Ion Temperature Anisotropies in the Venus Plasma Environment

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Ion Temperature Anisotropies in the Venus Plasma Environment

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Disclaimer

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Abstract

Velocity distributions are a key to understanding the interplay between particles and waves in a plasma. Any deviation from a Maxwellian distribution may be unstable and result in wave generation. Using data from the ion mass spectrometer IMA (Ion Mass Analyzer) and the magnetometer MAG on-board Venus Express, ion distributions in the plasma environment of Venus are studied. The focus lies on temperature anisotropy, that is, the difference between the ion temperature parallel and perpendicular to the background magnetic field. This study presents spatial maps of the average ratio between the perpendicular temperature $T_{\perp}$ and parallel temperature $T_{\parallel}$, both for proton and heavy ions (atomic oxygen, molecular oxygen and carbon dioxide). Furthermore average values of $T_{\perp}$ and $T_{\parallel}$ are calculated for different spatial areas around Venus. The results show that proton $T_{\perp}$ and $T_{\parallel}$ are nearly equal in the solar wind. At the bow shock and in the magnetosheath, the ratio $T_{\perp}/T_{\parallel}$ increases to provide conditions favoring mirror mode wave generation. An even higher anisotropy is found in the magnetotail with $T_{\perp}/T_{\parallel} \approx 2$ for both protons and heavy ions.
Acknowledgments

Scientific research is nearly always team work, and this thesis is no exception to that. So obviously there are many people who deserve at least a few lines here:

First of all, I want to thank Gabriella Stenberg for being the best supervisor I could have wished for, really. You encouraged me to be bold and think for myself, making me not only a better student but also showing me how interesting science can be. Without the time under your guidance, I probably would not have decided to become a PhD student in space physics. Thanks for believing in me, for being patient with me and also for listening to my complaints about the bad weather in Kiruna. And all that while keeping up your good mood!

Many thanks also to Mats André from IRF in Uppsala for your explanations and thoughts on the more theoretical side of this project, be it in person or on the phone. You helped me understand a bit better what I was actually doing, and your comments on the text were very useful.

Although not directly involved with this thesis, Martin Wieser recently had some good ideas for a new algorithm to replace the flawed one presented here. Thanks already for explaining it to me, and for helping me implement it in the coming weeks.

This list could go on and on, but to make it short I’ll just give a huge shout-out to all the folks at IRF and LTU, be it researchers, students or campus administration. You are an awesome bunch of people, many of whom helped me here and there a number of times or just had fun chatting, climbing or playing ping pong. I know I’m not the most sociable person, but I definitely enjoyed my time with you here in Kiruna.

Furthermore, I want to thank my family for always being there for me; whether it’s for life advice, earnest talking or just fooling around. You’re the best parents and the best brother in the whole wide world.

Same goes for my extended family, a.k.a. Spacemasters Round 11 and other friends. The last two years have been an incredible experience I will hold dear for the rest of my life. Hiking trips, climbing sessions, barbecue nights, GoT evenings, aurora and midnight sun watching, ... I feel honored to call you my friends and I look forward to many meetups in the future.
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Chapter 1

Introduction

Those who are skeptical about carbon dioxide greenhouse warming might profitably note the massive greenhouse effect on Venus. No one proposes that Venus's greenhouse effect derives from imprudent Venusians who burned too much coal, drove fuel-inefficient autos, and cut down their forests. My point is different. The climatological history of our planetary neighbor, an otherwise Earthlike planet on which the surface became hot enough to melt tin or lead, is worth considering – especially by those who say that the increasing greenhouse effect on Earth will be self-correcting, that we don’t really have to worry about it, or ... that the greenhouse effect is a ‘hoax’.


By the time this thesis was written, the presented quote is already 23 years old; and its author Carl Sagan had passed away 21 years ago. A lot of things have improved since then, especially in the scientific world - with ever more technological advancements and an increasing level of education all over the world, scientific research is becoming more fast-paced than ever. While numerous bright minds continue to succeed in unveiling more and more secrets of our planet and our universe, their past and present, one thing has not improved very much: the public perception of science.

Back in the 1960’s, the whole world was excited about space exploration, culminating in the first Moon landing in 1969. An estimated 530 million people followed the event live on TV, making the broadcast one of the most watched TV events of all time - science was inspiring, science was the talk of the town.

While space exploration continued achieving ever more remarkable feats like sending the *Voyager* spacecraft beyond the termination shock of the solar wind [Stone et al., 2005] or following and landing on a comet with the *Rosetta* mission [Glassmeier et al., 2007], public interest has somehow decreased over the last decades.
Furthermore, the once small group of people suspecting conspiracies behind every scientific achievement has built a broad readership in the depths of the internet - spreading not only baseless counter-theories, but mainly ignorance. While questioning observations and investigating even improbable theories is a crucial part of scientific research, facts have the last word. Ignoring fact and proof while persisting to believe in a maybe more comfortable, but disproved view of the world is not only close-minded, but can as well prove dangers for our planet.

Instead of being rooted in factual reality, society recently seems to have moved towards a different mindset - ‘alternative facts’ and ‘post-factual’ are common buzz words. Conspiracy theories are believed to be just as feasible as already proven scientific models; and people are more concerned with economic, religious, nationalistic and racial quarrels than the welfare of the one world we all live in.

A prominent example of this is global warming - since the days of Carl Sagan, absolutely nothing has changed. World leaders see the global temperatures rising year in, year out - with the American president calling the climate change a ‘hoax’ and planning on severely cutting funds for climate research organizations [e.g., Waldman, 2017] just as I write this line. In this situation, it is of utmost importance for the science community to carry on and bring word of their findings into the world. Every new result might make one or the other reconsider his beliefs and change the world one step at a time. This thesis should be seen as one such fragment of the current scientific progress, joining its voice to all the publications out there in a call for reason.

In this project, ion measurements from the Venus environment, taken by the ASPERA-4 instrument on the Venus Express (VEX) spacecraft, are analyzed statistically. Using about four years of data, the aim is to derive average ion properties in a magnetic reference frame, which allows to compare the properties parallel and perpendicular to the magnetic field. In cases of for example high anisotropy between parallel and perpendicular temperatures, low-frequency ion waves can be generated in the Venusian plasma environment. These waves are connected to different physical processes in the outer atmosphere, such as ionization and pickup of neutral gas particles.

While this project might mainly be perceived as a space physics study, it is strongly connected to atmospheric physics and also represents a small step towards a better understanding of Venus’ atmosphere and its loss of ionized gas to the passing solar wind. And a better understanding of the Venustian atmosphere naturally improves the knowledge about our own planet’s atmosphere - which hopefully helps appreciate and protect our livable environment more.

The following chapter presents a short introduction to the planet Venus and its
plasma environment, before giving a brief overview of fundamental kinetic theory and the physics of velocity distribution functions. With the basic principles covered, the last part of chapter 2 will introduce the most important concepts of low-frequency plasma waves in planetary environments, completing the theoretical background necessary to follow the discussion of this study. In chapter 3, an overview is given over the VEX spacecraft and the operation principles of the instruments of importance to this analysis. Chapter 4 describes the pre-processing of the raw data and thoroughly explains the analysis methods used in this study. This part acts as a description of the programming code written for the analysis. The results are presented, discussed and compared with previous studies in chapter 5. Chapter 6 concludes the study by pointing out possible improvements to this study and highlighting remaining or newly discovered open questions to be answered by future research.
Chapter 2

On Venus and Basic Space Plasma Physics

2.1 Venus - Exploring Our Planetary Neighbor

The planets of the Solar System can be divided into two groups:

- Giant planets in the outer Solar System: Jupiter, Saturn, Uranus and Neptune. They primarily consist of light elements, gravitationally bound in deep atmospheres to a pressurized core of liquidized or solidified H/He.

- Terrestrial planets in the inner Solar System: Mercury, Venus, Earth and Mars; pictured in figure 2.1. They have a much higher density and a rocky surface and are considerably smaller and lighter than the gas planets.

Of the four terrestrial planets, Venus is probably most similar to Earth; a comparison of different properties of Earth, Venus and Mars is given in table 2.1.

Venus is roughly the same size and slightly less dense than Earth and its orbit is only a little closer to the Sun. The inner composition of the two is estimated
Table 2.1: Properties of Venus, Earth and Mars for comparison, compiled from Cole and Woolfson [2013] and Lissauer and De Pater [2013]

<table>
<thead>
<tr>
<th></th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbital Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-major axis (AU)</td>
<td>0.723</td>
<td>1.000</td>
<td>1.524</td>
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<tr>
<td>Sidereal orbital period (a)</td>
<td>0.6152</td>
<td>1.000</td>
<td>1.8809</td>
</tr>
<tr>
<td>Sidereal rotation period (h)</td>
<td>-5832.3</td>
<td>23.93</td>
<td>24.62</td>
</tr>
<tr>
<td><strong>Physical Properties</strong></td>
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<td></td>
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</tr>
<tr>
<td>Mass ((10^{24} \text{ kg}))</td>
<td>4.869</td>
<td>5.972</td>
<td>0.6419</td>
</tr>
<tr>
<td>Equat. radius (km)</td>
<td>6052</td>
<td>6378</td>
<td></td>
</tr>
<tr>
<td>Mean density ((10^{3} \text{ kg m}^{-3}))</td>
<td>5.204</td>
<td>5.520</td>
<td>3.933</td>
</tr>
<tr>
<td>Equa. surface gravity (m s(^{-2}))</td>
<td>8.87</td>
<td>9.78</td>
<td>3.69</td>
</tr>
<tr>
<td><strong>Atmospheric Properties</strong></td>
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<td></td>
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<td>Bond Albedo</td>
<td>0.75</td>
<td>0.306</td>
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</tr>
<tr>
<td>Surface Temperature (K)</td>
<td>737</td>
<td>288</td>
<td>215</td>
</tr>
<tr>
<td>Surface Pressure (bar)</td>
<td>92</td>
<td>1.013</td>
<td>0.0064</td>
</tr>
<tr>
<td>CO(_2) abundance (vol. %)</td>
<td>96</td>
<td>0.033</td>
<td>95</td>
</tr>
<tr>
<td>N(_2) abundance (vol. %)</td>
<td>3.5</td>
<td>78</td>
<td>2.7</td>
</tr>
<tr>
<td>O(_2) abundance (vol. %)</td>
<td>-</td>
<td>21</td>
<td>0.13</td>
</tr>
<tr>
<td>H(_2)O abundance (ppm)</td>
<td>30</td>
<td>$&gt;1000$</td>
<td>100</td>
</tr>
<tr>
<td><strong>Magnetic Field Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative magnetic moment</td>
<td>&lt; 4 \cdot 10^{-4}</td>
<td>1</td>
<td>&lt; 2 \cdot 10^{-4}</td>
</tr>
<tr>
<td>Equat. magnetic field ((10^{-4} \text{ nT}))</td>
<td>&lt; 0.0003</td>
<td>0.305</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

to be quite similar, featuring a metal core and a rocky surface. Nevertheless, the conditions on the Venusian surface are vastly different from Earth; a thick atmosphere mainly composed of CO\(_2\) causes a great surface pressure and a strong greenhouse effect, resulting in a high surface temperature. Clouds of sulfuric acid keep the surface hidden to an outside observer at all times, causing acid rain which evaporates before even reaching the ground.

