAP, Toulouse, France;
- Visit to collaborating institute MPI-MPS, Göttingen, Germany;
- Paper on mirror mode waves at Venus and Mars;
- Paper on ion cyclotron waves at Venus and Mars (possibly combined with MM paper);

Y3
- Characterization of the low frequency turbulence at Venus and Mars using the same analysis method.
- Determination if the development of the turbulent cascade of energy along the streamlines differs for both planets and for different solar activity.

M3
- Presentation of results at EGU general assembly and e.g. Chapman confrerence;
- Visit to collaborating institute U. Buenos Aires, Argentina;
- Paper on the turbulence in the magnetosheath of Venus and Mars;

Data availability

All the data that is needed in this project are publicly available at ESA's Planetary Science Archive (PSA) and at NASA's Planetary Data System (PDS). The plasma data from the ASPERA-4

[5]Because of the vicinity of Vienna the EGU general assembly is a standard meeting at IWF, other meetings mentioned here are examples and will depend on their presence and programme.

instrument on Venus Express are available from the Swedish Institute of Space Physics (IRF) through a direct Python interface. Naturally, as a PI institute, the magnetometer data from Venus Express are also stored at IWF.

Large scale impact of the study

This project studies the structure of the bow shock at Venus and Mars for different parts of the solar activity cycle, at solar minimum and maximum, as studies of mirror mode waves have shown that they behave differently for different solar activity. If the result is that the bow shock is different, this will have consequences not only for Venus and Mars, but for all planetary bow shocks in the solar system, as well as for exoplanets.

If, however, the bow shock does not have a different structure for solar minimum and maximum, then a plasma physical reason will have to be found for the behaviour of the mirror mode waves. This will have an impact on our knowledge of plasma instabilities generated by temperature asymmetries in the plasma. Also the interplay of the two temperature-asymmetry dependent wave modes, MM and IC, and their presence in different locations of the magnetosheath will bring general knowledge about the development of this instability along stream lines. Also, the development of plasma turbulence along streamlines in the magnetosheath is of major importance in fundamental plasma physics.

A similar investigation can be done for the Earth's magnetosheath, in which a grand flotilla of spacecraft is flying. This however, falls outside the scope of this proposal, both based on time investment by the postdoc and because of the extra processes that can happen at the magnetopause of magnetized planets. Day side reconnection processes at magnetized planets will introduce other energy sources for the development of wave modes and turbulence. The results of this project will be able to be applied to steady conditions of the magnetosheath, i.e. for longer periods without reconnection.

Local Infrastructure

The Institut für Weltraumforschung (IWF) of the Österreichische Akademie der Wissenschaften (ÖAW) in Graz is the main space research institute in Austria, with approximately 100 scientists and engineers. The institute is involved in many Earth magnetospheric missions such as Cluster, DoubleStar, THEMIS and MMS, as well as planetary magnetospheric missions such as Venus

Express, Cassinin-Huygens, Rosetta, Bepi-Colombo and JUICE.

The postdoc will work in a team of magnetospheric and plasma physics experts, a.o. **Dr. Tielong Zhang** (PI Venus Express magnetometer, expert in magnetospheres of non-magnetized planets), **Dr. Magda Delva** (CoI Venus Express magnetometer, expert on exospheric plasma pick-up), **Dr. Rumi Nakamura** (CoI Bepi-Colombo magnetometer, expert in magnetospheric physics), **Dr. Ferdinand Plaschke** (expert in magnetopause and magnetosheath physics), **Dr. Zoltan Vörös** (expert on plasma turbulence) and **Dr. Martin Volwerk** (Project leader, CoI on Rosetta Plasma Consortium, expert in Earth and planetary magnetospheric physics). Apart from the project leader, these persons will not have an official role in this project. However, it cannot and shall not be excluded that collaborations will develop.

International Collaborators

This project will have the following international collaborators:

- Dr. Yoshifumi Futaana, PI of ASPERA-4 on Venus Express.
  Swedish Institute of Space Physics (IRF), Kiruna, Sweden
- Dr. Christian Mazelle, Expert in the enviroments of unmagnetized planets, bow shocks
  Astrophysics and Planetary Physics Institute (IRAP), Toulouse, France
- Dr. Cesar Bertucci, Expert in the enviroments of unmagnetized planets
  University of Buenos Aires, Argentina
- Dr. Marcus Fränz, Expert in the interaction between the Sun and the planets and particle instruments
  Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany

Ethical Aspects

There are no ethical aspects to consider in this research.

Finances

This research project seeks for the financing of a Postdoctoral Researcher, for three years at €64.670,00 per year. Included in the financial request are trips to the international collaborators by the postdoc, as support for the research and to build/expand a professional network.

- One week visit to IRF, Kiruna, Sweden for Postdoc and PI: flight, hotel & per diem @ €2500
  At the beginning of the project to learn how to fully exploit the ASPERA plasma data through the dedicated Python software developed at IRF, Kiruna.