Most interesting from a plasma physics point of view however are the differences in the magnetic fields. While Earth features a strong intrinsic magnetic moment, caused by dynamo processes in its metal core, the Venusian magnetic field is barely measurable. The magnetized solar wind can therefore strongly interact with the Venusian atmosphere. The implications and effects of this are described in 2.3.
Table 2.2: Average solar wind and IMF conditions at Venus, Earth and Mars [Slavin and Holzer, 1981; Kivelson and Russell, 1995]

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (km s(^{-1}))</td>
<td>430</td>
<td>430</td>
<td>430</td>
</tr>
<tr>
<td>Density (cm(^{-3}))</td>
<td>14</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Proton temperature (eV)</td>
<td>8.6</td>
<td>6.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Electron temperature (eV)</td>
<td>14.6</td>
<td>12.9</td>
<td>11.2</td>
</tr>
<tr>
<td>IMF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnitude (nT)</td>
<td>10</td>
<td>6</td>
<td>3.3</td>
</tr>
<tr>
<td>Spiral angle (°)</td>
<td>36</td>
<td>45</td>
<td>57</td>
</tr>
</tbody>
</table>

Due to its closeness to Earth and the many similarities between Venus and our home planet, many early interplanetary missions were undertaken to unveil the planet’s secrets. The missions included flyby maneuvers, orbiters, atmospheric probes and landers covering a wide range of scientific research.

The first notable missions were flybys of several Mariner space probes [e.g. Fjeldbo et al., 1971] as well as orbiters and landers from the Venera program [e.g. Keldysh, 1977], conducting first descents and surface analyses as well as transmitting first images from the surface.

Following in the late 1970’s, Pioneer Venus reached Venus [Colin, 1980]. The lander module entered the atmosphere to conduct important measurements while the orbiter module was operated until 1992, observing the atmosphere, surface and plasma environment for a full solar cycle.

Magellan was a mission of high importance for the geophysical community. The orbiter spent four years in orbit, collecting gravimetric data and mapping the Venusian surface utilizing a synthetic aperture radar [Saunders et al., 1992].

The latest notable Venus mission, Venus Express (VEX), was focused on investigating the Venusian atmosphere and plasma environment [Svedhem et al., 2007]. Details of this mission are given in chapter 3.

2.2 Solar Wind and Interplanetary Magnetic Field

The Sun’s outer layer, the corona, shows very high temperatures of the order of 10\(^6\) K. Charged particles are therefore highly energetic and able to overcome the Sun’s gravity; magnetic fields created by convection inside the Sun further accelerate escaping particles. Leaving the corona at supersonic speeds, a constant
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Figure 2.2: Spiral interplanetary magnetic field lines frozen into the radial solar wind expansion [Parker, 1963].

Figure 2.3: Heliospheric current sheet [Kallenrode, 2013].

As the solar wind can be described as the Sun’s corona being blown outwards, its composition is naturally the same as the corona’s composition. The most prevalent particle types are electrons and protons resulting from the ionization of hydrogen; about 8% of solar wind particles are He$^{2+}$ particles. Heavier particles like ions of carbon, nitrogen, oxygen and silicon can only be found in trace amounts. During coronal mass ejections (CMEs), the solar wind composition is substantially different - the share of alpha particles can increase to 30% and higher amounts of heavier ions can be observed [Kallenrode, 2013, Ch. 6.2].

The radial speed of the solar wind depending on the distance from the Sun can be approximated using Parker’s hydrodynamic corona model [Parker, 1958]. According to this model, the solar wind accelerates directly after leaving the Sun’s corona until it reaches a distance of about 40R$_\odot$. From there, it continues streaming at a near constant speed until its pressure and density decrease too far to allow supersonic flow - a termination shock forms (~70 AU). The solar wind is slowed down and eventually stopped by the pressure of the interstellar gas at the heliopause (~100 AU).

The solar wind is a plasma with very high conductivity. Therefore, the motion of the plasma couples to the deformation of the magnetic field such that the field lines follow the motion of the transported matter. This effect is called ‘frozen-in magnetic field’ and allows the Sun’s magnetic field to be carried along with the
Figure 2.4: Formation of an induced magnetosphere around an unmagnetized planet with an atmosphere. The process begins with a planet with a neutral atmosphere (a), which is ionized by solar radiation (b). The conductive ionosphere acts as an obstacle to the solar wind (c) and an induced magnetosphere is created (d), bending the magnetic field lines and forcing the solar wind to decelerate at the bow shock. From Russell et al. [2016].

Due to the 27-day rotation of the Sun the IMF is not a simple radial field, but instead has spiral shape as shown in figure 2.2. This is because the Sun slowly rotates while plasma is being radially ejected - and with the Sun’s rotation the base of the plasma stream also rotates. Similar to water flowing out of a rotating hose, the magnetic field line frozen into the moving plasma becomes curved.

Additionally, the Sun’s magnetic dipole is not parallel to its rotation axis. The heliospheric current sheet (see figure 2.3), marking the ‘neutral’ plane between the north and south magnetic poles of the Sun, is therefore not in the ecliptic plane. Furthermore, the inhomogeneous solar magnetic field leads to a ‘wavy’ shape of the current sheet [Kallenrode, 2013] - the orientation of the IMF is therefore very changeable throughout time.

2.3 The Induced Magnetosphere of Venus

During its outward travel through the Solar System, the solar wind encounters different obstacles which affect its flow in many different ways.

On one hand magnetized bodies like Earth and Jupiter are surrounded by their
own intrinsically maintained magnetic field which interacts with charged particles of the solar wind through numerous and highly complex processes - many of which are not fully understood yet.

On the other hand there is a variety of unmagnetized objects which the solar wind passes. Lunar-type objects like the Earth’s moon exhibit neither a magnetic field nor an atmosphere, but the absorption of solar wind particles impacting the surface leads to the formation of a wake. Downstream, a slight disruption in the frozen-in magnetic field can be measured as the IMF diffuses through the weakly conducting body without much hindrance. Comets have a variable atmosphere depending on their distance to the Sun - with a more prominent atmosphere building up, the solar wind is mass-loaded by atmospheric ions and deflected.

Lastly there is Venus-type solar wind interaction, graphically explained in figure 2.4. Venus is covered with a thick atmosphere, but lacks a strong intrinsic magnetic field. In the upper layers of the atmosphere, neutral particles are ionized through photoionization; creating a large ionosphere. The magnetized plasma flow of the solar wind induces currents in the Venusian ionosphere and thereby creates an induced magnetosphere - the IMF carried in the solar wind drapes around the planet. The boundary between solar wind plasma and the upper ionosphere is referred to as induced magnetosphere boundary (IMB) and acts as an obstacle for the solar wind, which leads to the formation of a bow shock above the IMB. The bow shock is positioned in the region where the supersonic solar wind is decelerated to subsonic speeds and marks the boundary between undisturbed solar wind (upstream) and the disturbed magnetosheath plasma (downstream).

The shape and structure of the Venusian induced magnetosphere as shown in figure 2.4(d) are very similar to the Earth’s magnetosphere, but its size is considerably smaller. While the subsolar magnetopause of the Earth, the boundary layer between solar wind plasma and planetary plasma, is located at about 10 Earth radii from the planet’s center, the IMB of Venus is a mere 300 km from the surface (about 1.05 Venus radii from its center). All of the Earth’s atmosphere is therefore easily contained in the magnetosphere even in times of high solar activity, whereas the Venusian upper atmosphere is regularly exposed to the passing solar wind plasma. This strongly impacts the atmospheric properties and composition of Venus and leads to a constant outflow of charged particles picked up and carried away by the solar wind [Baumjohann and Treumann, 1997; Russell et al., 2016].
2.4 Kinetic Theory and Phase Space

A plasma is a medium entirely composed of charged particles which are not bound to each other, but interact strongly. Simply the proximity of equal or opposite charges or the relative motion of any one charged particle will affect the plasma environment by inducing electromagnetic fields and forces. The most straightforward approach to physically describing such a medium is to follow a single particle along its trajectory in time and space, describing how its surroundings determine its motion and how the presence of the particle affects the environment.

While this theory of single particle motion might be very exact and useful, it is not very well suited for the description of a macroscopic plasma. The reason for this is the collective behavior of a plasma due to the manifold interactions between its high number of particles - and solving every particle’s equation of motion requires taking into account the microscopic fields generated by all particles in the plasma. From a single particle point of view, calculating bulk properties of a plasma quickly turns into a futile task overwhelming even the most powerful computer.

It is therefore suitable to describe a plasma in terms of phase space density. Phase space is a hypothetical six-dimensional space combining the time dependent position \( \mathbf{x}_i(t) \) and velocity \( \mathbf{v}_i(t) \) of each particle. The phase space coordinate axes are then \((\mathbf{x}, \mathbf{v})\); a particle at a certain point in time is represented as one point in a phase space volume element \( d\mathbf{x}d\mathbf{v} \).

The exact phase space number density of a single particle \( i \) is then given by

\[
F_i(\mathbf{x}, \mathbf{v}, t) = \delta(\mathbf{x} - \mathbf{x}_i(t)) \delta(\mathbf{v} - \mathbf{v}_i(t)),
\]

(2.1)

with \( \delta(\mathbf{x} - \mathbf{x}_i) = \delta(x - x_i)\delta(y - y_i)\delta(z - z_i) \) and \( \delta(\mathbf{v} - \mathbf{v}_i) \), similarly, as three-dimensional Dirac delta functions. The total exact phase space number density of a plasma is the sum over all single particle densities,

\[
F(\mathbf{x}, \mathbf{v}, t) = \sum_i \delta(\mathbf{x} - \mathbf{x}_i(t)) \delta(\mathbf{v} - \mathbf{v}_i(t)).
\]

(2.2)

From this exact number density, we can define an average phase space density, \( \langle F(\mathbf{x}, \mathbf{v}, t) \rangle = f(\mathbf{x}, \mathbf{v}, t) \), also known as phase space distribution function.

2.5 A Variety of Different Velocity Distributions

A good way to handle velocity distributions is to investigate at them at a fixed position - effectively reducing the problem to three dimensions. Assuming a (locally) spatially homogeneous and stationary plasma, we obtain velocity distribu-
Maxwellian Distributions

In a gas, single molecules frequently collide with each other - exchanging energy and changing their direction of motion with every collision. While their kinetic energies might be different in an arbitrary initial state, the frequent collisions will eventually establish an equilibrium distribution. The kinetic energies of all molecules are then distributed around the average energy of random motion, which is measurable through the temperature of the gas. This distribution is called a Maxwellian distribution [Kivelson and Russell, 1995].

Even though many space plasmas are collisionless, their particle velocities are, in a thermal equilibrium state, often distributed randomly around the average velocity in the same shape. The one-dimensional equilibrium velocity distribution function for a plasma at rest is then

\[
f(v_x) = \frac{n}{(\pi \langle v_x^2 \rangle)^{1/2}} \exp \left(-\frac{v_x^2}{\langle v_x^2 \rangle}\right)
\] (2.3)

with \(v_x\) as one component of the velocity, \(\langle v_x^2 \rangle\) as the velocity spread in the same direction and \(n\) as the local plasma density.

In three dimensions, the isotropic Maxwellian velocity distribution as a function
Figure 2.6: Anisotropic bi-Maxwellian (left) and drifting Maxwellian (right) velocity distributions. Modified from Baumjohann and Treumann [1997].

of scalar velocity $v$ becomes

$$f(v) = \frac{n}{(\pi \langle v \rangle^2)^{3/2}} \exp\left(-\frac{v^2}{\langle v \rangle^2}\right); \quad (2.4)$$

where the velocity spread $\langle v \rangle$ can be identified as the thermal velocity

$$\langle v \rangle = v_{th} = \left(\frac{2k_B T}{m}\right)^{1/2}. \quad (2.5)$$

With the same assumptions, the Maxwellian velocity distribution for plasma with a constant bulk velocity can be derived, the so called drifting Maxwellian velocity distribution. In three dimensions, a simple replacement of $v$ by $v - v_0$ will yield the desired general distribution function

$$f(v) = \frac{n}{(\pi v_{th}^2)^{3/2}} \exp\left(-\frac{(v - v_0)^2}{v_{th}^2}\right). \quad (2.6)$$

Sketches of both a Maxwellian and a drifting Maxwellian velocity distribution are shown in figure 2.5.

**Anisotropic Distributions**

In the presence of magnetic fields a plasma can show different properties parallel and perpendicular to the magnetic field; for example the plasma might exhibit
different drift velocities \((v_\parallel, v_\perp)\) and thermal velocities \((v_{\text{th}}\parallel, v_{\text{th}}\perp)\) in the two different directions due to e.g., a gyrating motion about the magnetic field lines. Since parallel and perpendicular velocity components are independent, the equilibrium distribution in a magnetized plasma can be approximated by a product of two Maxwellians,

\[
f(v_\parallel, v_\perp) = \frac{n}{(\pi^3 v_{\text{th}}\parallel v_{\text{th}}\perp)^{1/2}} \exp \left( -\frac{v_\parallel^2}{v_{\text{th}}\parallel} - \frac{v_\perp^2}{v_{\text{th}}\perp} \right),
\]

(2.7)
a so called bi-Maxwellian distribution [Kivelson and Russell, 1995]. The left panel of figure 2.6 shows an ideal bi-Maxwellian velocity distribution with a higher perpendicular than parallel thermal velocity, deforming the circular contours of constant \(f\) of an isotropic Maxwellian into elliptic shapes.

To model a Maxwellian velocity distribution with a preferred drift direction with respect to the magnetic field, equation (2.7) can be modified to include constant drift velocities in parallel and perpendicular directions \((v_0\parallel, v_0\perp)\). Similarly to (2.6) we obtain

\[
f(v_\parallel, v_\perp) = \frac{n}{(\pi^3 v_{\text{th}}\parallel v_{\text{th}}\perp)^{1/2}} \exp \left( -\frac{(v_\parallel - v_0\parallel)^2}{v_{\text{th}}\parallel} - \frac{(v_\perp - v_0\perp)^2}{v_{\text{th}}\perp} \right)
\]

(2.8)
for the general form of the anisotropic drifting Maxwellian. The right panel of figure 2.6 shows a drifting Maxwellian with a greater than zero average particle velocity perpendicular to the magnetic field.

**Loss Cone Distributions**

In planetary magnetospheres, particles traveling almost parallel to the magnetic field can follow the field lines towards the planet. If the angle between the particle’s velocity vector and the magnetic field direction, the so called pitch angle, is small enough, the magnetic mirror force is not strong enough to reflect the particle above the planet’s atmosphere. When a particle enters the atmosphere it starts to collide with gas molecules, is eventually neutralized and will not travel back up along the magnetic field line. This strongly influences the local velocity distribution function and often results in a loss cone distribution with a shape similar to that shown in figure 2.7. The shape of empty and partially filled loss cones around the \(v_\parallel\)-axis can be modeled [e.g., Dory et al., 1965], providing means for investigating relations between atmospheric properties, velocity distributions and plasma wave generation.
2.6 Measuring Velocity Distributions in Practice

At its core a distribution function is a probability distribution in phase space and as such not a measurable quantity. Closely related and in principle straightforward to measure is the differential particle flux, which can be related to a velocity distribution.

Differential particle flux $J(W, \alpha, x)$ describes the flux of particles at a certain energy $W$, pitch angle $\alpha$, and position $x$. In reality the differential flux will be measured at an approximate position and within a small energy range $dW$ and a solid angle $d\Omega$.

This same flux can also be derived in phase space; particles in a velocity interval $dv$ arriving from a solid angle $d\Omega$ will result in a number density of

$$dn = f(v, x) \, dv$$

for particles with velocity $v$ in a phase space volume element. In spherical coordinates, this can be rephrased as

$$dn = f(v, x) \, vd\varphi \, v \sin \vartheta d\vartheta \, dv = f(v, x) v^2 \, dv \, d\Omega$$

using $d\Omega = \sin \vartheta \, d\vartheta \, d\varphi$ as the differential of the solid angle. Multiplying this differential number density by $v$ yields the differential flux of particles with velocity $v$; it follows

$$J(W, \alpha, x) dW d\Omega = f(v_\parallel, v_\perp, x) v^3 \, dv \, d\Omega.$$  \hspace{1cm} (2.9)
Rewriting the energy interval $dW$ on the left-hand side to $dW = mv dv$ allows for a further simplification so that

$$J(W, \alpha, x) = \frac{v^2}{m} f(v_\parallel, v_\perp, x)$$  \hspace{1cm} (2.10)

results as the relation between differential flux and velocity distribution [Kallenrode, 2013].

### 2.7 Low-Frequency Waves and Instabilities

Waves are a very common occurrence, both on Earth and in the wide universe. While we might know for example sound waves and light waves from our daily lives on Earth, plasma waves are neither humanly perceivable nor are they commonly encountered on or near the surface of our planet. With the first spacecraft leaving humankind’s natural environment however, investigating plasma and its complex behavior became a possibility.

Just a very rough overview over all the different plasma waves which have been observed and/or theoretically explained would go far beyond the scope of this thesis. This introduction on plasma waves is therefore limited to the formation and characterization of two low-frequency wave modes commonly observed in planetary plasma environments.

Plasma waves are commonly observed by measuring oscillations in the magnetic field $B$ and/or the electric field $E$. While providing valuable information about the occurrence and properties of waves, the generation mechanisms cannot be thoroughly investigated this way.

This is where velocity distributions become interesting, as they provide valuable information about the current state of the local plasma environment. Velocity distributions allow us to investigate how certain plasma conditions with their specific particle populations lead to the formation of certain plasma waves; and how these plasma waves impact the environment they propagate through in return.

An isotropic Maxwellian distribution contains no excess free energy and is therefore not expected to generate plasma waves. Any sort of anisotropic distribution on the other hand contains free energy and is unstable to the generation of different plasma waves in order to return into a stable isotropic state.

This study is focused on investigating bi-Maxwellian velocity distributions with different temperatures parallel and perpendicular to the magnetic field. This certain type of anisotropic distribution is likely to create ion cyclotron (IC) and mirror mode (MM) waves, both of which are introduced in the following sections.
Ion Cyclotron Waves

IC waves are transverse electromagnetic waves oscillating at frequencies slightly below the ion cyclotron frequency in the plasma rest frame. They travel parallel to the magnetic field, are typically left-hand polarized and can be observed in the vicinity of planets, moons and comets [Russell et al., 2016].

A common scenario which can lead to IC wave generation occurs in plasma environments where ion pickup takes place. Newly ionized particles in the outer atmosphere of a planet are accelerated by the convection electric field and create a secondary unstable population with a high velocity component perpendicular to the magnetic field. The velocity distribution now contains excess free energy which is transferred into IC waves. While traveling along the magnetic field, the IC waves are damped by the plasma environment - heating the distribution of the ambient plasma and making it more Maxwellian [Russell et al., 2008]. This way, IC waves are acting to regain the equilibrium state of the plasma.

As different ions have their own gyrofrequencies, observations of IC waves can be very useful to characterize the composition of the plasma environment and especially particle outflow from the outer atmosphere. At Venus for example, proton cyclotron (PC) wave observations upstream of the bow shock proved that the hydrogen exosphere reaches out far beyond the IMB or even the bow shock [Delva et al., 2011], leaving it unprotected against ionization and pickup and thereby accounting for a continuous hydrogen outflow. Even plasma regions unreachable by spacecraft can be investigated due to the IC waves’ distinct propagation along the magnetic field, which allows to estimate the region of their origin [Russell et al., 2008, 2016].

An example of a PC wave observation taken upstream of the Venusian bow shock is shown in figure 2.8. A frequency analysis (bottom panel) clearly shows an enhanced wave power at frequencies slightly below the local proton gyrofrequency for left-hand polarized waves.

Mirror Mode Waves

MM waves are compressional waves moving along the magnetic field. Their frequency is very low, similar to the IC wave frequency; typically in the order of $10^{-1}$ Hz. They are also generated by ion distributions with a temperature anisotropy, and mostly observed in planetary magnetosheaths [Russell et al., 2016].

In the magnetosheath, a temperature anisotropy can be created by different processes apart from ion pickup. For instance, ions are reflected at the bow shock under certain conditions, increasing their pitch angle and thereby their gyratory
Figure 2.8: Proton cyclotron (PC) wave observation upstream of Venus on the 6th of July 2006 (00.40 to 00.50 UTC). The top panel shows the three components of the magnetic field measurements and the total magnetic field during the period of observation. The bottom panel shows the compressional power and the left- and right-hand polarized transverse power as a function of frequency as obtained through a Fourier transform. The dashed vertical line marks the local PC frequency. The strong increase in left-hand polarized transverse wave power slightly below the local PC frequency is due to PC waves. From [Delva et al., 2008b].
Figure 2.9: MM wave observation on the 5th of May 2006. The top panels show the magnetic field components and magnitude as well as their low-pass filtered curves (used as a baseline to determine the fluctuation amplitudes) while the spacecraft moves from the solar wind (SW) through the bow shock (BS) into the magnetosheath (MS). The lower two panels show the magnetic field fluctuation $\Delta B/B$ as well as the angle $\theta$ between the maximum variance direction and the mean magnetic field (dots) and the angle $\Phi$ between the minimum variance direction and the mean magnetic field (crosses). MM observations are marked with a grey overlay. From Volwerk et al. [2008a].
motion and perpendicular temperature. Close to the planet, a compression of the magnetosheath leads to an increase in the magnetic field strength - increasing the ions' pitch angle due to the mirror force [e.g., Volwerk et al., 2008b; Baumjohann and Treumann, 1997]. Both these effects create anisotropic velocity distributions with an enhanced perpendicular ion temperature $T_\perp$ compared to the parallel temperature $T_\parallel$.

From the traditional description of the mirror instability as a fluid magnetohydrodynamic (MHD) instability it can be derived that if

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

holds, the interplay between dynamic/thermal and magnetic pressure can generate compressional proton MM waves [Hasegawa, 1969]. Equation (2.11) is therefore the theoretically derived instability criterion for the generation of MM waves. Here $\beta_\perp$ denotes the perpendicular ion plasma beta,

$$\beta_\perp = \frac{n k_B T_\perp}{B^2/2\mu_0}$$

with $T_\perp$ as the perpendicular ion temperature. A detailed description of the MM instability from different points of view is given in Southwood and Kivelson [1993].

MM waves have been observed in the Venusian magnetosheath and both case
studies and statistical studies have been performed [e.g., Volwerk et al., 2008a, 2016]. An example of an MM wave observation is shown in figures 2.9 and 2.10. The grey areas mark where MM waves have been observed. It is clearly visible that the angle between the maximum variance direction and the magnetic field $\theta$ (black dots in the bottom panel) is nearly zero, indicating the movement of a compressional wave along the magnetic field. At the same time, the fluctuation of the magnetic field $\Delta B/B$ is strongly increased.
Chapter 3

Venus Express: Europe’s First Venus Mission

Venus Express (VEX) [Titov et al., 2006; Svedhem et al., 2007] was the first European-led mission to the planet Venus. Planned as a follow-up mission after Mars Express (MEX) [Chicarro et al., 2004], it was possible to use a slightly modified version of the MEX satellite bus for this Venus mission. Similar instrumentation allowed for unprecedented comparative studies and resulted in lower development costs and a shorter time frame from conception of the project until launch [Fabrega et al., 2003]. From the mission proposal in 2001 it took only about four years to ready the spacecraft for launch, taking place at the Baikonur Cosmodrome in Kazakhstan in November 2005. VEX arrived at Venus in April 2006 and was inserted into a highly-elliptical 24-hour quasi-polar orbit with an apocenter distance of 66,000 km and a pericenter distance of 250 – 350 km enabling a wide range of scientific observations [Titov et al., 2006].