- One week visit to IRAP, Toulouse, France: flight, hotel & per diem @ €2000
  Part of Project 1: discussion about the physic of the bow shocks of Venus and Mars with the experts at IRAP.

- One week visit to MPS, Göttingen, Germany: flight, hotel & per diem @ €2000
  Part of Project 2: discussions about the ULF waves in the magnetosheaths with the experts at MPS.

- Two week visit to U. Buenos Aires, Argentina: flight, hotel & per diem @ €3500
  Part of Project 2: discussions on the draping of the solar wind magnetic field and ULF waves with the experts at UBA

Also a request is made for the possibility of having student assitants do research (e.g. for their Master's thesis) within this project at €17.570,00 per year (@ 50%). Both in Project 1 and 2 there are some statistical studies that can be performed by students, after the postdoc has identified and created appropriate data sets. Also, there is the possibility that single interesting events can be worked out for a master's thesis. The specifics of the work for the students will be determined by the postdoc, depending on their interests. The total work load will be about 10% of the submitted project.

Abbreviations

AGU - American Geophysical Union; **CME** - Coronal Mass Ejection; **EGU** - European Geosciences Union; **EPSC** - European Planetary Science Congress; **IC** - Ion Cyclotron (wave); **IMF** - Interplanetary Magnetic Field; **MAVEN** - Mars Atmosphere and Volatile EvolutioN; **MGS** - Mars Global Surveyor; **MHD** - Magneto Hydro Dynamics; **MM** - Mirror Mode (wave); **MPB** - Magnetic Pile-up Boundary; **PSD** - Power Spectral Density; **ULF** - Ultra Low Frequency; **VEX** - Venus Express; **VSO** - Venus Solar Orbital (coordinate system)

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Scientific Curriculum Vitae Dr. Martin Volwerk

Dr. Martin Volwerk was born on 3 August 1963 in Rotterdam, the Netherlands.

1989 – Master's Thesis, Utrecht University, the Netherlands: "Magnetic flaring near Accreting Black Holes."

1993 – PhD Thesis, Utrecht University, the Netherlands: "Strong Double Layers in Astrophysical Plasmas."

1994-1995: Postdoctoral fellow at "Centre d'étude des Environnements Terrestre et Planétaires" in Velizy, France, working on solitary kinetic Alfvén waves with data from the Freja project.

1996-1997: Postdoctoral fellow at the "Lunar and Planetary Laboratory" of the University of Arizona, USA, working on the Io plasma torus in the Jovian magnetosphere using data from the Galieo and Voyager spacecraft.

1997-2001: Postdoctoral fellow at the "Institute for Geophysics and Planetary Physics" at the University of California in Los Angeles working on the interaction between the Jovian magnetosphere with the Galilean moons using Galileo data

2001-2007: Postdoctoral fellow at "Max Planck Institut für Extraterrestrische Physik" in Garching, Germany, stationed at "Institut für Weltraumphysik" of the "Österreichische Akademie der Wissenschaften" in Graz, Austria, working on Earth magnetotail dynamics using data from the Cluster, DoubleStar and THEMIS spacecraft.

2008-present: Scientist at the "Institut für Weltraumforschung" of the "Österreichische Akademie der Wissenschaften" in Graz, Austria, working on magnetotail dynamics using data from the Cluster, DoubleStar and THEMIS spacecraft and on Venus magnetospheric physics using the data from Venus Express, currently working on the Rosette Plasma Consortium data investigating the plasma environment of comet 67P/Churyumov-Gerasimenko.

Refereed Publications: 164 (41 as first author), h-index 37

Co-Investigator:

- Double Star magnetometers
- Venus Express magnetometer
- Rosetta Plasma Consortium
- Juice Magnetometer
- BepiColombo MerMag

Co-supervisor of PhD thesis students:

- MingYu Wu – Development of turbulence along the Earth's magnetotail (USTC, Hefei, China)
- Daniel Schmid – Magnetotail dipolarization fronts (FWF P25257-N27, IWF, KFU Graz)
- Guoqiang Wang – Ultra-low-frequency waves in the magnetotail (USTC, Hefei, China)
- Alexandre de Spiegeleer – Fast flows in the Earth's magnetotail (U. Umeå, Sweden)

Co-supervisor of master's thesis students:

- Daniel Schmid – A statistical and even study of magnetotail dipolarizations
- Relindis Rott – A statistical study of reconnection in the Earth's magnetotail

Financed Projects:

- November 2013 – November 2017: Multi-scale analysis of magnetotail dipolarizations (FWF P25257-N27), PhD project

10 Most Important Publications

Volwerk,M., R. Nakamura, W. Baumjohann, R. A. Treumann, A. Runov, Z. Vörös, T. L. Zhang, Y. Asano, B. Klecker, I. Richter, A. Balogh, and H. Rème, A statistical study of compressional waves in the tail current sheet, *J. Geophys. Res*., **108**, 1429, 2003

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