The mission was planned to last for only 500 Earth days, but it was extended several times until contact with the spacecraft was lost in November 2014. The spacecraft was expected to be naturally deorbited by February 2015.

3.1 Objectives and Instrumentation

Many previous orbiter or lander missions have investigated the Venusian surface and atmosphere. Extensive radar mapping broadened our understanding of geology and geophysics on Venus, while space- and ground-based observations analyzed the highly complex and exotic atmosphere of the Earth’s sister planet.

VEX sought to support and enhance the previously taken measurements to contribute to a thorough characterization of atmospheric composition, structure, and dynamics. A number of instruments, both newly developed ones and modified ones from MEX, were on board to conduct high quality atmospheric measurements:

- **PFS** (Planetary Fourier Spectrometer), a high-resolution IR Fourier spec-
• **SPICAV/SOIR** (Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus / Solar Occultation at Infrared), a suite of three UV and IR spectrometers for occultation, limb and nadir geometry studies [Bertaux et al., 2007],

• **VERA** (Venus Express Radio Science Experiment), a radio experiment to study atmosphere and ionosphere, gravitational anomalies and the solar corona [Häusler et al., 2006],

• **VIRTIS** (Visible and IR Thermal Imaging Spectrometer), a near-IR imaging and high-resolution spectrometer [Drossart et al., 2007].

To understand the origin and evolution of the Venusian atmosphere it was also of high priority to study the plasma environment of Venus with a focus on escape processes [Svedhem et al., 2007]. This is particularly interesting in comparison to Earth’s plasma environment and atmospheric properties, as Venus and Earth are very similar in size, density, and location in the Solar System. For this purpose, VEX was additionally equipped with

• **ASPERA-4** (Analyzer of Space Plasmas and Energetic Atoms), a suite of particle detectors for neutral atoms, electrons, and ions [Barabash et al., 2007],

• **MAG** (Magnetometer), a two-point 3-axis fluxgate magnetometer [Zhang et al., 2006].

Additionally, **VMC** (Venus Monitoring Camera) is a wide-angle camera for imaging in different wavelengths used for atmospheric studies and surface mapping [Markiewicz et al., 2007]. In this work, only data from MAG and ASPERA-4 were used.

### 3.2 ASPERA-4: Analyser of Space Plasmas and Energetic Atoms

**Overview**

ASPERA-4 was intended to study the solar wind-atmosphere interaction and characterize the plasma and neutral gas environment in the near-Venus space [Barabash et al., 2007]. Its objectives are very similar to those of its predecessor, ASPERA-3 on MEX - as is the instrument itself. Apart from slight modifications
accounting for the different thermal and radiation environment, ASPERA-4 is a direct replica of ASPERA-3.

The instrument package includes four sensors for energetic neutral atom (ENA), electron and ion detection. The Neutral Particle Imager (NPI) and the Neutral Particle Detector (NPD) both measure ENA flux with a high angular resolution (NPI) and a high velocity and mass resolution (NPD). The Electron Spectrometer (ELS) is mounted on the main unit of the instrument together with the NPI, NPD, and the Digital Processing Unit (DPU). The main unit features a turntable-construction to provide full $4\pi$ scanning coverage.

IMA, the Ion Mass Analyzer, is a mechanically separate unit for measuring ion mass compositions [Barabash et al., 2007]. In this thesis only IMA data is used from the ASPERA-4 instrument package; the IMA sensor is therefore described in more detail below.

**IMA: Ion Mass Analyser**

IMA is an imaging mass spectrometer capable of measuring three-dimensional ion flux distributions over wide ranges in particle mass and energy. A diagram is shown in figure 3.2.

Particles enter the radially symmetric instrument through an external grounded grid and an electrostatic deflector system which can vary the elevation angle
between $\pm 45^\circ$, resulting in a total field of view of $90^\circ \times 360^\circ$. The deflector system utilizes two curved electrodes to select an elevation angle depending on the inter-plate voltage. Scanning occurs through 16 elevation steps.

After passing the deflector system, the particles enter the top-hat electrostatic analyzer composed of two curved concentric electrodes. The voltage between the plates allows only particles with a certain energy per charge $E/q$ to pass. It is to note that the electrostatic analyzer and the deflector system voltages are coupled - particles with different energies arriving from the same elevation angle require different deflector voltages in order to pass. IMA covers an energy range of $10\text{ eV}$ per charge to $30\text{ keV}$ per charge in 96 logarithmically equidistant steps with an energy resolution of $\Delta E/E = 0.07$.

The momentum per charge $p/q$ of particles exiting the electrostatic analyzer is then determined in the momentum analyzer consisting of a circular array of 16 magnets as shown in figure 3.2. At this point all particles will have the same energy per charge, but different masses/velocities. The magnetic field in the momentum analyzer causes the Lorentz force $F = qvB$ to act on the particles, causing a radial acceleration $a = qvB/m$ to bend their trajectories. The resulting radial deviation codes the particle mass per charge, with heavy particles staying

Figure 3.2: Schematical cross section of the IMA sensor with example ion trajectories (left), top view cross section of the magnetic separator (right) [Barabash et al., 2007].
near the center and light particles moving further outward.

A multichannel plate (MCP) with 16 azimuthal sectors of 22.5° each and 32 rings records ion impacts. The azimuth angle resolution is therefore 22.5° while IMA is able to distinguish between ions with different unit mass to unit charge ratios such as \( \frac{m}{q} = 1, 2, 4 \) (\( \text{H}^+ \), \( \text{He}^{2+} \), and \( \text{He}^+ \) respectively) and heavier compounds with \( \frac{m}{q} = 8, 16, 32 \) and \( > 40 \) (\( \text{O}^{2+} \), \( \text{O}^+ \), \( \text{O}_2^+ \), and \( \text{CO}_2^+ \) respectively). A distinction of different ion types is not always possible however, as for example \( \text{H}_2^+ \) and \( \text{He}^{2+} \) both have the same mass to charge ratio \( \frac{m}{q} = 2 \). Their radial deviation will therefore be the same and their fluxes will add up in the corresponding mass-azimuth bin.

Each measurement has an exposition time of 125 ms during which all mass and azimuth bins are measured for a certain energy-elevation pair. For a full measurement over all energies and elevations, this adds up to

\[
96 \text{ energy bins} \times 16 \text{ elevation bins} \times 125 \text{ ms} = 192 \text{ s}.
\]

To also allow measurements of light particles with low energies, an acceleration voltage can be applied between the electrostatic analyzer and the momentum analyzer. This increases the gyroradius of for example low energy protons such that they hit one of the MCP’s outer mass rings instead of colliding with the instrument wall [Barabash et al., 2007].

### 3.3 MAG: Dual Fluxgate Magnetometer

The magnetometer on VEX is based on the ROMAP magnetometer on the Rosetta lander [Auster et al., 2007]. It consists of two triaxial fluxgate magnetometers, one of which is mounted on an extendable boom with a length of 1 m on the outside of the spacecraft. The second sensor is directly attached to the top panel of VEX, measuring the spacecraft’s magnetic field and allowing for corrections due to the disturbances caused by VEX itself. This is necessary as the ambient magnetic field is small compared to the field brought in by the space probe.

The sensor operates at a frequency of up to 128 Hz with a default resolution of 8 pT and a default range of ±524 nT [Zhang et al., 2006]. In this study cleaned and averaged data with a resolution of 4 s is used.
Chapter 4

Analyzing Ion Flux Measurements

4.1 Data Acquisition and Processing

For more than 8 years of time in orbit, ASPERA-4 on VEX provided great amounts of valuable data of the Venusian plasma environment. This analysis takes into account all IMA measurements between the 14th of May 2006 and the 28th of December 2009, as pre-processed data was available for this whole period. With about 3.5 years of continuous coverage, the dataset is easily big enough to justify reliable statistical analyses. This section gives a short overview on the accumulation and processing of data, tracing the data path from its measurement up to the beginning of this analysis.

In-Situ Measurement Data

During the exposition time of each measurement, the number of impact events on the MCP of IMA is counted by the DPU and saved into a data package. Each measurement at a certain energy and elevation angle yields an array representing the physical shape of the MCP; it includes the counts for

$$32 \text{ mass bins} \times 16 \text{ azimuth bins}.$$ 

A full scan over all energy and elevation bins adds up to a four-dimensional array of the size

$$32 \text{ mass bins} \times 16 \text{ azimuth bins} \times 96 \text{ energy bins} \times 16 \text{ elevation bins}.$$ 

These arrays are downlinked to and further processed on Earth.

Raw Data Processing

For many studies, including ours, it is important to consider each ion species separately. For a full IMA scan one can sum over all azimuth and elevation
angles to get a so-called energy-mass matrix like shown in figure 4.1. The lines in figure 4.1 indicate the calibrated position of protons and heavy ions respectively.

This plot allows to determine mass ranges in which a certain ion species is generally observed in order to extract datasets of counts including only this species. The data are thereby reduced to the dimensions

$$16 \text{ azimuth bins} \times 96 \text{ energy bins} \times 16 \text{ elevation bins},$$

for each ion species.

### 4.2 Obtaining Velocity Distributions

The data used for this analysis are pre-processed and saved in Matlab files. They include separate variables for $\text{H}^+$, $\text{He}^+$ and $\text{He}^{2+}$. Different heavy ions cannot be distinguished due to the mass resolution of IMA, so they are combined into one additional ‘Heavy ion’ data variable.

While the raw data files include simply the number of counts for each azimuthal sector, each mass channel, each energy and each time instance, the data

---

**Figure 4.1:** Mass-energy plot calculated from a full IMA scan over all elevation and azimuth angles. White lines with asterisks mark the mass channel at which protons or heavy ions ($m/q = 16$) are expected to be observed in each energy bin. This example shows strongly increased proton fluxes over a wide energy range, while no significant number of heavy ions has been measured.
in the processed Matlab files have been converted to fully differential flux in units of \([\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{eV}^{-1}]\) by applying the geometric factor of the sensor. For each species, an array containing the differential flux distribution over the 16 azimuthal sectors and the 96 energy steps is provided for each 12-s energy sweep. Additional variables give information about the pointing direction of the azimuthal sectors (thereby including information about the elevation angle at the time of measurement) as well as the spacecraft position and velocity in the Venus Solar Orbit (VSO) reference frame.

In the VSO frame, the \(X_{\text{VSO}}\) axis is directed from Venus’ center of gravity towards the Sun. This reference frame is further defined based on the orbital plane of Venus, with \(Z_{\text{VSO}}\) pointing northward and perpendicular to the orbital plane and \(Y_{\text{VSO}}\) completing the right-hand system. The orbit of Venus follows the \(-Y_{\text{VSO}}\) direction; \(+Y_{\text{VSO}}\) points towards the dawn side. A detailed description of the VSO reference frame is given in appendix A.

From these flux measurements, we now want to calculate an ion velocity distribution. The result should look similar to one of the idealized examples of velocity distributions in figures 2.5 to 2.7. These distributions will then be analyzed as described in the following section 4.3 in order to determine possible anisotropies which can be responsible for the generation of plasma waves.

First we need to correct the measured particle energy for the spacecraft velocity in order to move our data into the planetary reference frame. After determining the orientation of the magnetic field at the time of each measurement, we can calculate the angle between the ion flow and the magnetic field (pitch angle).

As IMA measures into several directions during one energy sweep, we have a high chance of observing flux distributions with different pitch angles. This means that we can select flux distributions parallel and perpendicular to the magnetic field, representing cuts through the 3-dimensional flux distribution in the respective directions. These are then converted into one-dimensional velocity distributions.

**Ram-Velocity Correction**

As the spacecraft moves with a certain orbital velocity through the plasma, the particle energies which are measured are in fact their kinetic energies in the spacecraft reference frame and not in the VSO reference frame as desired.

A particle moving in the opposite direction of the spacecraft will be recorded at an energy greater than the actual particle energy. Vice versa, a particle moving in the same direction as the spacecraft will ‘catch up’ to the sensor, registering at an energy below its actual value.

This difference between the measured energy \(E_m\) and the ‘true’ energy \(E_p\) in
the planetary reference frame can be calculated and taken into account for if the spacecraft velocity $v_{s/c}$ at the time of the measurement is known.

A particle’s velocity in the spacecraft frame is given by

$$v_{\text{rel}} = \sqrt{\frac{2E_m}{m}}$$

(4.1)

with $m$ as the mass of the particle.

The correction velocity $v_{\text{corr}}$ is calculated as the scalar product between the normalized viewing direction $\hat{x}$ of the sensor and the spacecraft velocity $v_{s/c}$,

$$v_{\text{corr}} = \hat{x} \cdot v_{s/c}. \quad (4.2)$$

If the instrument for example points in the direction of the spacecraft motion, the correction velocity $v_{s/c}$ is positive - it describes how much larger the particle’s velocity appears due to the ram velocity.

The particle’s velocity in the planetary reference frame is then

$$v_p = v_{\text{rel}} - v_{\text{corr}}, \quad (4.3)$$

which can in turn be used for calculating the corrected particle energy according to

$$E_p = \frac{m}{2} v_p^2. \quad (4.4)$$

We use this procedure to correct the 96-step energy table defining the energy bins for each scan. The recorded fluxes are then interpolated to the original energy table.

In many cases the corrected particle energy can be lower than the lowest energy bin of the original energy table. Therefore additional energy steps between $0\text{eV}$ and $12\text{eV}$ (IMA measures down to $12\text{eV}$) are introduced in order to retain all measurements.

**Pitch Angle Calculation**

Now we want to determine the angle between the ion flow and the magnetic field $\mathbf{B}$. The ion flow direction is well-determined by the viewing direction of the IMA sensor, but the direction of $\mathbf{B}$ first has to be calculated in a stable way as well.

The magnetic field is measured as a three component vector giving both the direction and the magnitude of the $\mathbf{B}$-field. The data is provided in a processed format; all possible noise sources have been subtracted. Its 4s resolution is fine enough for usage with measurements from the IMA sensor, which completes an energy sweep with fixed elevation in 12s and a full scan over the whole field of
Analyzing Ion Flux Measurements

view in 192 s.

Since for some time instances there is no magnetic field data available and the sweep duration is higher than the time step of the magnetic field measurements, more than one magnetic field vector is taken into account for each IMA sweep. In this study, the average of all magnetic field vectors in a window of ±15 s around the time at which the IMA sweep was provided is used.

To determine the angle between the magnetic field and a single measurement with certain azimuth and elevation, a scalar product between the normalized magnetic field direction, \( \hat{B} \), and the normalized viewing direction of the sensor, \( \hat{x} \), is used. The definition of the scalar product,

\[
\mathbf{a} \cdot \mathbf{b} = \|\mathbf{a}\| \|\mathbf{b}\| \cos(\alpha),
\]

simplifies to

\[
\mathbf{a} \cdot \mathbf{b} = \cos(\alpha)
\]

if both \( \mathbf{a} \) and \( \mathbf{b} \) are normalized. The angle \( \alpha \) between the two vectors, also called pitch angle, can then be calculated by

\[
\alpha = \arccos(\mathbf{a} \cdot \mathbf{b}).
\]

In this case, the pitch angle is

\[
\alpha = \arccos(-\hat{x} \cdot \hat{B}).
\]

The minus sign indicates that the direction of a measured particle flux is opposite to the viewing direction \( \hat{x} \) of the detector. The pitch angle \( \alpha \) can assume values between 0° and 180°, which corresponds to measurements parallel and antiparallel to the magnetic field direction. A pitch angle of 90° corresponds to measurements perpendicular to the magnetic field. While the (anti-) parallel direction is well-defined by the magnetic field direction, perpendicular directions can no longer be distinguished. This would require the definition of a second reference direction perpendicular to the magnetic field and the definition of a second angle. For this project, a distinction of different perpendicular directions is not necessary however.

Velocity Distribution

The available pitch angle interval between 0° (parallel) and 180° (antiparallel) is divided into 8 bins of 22.5° each into which the observed ion fluxes of a single sweep are sorted. By averaging the flux distributions in each bin, a 2D pitch
angle distribution is obtained. The attentive reader might wonder at this point why only fluxes of a single sweep instead of a full scan are binned - we will come to that in the next section.

Finally, the fully differential flux distribution has to be converted into a velocity distribution. This is done by ‘integrating’ over the solid angle covered by each pitch angle bin, which in this case (we assume angular symmetry around a magnetic field line, i.e., don’t distinguish perpendicular directions) is a simple multiplication of the binned fluxes with the respective solid angles. The velocity distribution is then calculated using equation (2.10).

An example of a velocity distribution resulting from a 12 s sweep is shown in figure 4.2; the magnetic field points vertically upward. As all parallel directions are treated equal, a spectrum with full coverage would only make up half a circle; this allows mirroring the distribution along the vertical axis to fill the circle and enhance visibility. For this reason positive perpendicular velocities are found both in positive and negative directions along the x-axis.

**Figure 4.2:** An example velocity distribution calculated from a 12 s IMA sweep for one elevation angle. In this case no full coverage was achieved, the angular bins parallel and antiparallel to the magnetic field are empty. This sweep was taken on the 7th of February 2007 at 06:51 UTC, at location X\textsubscript{VSO} = 0.1 R\textsubscript{V}, R\textsubscript{VSO} = 1.7 R\textsubscript{V}. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{velocity_distribution.png}
\caption{H\textsuperscript{+} velocity distribution log\textsubscript{10} [m\textsuperscript{-6} s\textsuperscript{2}].}
\end{figure}
Analyzing Ion Flux Measurements

**Figure 4.3:** A 2D velocity distribution with sections marked according to which parts are extracted for the calculation of 1D distributions parallel, perpendicular and antiparallel to $B$. In this case all angles between $0^\circ$ and $45^\circ$ are considered as parallel to $B$, while the regions $45^\circ < \alpha < 135^\circ$ and $135^\circ < \alpha < 180^\circ$ are considered as perpendicular and antiparallel respectively.

**Constructing 1D Velocity Distributions**

In order to determine the perpendicular and parallel temperatures, a Maxwellian distribution is fitted to the distribution function. Instead of attempting to fit a 2D Maxwellian to a, in most cases, incomplete pitch angle distribution, 1D velocity distributions perpendicular and parallel to the magnetic field are constructed first. A perpendicular distribution results from averaging the phase space density in the four most perpendicular angular bins (red sectors in figure 4.3). Similarly, a parallel and an antiparallel distribution are calculated from the two most parallel and antiparallel angular bins (blue and green sectors in figure 4.3, respectively). This simplifies the following fitting procedure and minimizes the number of discarded sweeps, as even sweeps with for example no parallel or antiparallel coverage can still be used to extract $T_\perp$.

At first, a distinction of parallel and antiparallel directions was made, but it did not have any impact on the results. It was therefore dropped and antiparallel
directions are regarded as parallel directions in this study (i.e., the blue and green sectors in figure 4.3 are combined into a single parallel distribution).

Each 12-s sweep has a high probability to cover a direction perpendicular to the magnetic field due to the circular field of view of IMA. In fact, every sweep with an elevation angle of 0° is bound to cover a perpendicular direction. While parallel or antiparallel directions are not as likely to be observed, inspection of the data showed sufficient coverage in the area of interest ($-3R_V < X_{VSO} < 2R_V$, $R_{VSO} < 3.4R_V$). Measurements in both parallel and antiparallel directions at the same time are however highly unlikely - most velocity distributions will therefore not cover all pitch angles. In the used dataset, 91.6% of all proton sweeps show sufficient angular coverage to allow for a calculation of both a parallel and a perpendicular distribution by the described method. For heavy ions, this is the case for 83.4% of all sweeps. The remaining 8.4% or 16.6%, respectively, can only be used to calculate either a parallel or a perpendicular distribution depending on the coverage of the sweep.

As mentioned earlier, it might seem reasonable to bin all sweeps of a 192-s scan into a single pitch angle distribution to take advantage of the full field of view of IMA. This would however mean that in some pitch angle bins some tens of flux distributions must be averaged, which was shown to be counterproductive. The issue is that we mainly want to calculate the ion temperature, that is, the width of the usually Maxwellian-shaped peak of the velocity distributions we just calculated. We can safely assume that the plasma environment we measure will not stay exactly the same for a whole 192-s scan, so we would end up averaging a number of Maxwellian peaks slightly shifted to each other - in most cases producing a Maxwellian peak again. This averaged peak will however be wider than all the single peaks it was calculated from; which would lead to an overestimation of the ion temperature. Since no information is lost by studying every single sweep on its own, this method is preferred.

### 4.3 From Velocity Distributions to Plasma Parameters

In the previous section we have calculated velocity distributions, or rather their 1-dimensional cuts parallel and perpendicular to the instantaneous magnetic field $\mathbf{B}$. These are now fitted using a Maxwellian distribution in order to extract several parameters describing the local plasma environment. As each sweep has been measured at different locations along VEX’ orbit, the obtained parameters are binned according to the spatial position in the cylindrical Venus Solar Orbit (VSO) and Venus Solar Electric (VSE) reference frames and averaged. Now we
can create maps showing how plasma parameters vary between different regions around Venus.

**Distribution Fitting**

Each 1D velocity distribution was least-squares-fitted using a Maxwellian distribution of the form

\[
f(v, C, v_0, v_{th}) = C \exp \left( -\frac{(v - v_0)^2}{v_{th}^2} \right)
\]  

(4.9)

with the fit parameters \(v_0\) (bulk velocity) and \(v_{th}\) (thermal velocity). The third parameter \(C\) denotes the maximum of the fitted Maxwellian distribution and can be further described by

\[
C = \frac{n}{(\pi v_{th}^2)^{1/2}}.
\]  

(4.10)

This fit corresponds to a one-dimensional drifting Maxwellian as can be derived from equations (2.3) and (2.6).

In the solar wind, the core proton velocity distribution is known to be reasonably well approximated by a 2D drifting Maxwellian distribution if the pitch angle anisotropy is not too high [e.g., Marsch et al., 1982; Gary et al., 2001; Kasper et al., 2002]. This infers that the 1D distributions calculated as shown above are well approximated by a Maxwellian even in cases with high pitch angle anisotropy. Similarly, ion distributions in the planetary magnetosheaths can generally be characterized by a hot anisotropic Maxwellian [e.g., Thomsen et al., 1985]. In the magnetotail, ion distributions are often poorly described with a Maxwellian distribution [e.g., Kollmann et al., 2014]; in this study only cases where a Maxwellian fit produces a reasonable result are considered and non-Maxwellian distributions are sorted out (see following section).

Figure 4.4 shows the set of one-dimensional velocity distributions derived from the distribution in figure 4.2 with the corresponding Maxwellian fits. The top left-hand panel shows the velocity distribution parallel to \(B\), the top right-hand panel for the perpendicular direction. The distribution antiparallel to \(B\) is shown in the bottom left-hand panel. The bottom right-hand panel shows the distribution which is obtained when no distinction between parallel and antiparallel directions is made. The corresponding Maxwellian fits are drawn in green or red depending on whether the fit selection algorithm has accepted or discarded the fit for further calculations. A description of the selection procedure is given in the following section.
Figure 4.4: One-dimensional velocity distributions (blue) as extracted from the 2D distribution in figure 4.2. In this case the distribution parallel to $B$ has a very low intensity and does not provide a good fit. The perpendicular and antiparallel components allow for reasonable fitting, while the combined parallel and antiparallel distribution is clearly dominated by the antiparallel part and therefore fittable as well.
Fit Selection

Not every sweep provides a data set to which a Maxwellian can be fit properly. Different types of data contamination due to the instrument response to especially high fluxes or extreme ultraviolet radiation can render the dataset useless; or simply the momentary conditions of the local plasma environment were non-Maxwellian. A fit is attempted for every distribution - if it is successful, its quality needs to be judged reliably. The hereby used method is a chi-squared-like test, but the resulting values are by no means to be compared to the chi-squared distribution table.

The main aim is to calculate a comparable value for each fitted distribution which provides information about how much the determined fit deviates from the data set it was fitted to. Since all distributions have the same number of data points $i$ (as defined by the number of measured energy bins), a simple sum over the squared difference between each measured velocity distribution probability density $x_i$ and the corresponding fitted value $f(v_i, C, v_0, v_{th})$,

$$\sum_i (x_i - f(v_i, C, v_0, v_{th}))^2,$$

will already give a reasonable estimate of the fit quality. One obvious issue is the different flux level of each dataset: as the fluxes sometimes show differences of several orders of magnitudes between sweeps, these sums are not comparable between different samples. Therefore a division by the maximum value of the fit, $C$, yields a good indicator value of the goodness of fit,

$$\sum_i \frac{(x_i - f(v_i, C, v_0, v_{th}))^2}{C}.$$

It remains to choose a limiting value to determine whether to keep or discard the current fit. Since no tabulated values can be used with the presented indicator values, the method of choice is to calculate indicator value histograms from all fits at selected spatial positions in the Venus environment, compare a number of fits by eye and decide on a few limit values to test run with. Of course there is no perfect limit value; it is rather a matter of finding the appropriate middle ground between discarding too many measurements and taking in too many faulty fits.

Spatial Binning

We now have a set of plasma parameters describing the plasma properties we observed during each sweep which could be processed successfully. As these sweeps have been measured at different locations and in different plasma environments
Ion Temperature Anisotropies in the Venus Plasma Environment

along the orbit of VEX, we need to sort them according to their measurement location. This way, we can for example investigate how plasma conditions differ between the solar wind and the magnetosheath.

Spatial binning occurs in cylindrical coordinates in two different coordinate systems: in the Venus Solar Orbit (VSO) frame as described previously and in the Venus Solar Electric (VSE) frame.

The $X_{\text{VSE}}$ axis is parallel to the $X_{\text{VSO}}$ axis and pointing from the center of Venus towards the Sun. The remaining two axes of the VSE frame are defined with respect to the orientation of the interplanetary magnetic field (IMF): $Y_{\text{VSE}}$ is pointing in the direction of the IMF and $Z_{\text{VSE}}$ is oriented parallel to the convection electric field $\mathbf{E} = -\mathbf{v}_{\text{SW}} \times \mathbf{B}_{\text{IMF}}$ with $\mathbf{v}_{\text{SW}}$ as the solar wind velocity and $\mathbf{B}_{\text{IMF}}$ as the IMF. A detailed description of the VSO and VSE reference frames is given in appendix A.

In this study we use cylindrical coordinates $(X, R, \theta)$ instead of Cartesian coordinates $(X, Y, Z)$ for both systems. This is useful from a technical point of view, because the VSO and VSE frames share the same $X$-axis - a certain spatial position will always have the same $X$ and $R$ coordinates in both reference frames. Only the third coordinate, the polar angle $\theta$, differs between VSO and VSE. From a scientific point of view a cylindrical coordinate system also makes sense - Venus is obviously a round body and large-scale rotational invariance is to be expected (e.g. bow shock and IMB locations).

The region of interest is limited by the orbit of VEX and the operation periods of IMA. The region between $-3 R_V < X \leq 2 R_V$ and $0 < R \leq 3.4 R_V$ includes nearly all data which IMA could collect in the magnetosphere of Venus as well as in large parts of the solar wind region with orbital coverage; this area is therefore deemed adequate for this study. The bin size in the $X$ and $R$ dimensions is $0.2 \times 0.2 R_V$, resulting in a high enough number of samples per bin to allow for reliable statistical analyses.

The $360^\circ$ range of the cylindrical angle $\theta$ has been split into 4 sections with size $90^\circ$ each, as shown in figure 4.5. Any smaller angular bin size reduces the statistical reliability significantly. We obtain four ‘quadrants’, centered around $\pm Y_{\text{VSO}}$ (dawn/dusk) and $\pm Z_{\text{VSO}}$ (north/south) for VSO and $\pm Y_{\text{VSE}} = \pm B_{\text{IMF}}$ and $\pm Z_{\text{VSE}} = \pm E$ for VSE. This spatial binning technique has been used successfully by Nordström et al. [2013] with the same dataset.

To bin the data in the VSE system, we need to know the direction of the IMF at the time of each measurement. The IMF cannot be measured at all times - whenever VEX is located for example in the magnetosheath, the local magnetic field direction will likely differ from the direction of the IMF. This means that VEX can reliably measure the IMF direction only when located in the solar wind region; the IMF direction might not be known up to hours before or after an IMA
Figure 4.5: Definition of quadrants in the cylindrical VSO and VSE reference frames with Venus in the center. All samples in one quadrant are projected onto their respective coordinate planes.

We therefore want to determine the average IMF direction during one orbit and use this direction for all of the orbit’s measurements - this is of course only reasonable if the IMF does not vary too much within this one orbit. Therefore the IMF direction is calculated from MAG measurements during spacecraft passes through a region about $0.8 - 1 R_V$ upstream of the bow shock. Each orbit passes this region twice: once before passing through the magnetosheath into the magnetotail, and once more after leaving the magnetotail and -sheath on the opposite side. If the average IMF directions determined at these two regions do not differ by more than $45^\circ$, the IMF is assumed to be stable during this orbit and the VSE system is well defined.

In the end, no clear asymmetries between the different quadrants were found. The results will therefore be presented in $X_{VSO}-R_{VSO}$ coordinates, i.e. rotational invariance is assumed and the data of all four quadrants is combined.

**Averaging Approach**

By this stage the data has been reduced to spatially binned lists of fit parameters. Up to several thousands of fits have been calculated and accepted for each spatial
bin - and as no automated fit selection can be perfect, we can expect a number of outliers to be included. For this reason, we cannot calculate the mean of, say, all parallel temperatures \( T_\parallel \) in one bin; instead we have to take the median.

Our medians provide statistical estimates of ion bulk velocity and ion temperatures parallel and perpendicular to the magnetic field. The average temperature ratio \( T_\perp/T_\parallel \) at each covered location can then be estimated by dividing the median perpendicular and parallel temperatures (ratio of medians).

One might argue that calculating the temperature ratio for each sweep before averaging the resulting values (median of ratios) is a more physical approach to obtain a meaningful result, but there are some downsides to this. As in this case only distributions covering both parallel and perpendicular directions can be used for calculating \( T_\perp/T_\parallel \), statistics will be worse. This is aggravated by the fact that both the parallel and perpendicular distributions obtained from the same sweep have to pass the goodness-of-fit test.

We therefore prefer to use the ratio of medians for the calculation of the temperature ratios. Both the ratio of medians and the median of ratios have been investigated however, and the results are nearly identical.

It is to note that using medians encompasses a general downside: while it largely ignores outliers and extreme events, it unfortunately also ignores the skew of the distribution. If for example 60\% of sweeps show equal parallel and perpendicular temperatures, while in 40\% of cases perpendicular heating is observed, the median of ratios will yield the value 1 - the dataset clearly shows signs of perpendicular heating, but the information is lost in the averaging process.

\section*{Ion Temperatures and Temperature Ratios}

The output parameters of the Maxwellian fits are the fit maximum \( C \) and the drift and thermal velocities in the given direction, \( v_0 \) and \( v_{th} \). The ion temperature can easily be calculated using a reorganized form of equation (2.5),

\[
T = \frac{mv_{th}^2}{2k_B}.
\] (4.13)

Following common conventions it is more useful to give the temperature in terms of thermal energy,

\[
k_B T = \frac{mv_{th}^2}{2}.
\] (4.14)

Whether this conversion is performed before or after averaging the binned parameters does not matter since the median is used for averaging.
4.4 Data Verification

In order to verify that the previously described methods give accurate results, the resulting fit parameters were compared to verified measurements in the solar wind taken by the Solar Wind Ion Composition Spectrometer (SWICS) on NASA’s Advanced Composition Explorer (ACE) spacecraft [Gloeckler et al., 1998].

The available dataset from the SWICS instruments includes 12-minute averages of proton density, proton bulk velocity and proton thermal velocity. While the density was determined directly through accumulation of raw ion counts, bulk and thermal velocities were derived from the ion distribution similarly to the analysis method used in this study. It is to note that SWICS measures solar wind properties only in the streaming direction of the solar wind.

ACE orbits the Lagrangian point L1, located at a distance of approximately 0.99 AU from the Sun on the directly line between Sun and Earth. With Venus located at about 0.73 AU, the SWICS measurements have to be adjusted for this difference in distance from the Sun. While the solar wind velocity is mostly constant at the terrestrial planets, the plasma density decreases with $1/r^2$ [Kivelson and Russell, 1995] due to spatial expansion. Proton temperature is reported to decrease with $1/r^3$ with $\beta \approx 0.5 - 0.7$ [Gazis et al., 1994]; however, in the inner Solar System a value of $\beta = 1$ is more appropriate [Kallenrode, 2013] and will be used here.

After propagating the SWICS measurements to fit the orbital distance of Venus, the histograms of all data measured between 2006 and 2009 can be compared to all VEX measurements in the solar wind for the same time period. The VEX histograms which are used for comparison are based on fit results of velocity distributions calculated from single IMA sweeps by integrating over their whole field of view; only sweeps measured in the solar wind region (for further explanations see section 5.3 and figure 5.5) have been used. The previously described method of fit selection has been applied as well. Figure 4.6 shows a histogram comparison of density, bulk velocity and thermal velocity results.

The bulk velocity histograms of VEX and ACE are very similar, indicating that the position of the peak of the Maxwellian distributions measured in the solar wind is well determined by the used fitting method.

The proton temperatures extracted by the same fit are higher by a factor of approximately 1.5 than those one would expect from the propagated SWICS measurements. This is a well-known issue with solar wind measurements of IMA and assumed to be caused by a bias towards unfortunate detector orientations which allow only incomplete observations into the Sun direction [H. Nilsson, personal communication], thereby excluding large amounts of solar wind flux. The specific issues which lead to this effect are not fully investigated however.
Figure 4.6: ACE-VEX histogram comparison
This similarly impacts the proton density values obtained from VEX - with a strongly limited field of view, the fluxes recorded during one IMA sweep are not a good representation of the actual conditions. The only way to calculate ion densities from single sweeps in this study is to extrapolate the measured flux to a $2\pi$ field of view; i.e., to multiply with a constant $\frac{2\pi}{\text{observed solid angle}}$. This obviously leads to very unreliable density values which strongly depend on the viewing direction of IMA. An obvious improvement would be to use the whole available field of view (a whole IMA scan) to estimate the ion density. A new algorithm including this and other improvements is currently being developed (see also chapter 6).

As a result of this unreasonable estimation, the spread of the density results is much bigger than observed in SWICS measurements. This can additionally be attributed to the different timescale of measurements: while the SWICS data includes 12-minute averages, this study calculates a density value for each 12-second sweep without any averaging. The data which can be collected in this short a time span is naturally more subject to fluctuations in the solar wind and considerably more susceptible to bad fits causing much larger measurement errors.

However, all results are certainly in the same order of magnitude and it is understood how the observed discrepancies between ACE and VEX arise; the analysis procedure can therefore be considered viable.
Chapter 5

Results and Discussion

5.1 Statistics

Figure 5.1 shows the number of sweeps included in the dataset which allow for a calculation of both parallel and perpendicular distributions. It can therefore be interpreted as the minimum number of sweeps which is used for calculating the different plasma parameters - the actual number of sweeps in a certain direction will be slightly higher, since also sweeps covering for example only perpendicular directions are included in the analysis.

Figure 5.1: Number of sweeps providing distributions parallel and perpendicular to the magnetic field for (a) protons and (b) heavy ions, shown in $X_{\text{VS}}$-$R_{\text{VS}}$ coordinates. The logarithm of the number of sweeps is shown in color scale. Venus is represented by the half gray and half black colored circle, showing day- and nightside, respectively; the Sun is located to the right of the plot. Units on the $X$ and $R$ axes are in Venus radii. White bins correspond to locations without spacecraft coverage in the analyzed time period. The average bow shock [Whittaker et al., 2010] and IMB [Martinecz et al., 2008] positions are indicated as black lines.
Originally we did all the calculations in the VSO/VSE reference frames distinguishing between the four quadrants as explained in section 4.3. However, no asymmetries could be observed, and distinctions between the quadrants were dropped. This provides a considerably higher number of sweeps per bin, greatly reducing ‘noise’ in the plots and improving reliability of the results. All following plots are hence shown in $X_{VSO} - R_{VSO}$ coordinates.

As can be seen in figure 5.1, the coverage for both protons and heavy ions is quite good throughout the area of interest, mostly providing about $10^3$ sweeps per bin. However, due to orbital constraints only small parts of the magnetotail region could be studied with reliable statistics. While the whole region of interest provides a high number of reliable proton sweeps, reasonable heavy ion fluxes could only be observed close to the planet. Figure 5.1(b) therefore displays only bins in which the median of the fit parameter $C$ (maximum phase space density of a 1D distribution $\parallel B$ or $\perp B$) is above $2 \times 10^{-9} \text{ m}^{-6} \text{s}^3$. Bins with less than 10 available sweeps are excluded from all plots.

## 5.2 Ion Temperatures and Temperature Anisotropies

The calculated proton temperatures parallel and perpendicular to $B$ are shown in figure 5.2. It is clearly visible how the solar wind is heated upon passing through bow shock into the magnetosheath. The heated ions then flow along the outside of the IMB, but don’t seem to transport a significant amount of energy.

![Figure 5.2: Proton temperatures (a) parallel and (b) perpendicular to $B$. The logarithm of the thermal energy in units of eV is displayed in color scale.](image-url)
Results and Discussion

Figure 5.3: Heavy ion temperatures (a) parallel and (b) perpendicular to \( B \). The logarithm of the thermal energy in units of eV is displayed in color scale.

into the magnetotail. This agrees well with the proton flow patterns investigated by Nordström et al. [2013], who observed only insignificant proton fluxes directed into the magnetotail. The majority of protons observed in the magnetotail have a very low temperature compared to solar wind or magnetosheath protons and are therefore estimated to originate from the ionosphere.

The corresponding plots for heavy ions are shown in figure 5.3; note the different range in the logarithmic color scale. The heavy ion temperatures in the magnetotail are similar to the proton temperatures in the same region. Furthermore, a tailward heating can be observed - the heavy ions close to Venus at around \( X_{VSO} = 0 \) have a low thermal energy below 1 eV, gradually increasing along the \(-X_{VSO}\) direction to reach thermal energies of several eV. The same can also be observed for protons if figure 5.2 is plotted with an appropriate color scale.

The tailward heating is likely connected to the acceleration of ions by the \( j \times B \) force. This force is caused by the strong curvature of the magnetic field in the wake of Venus, where \( B \) and the associated current \( J \) (Ampere’s law: \( \nabla \times B = \mu_0 j \)) are perpendicular and \( j \times B \) is directed tailward [Futaana et al., 2017]. Furthermore, different wave-particle interaction mechanisms are likely to heat ion distributions.

As can already be observed by comparing the ion temperature plots in figures 5.2 and 5.3, parallel and perpendicular temperatures are not always equal. To visualize this anisotropy, the ratio \( T_\perp/T_\parallel \) has been calculated for protons and heavy ions as described in section 4.3. The resulting maps showing the local proton and heavy ion temperature ratios are displayed in figure 5.4. Note that the color scale has been adjusted: a ratio of for example \( T_\perp/T_\parallel = 2 \) shows an anisotropy of the same magnitude as a ratio of \( T_\perp/T_\parallel = 1/2 \) and is therefore displayed with the same color intensity.

Just a quick glance shows a quite prominent red color cast in both plots - the perpendicular ion temperature is mostly higher than the parallel temperature.
Figure 5.4: Temperature ratios $T_\perp/T_\parallel$ with an adjusted color scale for (a) protons and (b) heavy ions. Red areas represent a higher perpendicular, blue areas a higher parallel temperature.

There are, however, more features to be seen. While the ratio seems to be quite variable but centered around $T_\perp/T_\parallel = 1$ in the solar wind, $T_\perp/T_\parallel$ sharply increases at the bow shock where the solar wind flow is forced to decelerate. One important reason for this is the reflection of some of the incident ions at the bow shock in quasi-perpendicular shock conditions ($\theta_{Bn} > 45^\circ$, with $\theta_{Bn}$ as the angle between the upstream magnetic field $B_{IMF}$ and the local shock normal $\hat{n}$). Ions which are reflected at the bow shock initially move towards the Sun, but gyrate back downstream towards the bow shock due to the orientation of $B_{IMF}$. The reflected ions have a strongly increased temperature and eventually gyrate through the bow shock into the magnetosheath, where they contribute to a significant temperature anisotropy $T_\perp > T_\parallel$ in the ion distribution. A good summary of this mechanism and related observations at the Earth’s bow shock are for example given in Gosling and Robson [1985] and Sckopke et al. [1990].

The resulting ion distribution found behind the bow shock is unstable to the generation of low-frequency plasma waves, which in turn isotropizes the distribution and decreases the anisotropy further downstream. The results from this study clearly support this assumption, showing that the initial temperature ratio of $T_\perp/T_\parallel \approx 3/2$ at the bow shock decreases to lower values further downstream.

The magnetotail shows strongly increased perpendicular temperatures, the ratio $T_\perp/T_\parallel$ reaching above $3/2$ in most bins. A reasonable explanation could be that the very cold ionospheric ions are heated for example through interaction with waves while being accelerated along the tail. Similar processes are frequently observed at Earth, where plasma waves have been shown to strongly enhance the perpendicular temperature of ionospheric oxygen ions [Waara et al.,]
5.3 Average Values

A general overview of the results being given in the previous section, it now makes sense to look at average values of certain plasma parameters. For this, average ion bulk velocities, temperatures and temperature ratios were calculated in different areas of the Venusian plasma environment. The regions were separated into solar wind, magnetosheath and magnetotail as shown in figure 5.5; the average bow shock [Whittaker et al., 2010] and IMB locations [Martinecz et al., 2008] were used as boundaries. Bins close to the nominal boundaries were omitted, as the bow shock and IMB locations are not fixed throughout time. Furthermore, the results should not be impacted by the special interactions taking place close to the boundaries.

The ion bulk velocities $v_{\text{bulk}}$ were calculated by integrating the recorded ion fluxes over the complete field of view covered in one sweep. The resulting velocity distribution was then fitted with a Maxwellian distribution as described previously. Due to the limited field of view, it can be expected that the direction with the dominating flow is often not covered. Especially in the solar wind and magnetosheath regions, the main ion flow direction is expected to be parallel to the $X_{\text{VSO}}$ axis. The spacecraft orientation is strongly biased in order to point cam-
Table 5.1: Median proton and heavy ion plasma parameters their median absolute deviations in the solar wind, magnetosheath and magnetotail

<table>
<thead>
<tr>
<th></th>
<th>H⁺</th>
<th>Heavy ions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solar wind</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_{\text{bulk}}$ [km/s]</td>
<td>371 ± 25</td>
<td>-</td>
</tr>
<tr>
<td>$T_{\perp}$ [eV]</td>
<td>17.6 ± 2.4</td>
<td>-</td>
</tr>
<tr>
<td>$T_{\parallel}$ [eV]</td>
<td>15.9 ± 1.9</td>
<td>-</td>
</tr>
<tr>
<td>$T_{\perp}/T_{\parallel}$ ratio</td>
<td>1.11</td>
<td>-</td>
</tr>
<tr>
<td><strong>Magnetosheath</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_{\text{bulk}}$ [km/s]</td>
<td>356 ± 19</td>
<td>-</td>
</tr>
<tr>
<td>$T_{\perp}$ [eV]</td>
<td>38.0 ± 2.9</td>
<td>-</td>
</tr>
<tr>
<td>$T_{\parallel}$ [eV]</td>
<td>29.8 ± 2.7</td>
<td>-</td>
</tr>
<tr>
<td>$T_{\perp}/T_{\parallel}$ ratio</td>
<td>1.28</td>
<td>-</td>
</tr>
<tr>
<td><strong>Magnetotail</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_{\text{bulk}}$ [km/s]</td>
<td>98 ± 24</td>
<td>31 ± 5</td>
</tr>
<tr>
<td>$T_{\perp}$ [eV]</td>
<td>1.40 ± 0.83</td>
<td>1.38 ± 0.25</td>
</tr>
<tr>
<td>$T_{\parallel}$ [eV]</td>
<td>0.73 ± 0.25</td>
<td>0.75 ± 0.19</td>
</tr>
<tr>
<td>$T_{\perp}/T_{\parallel}$ ratio</td>
<td>1.93</td>
<td>1.84</td>
</tr>
</tbody>
</table>

eras and other sensors towards Venus; it therefore has to be assumed that in some sections of the orbit IMA will nearly never be directed towards the solar wind flow. The bulk velocities calculated in the solar wind and the magnetosheath are therefore often uncertain in this study. A more advanced algorithm is currently being written to address this issue among others (see also chapter 6).

The average perpendicular ion temperature $T_{\perp}$ in each region was then calculated by taking the median of the dataset composed of the median temperature $T_{\perp}(X_{\text{VSO}}, R_{\text{VSO}})$ of each bin located in the respective region; and similarly for $T_{\parallel}$. This minimizes the impact of bins which show deviating values due to a low number of samples.

Uncertainties are given as median absolute deviation (MAD). The MAD of a dataset $\{x_i\}$ is calculated by

$$\text{MAD} = \text{median}( |x_i - \text{median}(\{x_i\})| ).$$

The temperature ratio for each area is then simply calculated through a single division of the respective average ion temperatures. Table 5.1 lists the average ion
Results and Discussion

bulk velocities and temperatures, their respective uncertainties and the resulting
temperature ratios.

In the solar wind, $T_\parallel$ is generally expected to be higher than $T_\perp$ by a factor of approximately 1.9 [Hundhausen, 1972]. Frequently occurring proton double streams however show either isotropic distributions (slow solar wind) or anisotropies with $T_\perp/T_\parallel > 1$ (fast solar wind) [Marsch et al., 1982, and references therein]. Overall, one would still expect a ratio of $T_\perp/T_\parallel < 1$ [e.g., Gary et al., 1976].

Here, a temperature ratio of $T_\perp/T_\parallel = 1.11$ is calculated in the solar wind, but it is to note that the area which is here labeled as ‘solar wind’ is very close to the Venusian bow shock. The extended hydrogen exosphere allows proton pickup upstream of the bow shock, generating ion cyclotron waves and increasing the perpendicular temperature [Delva et al., 2008a,b]. Furthermore, solar wind interaction with the bow shock and the foreshock may lead to specular reflection of ions, which then travel away from the planet in a gyratory motion [Sckopke et al., 1990; Yamauchi et al., 2011] with increased $T_\perp$. The temperature ratio calculated here can therefore not be directly compared to conditions in the undisturbed solar wind; and $T_\perp/T_\parallel$ should certainly be larger than in undisturbed conditions.

The thermal energy of ions having passed the bow shock is increased by about a factor 2 compared to the upstream solar wind thermal energy, which confirms the conversion of bulk kinetic energy into thermal energy. Perpendicular heating is more prominent than parallel heating, increasing the temperature ratio $T_\perp/T_\parallel$ from 1.11 to 1.28 and producing an unstable ion distribution.

Ion thermal energies in the magnetotail are more than an order of magnitude lower than in the solar wind and the magnetosheath. This shows that ions in the magnetotail cannot originate from the solar wind but must rather come from the ionosphere of Venus. We calculate that $T_\perp$ is slightly above and $T_\parallel$ slightly below 1 eV for both protons and heavy ions. These temperatures are still much larger than the typical ion temperature in the ionosphere, which ranges from slightly less than 1000 K or $8.6 \times 10^{-2}$ eV at an altitude of 150 km to about 2000 K or $17.2 \times 10^{-2}$ eV at an altitude of 500 km [Knudsen et al., 1979]. Furthermore, noticeable ion bulk velocities for both protons and heavy ions were observed - cold ion populations in rest in the ionosphere are heated and accelerated to reach escape velocity. Leaving the ionosphere and flowing into the magnetotail, the ions are then subject to complex processes like magnetic reconnection and the $\mathbf{j} \times \mathbf{B}$ force which can lead to additional tailward acceleration and heating.

Another thing to note is the difference in bulk velocities in the magnetotail: protons seem to have a considerably higher bulk velocity than heavy ions. This might indicate which acceleration mechanisms are at play in the Venusian magnetotail.
5.4 Mirror Mode Wave Generation

We now know that the velocity distributions in many parts of the Venus magnetosphere are not isotropic, but instead show a higher perpendicular than parallel temperature. This often leads to the generation of low frequency plasma waves like ion cyclotron (IC) and mirror mode (MM) waves which were described in section 2.7. In this section we want to investigate how the plasma parameters we observed in different regions in the Venus environment fit to direct observations of MM waves during the VEX mission.

The MM waves which have been observed in the Venusian magnetosheath were shown to have periods of \(4 \leq T \leq 15\) s. This means that ion data from IMA cannot be used for a direct identification of MM waves due to its low time resolution.

Nevertheless, we can calculate for each sweep with parallel and perpendicular coverage (figure 5.1 showed how many of these are available) whether the instability criterion for MM waves is fulfilled; this way we can estimate the probability of conditions favorable for MM wave generation. A map showing the percentage of sweeps during which the proton MM instability criterion was fulfilled is shown in figure 5.6.

The instability criterion is fulfilled frequently throughout most of the magnetosheath. The highest probability of encountering MM instabilities is given in the dayside magnetosheath, close to Venus where thermal pressure and temperature anisotropies are highest. Even in the solar wind conditions seem favorable for the generation of MM waves in \(20 - 30\%\) of all sweeps. In the magnetotail region on the other hand, the instability criterion is nearly never fulfilled. This can easily be explained with the comparably low temperatures and therefore low \(\beta_{\perp}\) in the wake region.

Areas with enhanced MM wave activity as investigated by Volwerk et al. [2008b] are approximately marked with the red ellipses. They found that MM wave events were most likely to be observed in the dayside magnetosheath (region A), and that the events in this area were also the most intense. This fits well to the observations of this study, suggesting that the MM instability criterion is fulfilled most frequently in this region.

However, further downstream in the magnetosheath \((-2R_V < X_{VSO} < 0R_V)\) a very similar probability of observing MM instabilities in the local velocity distribution is found; but Volwerk et al. [2008b] did not observe MM waves in this region very frequently.

As has been mentioned in section 2.7, not only MM waves are generated by this type of instability; IC waves, or more specifically PC waves, are also generated from velocity distributions with a high temperature anisotropy. Whether MM waves or PC waves are generated by a certain velocity distribution likely depends...
Results and Discussion

**Figure 5.6**: Percentage of IMA sweeps during which the proton MM instability criterion was fulfilled, in $X_{VSO}$-$R_{VSO}$ coordinates. The red ellipses A and B mark the approximate areas where Volwerk et al. [2008b] found enhanced MM wave activity in the dayside magnetosheath and the magnetotail respectively. The yellow ellipse C approximately marks a region where Delva et al. [2011] observed PC wave activity.

on many factors some of which IMA cannot observe. For example, the presence of Helium ions has been shown to suppress PC waves, leading to increased MM wave generation in planetary magnetosheaths [Gary et al., 1993].

The nightside magnetosheath seems to be a region like this: the local plasma conditions are slightly different from the dayside magnetosheath and no MM waves are observed. Instead, Delva et al. [2011] observed high-amplitude PC waves in the magnetosheath at about $X_{VSO} < -1 R_V$, $R_{VSO} > 1 R_V$ (region C). This shows that the MM instability criterion is a necessary, but not a sufficient criterion for MM wave observations.

Furthermore, Volwerk et al. [2008b] could also observe MM waves in the Venusian magnetotail (region B), albeit with significantly lower intensities than in the dayside magnetosheath. Since IMA measurements show that the MM instability criterion is nearly never fulfilled during the time of our observations, the observed MM waves cannot have been created by a homogeneously unstable plasma. Instead it must be assumed that small-scale inhomogeneities and fluctuations not measurable with the available spatial or temporal resolution of IMA gave rise to the observed structures.

5.5 Conclusions

Using VEX ion measurements between May 2006 and December 2009, the average ion temperature anisotropy in the Venus plasma environment between $2 R_V$
upstream and $3 R_V$ downstream of Venus has been determined.

Upstream of the bow shock, approximately equal parallel and perpendicular proton temperatures are observed; these are increased by about a factor 2 upon passing into the magnetosheath as some ions are initially reflected at the bow shock, but in quasi-perpendicular shock conditions gyrate further downstream nevertheless. Generally, reflected ions are heated stronger in directions perpendicular to the magnetic field, leading to a larger temperature anisotropy near and downstream of the bow shock.

Both protons and heavy ions presumably of planetary origin are found in the Venusian magnetotail with strongly increased temperatures compared to what is usually observed in the ionosphere, suggesting heating and acceleration processes acting on the ions in between the ionosphere and the measurement region. Due to the overall comparably low ion temperatures in the magnetotail, a transport of solar wind constituents into the magnetotail is deemed negligible.

Throughout all of the observed tail region, large values of the temperature ratio $T_\perp/T_\parallel$ are observed both for protons and heavy ions.

Furthermore the possibility of proton MM wave generation is investigated by calculating the MM instability criterion for all measurements. The criterion is found to be frequently fulfilled in the dayside magnetosheath, clearly confirming previous observations by Volwerk et al. [2008a,b, 2016] based on VEX magnetometer data. The plasma conditions are however found to be similar in the nightside magnetosheath, where PC waves have been observed [Delva et al., 2008a,b, 2011] instead of MM waves - indicating how slight differences in the local plasma properties can significantly change the respective growth rates of the MM and the PC instability.
Chapter 6

Outlook

This study already provides a lot of interesting information about the plasma conditions in the Venusian environment; nevertheless there is a lot of room for improvement.

A main issue which was identified only recently is the reference frame in which the calculations have been made. This study analyzes the measurements in a spatially fixed frame, so velocity distributions are calculated without subtracting the bulk flow. Let us consider solar wind flowing towards Venus along the $X_{VSO}$ axis and let the IMF be oriented perpendicular to the solar wind flow. If the observer is placed at a fixed position near Venus, he will (ideally) only measure particles with a high perpendicular velocity and therefore with high pitch angles close to $90^\circ$. Even particles which move completely parallel to the IMF with respect to the surrounding plasma will be measured at high pitch angles; their movement parallel to the IMF is drowned out by the bulk movement perpendicular to the IMF.

As for example plasma waves are mostly generated due to particle interactions inside a plasma bulk and not due to the movement of the plasma bulk relative to an arbitrarily ‘fixed’ frame, the calculations in this study will have to be adjusted to produce reliable results. This can be accomplished by determining the bulk velocity vector of each measurement and adjusting the reference frame accordingly.

Overall, calculating and studying velocity distributions in the environment of Venus opens up a huge area of research. This study but scratched the surface by attempting a simplified calculation of ion temperatures - improving this with a special focus on appropriate averaging and re-binning procedures to avoid a loss of accuracy while also selecting the more appropriate reference frame described above will be a first important step towards investigating wave-particle interaction more thoroughly. The ultimate aim should be to close the gap between wave observations and particle observations, taken by different instruments and so far mostly investigated separately.
Appendix A

Coordinate Systems

Venus Solar Orbit (VSO)

The Venus Solar Orbit reference frame is a commonly used Cartesian coordinate system for Venus and its environment. With Venus in its center, it uses the Sun and the Venusian orbit as reference directions - fixing it with respect to the orbital motion while omitting the planet’s rotation.

The $X_{\text{VSO}}$ axis points from the center of Venus towards the Sun. The $Z_{\text{VSO}}$ axis is perpendicular to the orbital plane of Venus and pointing northwards, while the $Y_{\text{VSO}}$ axis completes the right-hand system and points to the dusk side of Venus. In this frame, the Venusian orbit follows the $-Y_{\text{VSO}}$ axis. An illustration of the VSO system is shown in figure A.1.

![Figure A.1: The VSO reference frame oriented in the Solar System.](image)

A variant of the VSO reference frame which is used in this project is the cylindrical VSO system centered around the $X_{\text{VSO}}$ axis. While $X_{\text{VSO}}$ stays the same as compared to the Cartesian VSO system, the $Y_{\text{VSO}}$ and $Z_{\text{VSO}}$ component pair is replaced by a radial component $R_{\text{VSO}} = (Y_{\text{VSO}}^2 + Z_{\text{VSO}}^2)^{1/2}$ and a rotation angle $\theta$. 
Venus Solar Electric (VSE)

The Venus Solar Electric reference frame is very similar to the VSO system. The \( X_{\text{VSE}} \) axis is aligned with the \( X_{\text{VSO}} \) axis and pointing towards the Sun, while the \( Z_{\text{VSE}} \) is parallel to the convection electric field \( \mathbf{E} = -v_{sw} \times \mathbf{B}_{\text{IMF}} \), derived from the solar wind velocity \( v_{sw} \) and the interplanetary magnetic field \( \mathbf{B}_{\text{IMF}} \). Assuming that the solar wind velocity points radially away from the Sun (in \(-X_{\text{VSO/VSE}}\) direction) it follows that \( Y_{\text{VSE}} \) is aligned with \( \mathbf{B}_{\text{IMF}} \).

Transferring this to cylindrical coordinates it becomes obvious that the only difference between the VSO and VSE reference systems is a rotation about the \( X_{\text{VSO/VSE}} \) axis as is illustrated in figure A.3. The rotation angle between the two systems is equal to the angle between the interplanetary magnetic field direction and the normal on the orbital plane of Venus.
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List of Acronyms

**DPU** Digital Processing Unit

**IC** ion cyclotron

**IMA** Ion Mass Analyzer

**IMB** induced magnetosphere boundary

**IMF** interplanetary magnetic field

**MAD** median absolute deviation

**MAG** VEX Magnetometer

**MCP** multichannel plate

**MEX** *Mars Express*

**MHD** magnetohydrodynamic

**MM** mirror mode

**PC** proton cyclotron

**VEX** *Venus Express*

**VSE** Venus Solar Electric

**VSO** Venus Solar Orbit
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