

CHRISTIAN-ALBRECHTS-UNIVERSITÄT ZU KIEL

MASTER THESIS

---

# Thesis Title

---

*Author:*  
Anne Fischer

*Supervisor:*  
Prof. Dr.  
Wimmer-Schweingruber

Research Group Name  
Department or School Name

October 20, 2019



# Abstract

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...



# Contents

<b>Abstract</b>	<b>iii</b>
<b>1 Motivation</b>	<b>1</b>
<b>2 Pickup Ions</b>	<b>3</b>
2.1 The Heliosphere / Introduction . . . . .	3
2.2 Pickup Ions . . . . .	3
2.3 Interstellar Pickup Ions . . . . .	4
2.4 Inner-source Pickup Ions . . . . .	4
2.5 VDF . . . . .	5
2.5.1 1D reduced VDF, aim of this work...? . . . . .	7
<b>3 Instrumentation</b>	<b>9</b>
3.1 ULYSSES . . . . .	9
3.2 SWICS . . . . .	9
<b>A Frequently Asked Questions</b>	<b>11</b>
A.1 How do I change the colors of links? . . . . .	11
<b>Bibliography</b>	<b>13</b>
<b>Declaration of Authorship</b>	<b>15</b>
<b>Acknowledgements</b>	<b>17</b>



## Chapter 1

# Motivation





## Chapter 2

# Pickup Ions

Pickup ions are created when neutral atoms inside the heliosphere become ionised and are subsequently swept away with the heliospheric magnetic field that is embedded within the solar wind.

## 2.1 The Heliosphere / Introduction

Oder Überkapitel Solar Physics?

Heliosphere: Grenze zu LISM

Solar Wind: Zusammensetzung, schneller und langsamer

B-Feldgleichung

## 2.2 Pickup Ions

A neutral atom inside the heliosphere is only subjected to the gravitational force and radiation pressure of the sun. It is not sensitive to any electromagnetic forces until it becomes ionised by solar ultra-violet radiation, charge exchange with solar wind protons or electron impact (Q?). After ionisation the particle starts interacting with the solar wind plasma. In particular it is forced onto a gyro orbit about the heliospheric magnetic field that is embedded within the solar wind. As the freshly created ion is swept away with the magnetic field line it is “picked up” from its location of ionisation – a new pickup ion (PUI) has been created.

PUIs were first observed by Möbius et al. (1985) with the SULEICA Instrument on the AMPTE spacecraft. The particles measured at 1 AU were He<sup>+</sup> ions of interstellar origin.

Once the particle is ionised, its probability to become ionised another time decreases (Quelle). This characteristic of being only singly charged can help to discriminate PUIs from solar wind ions, that are mostly more often charged (Q?).

PUIs are mostly only single charged. This characteristic can help to distinguish them from solar wind ions of coronal origin which often have been ionized multiple times, if not completely. (Q?)

VDF non-maxwellian, spatial density pattern

There have been observed several species of PUIs:

## 2.3 Interstellar Pickup Ions

Heliosheath, relative motion

The neutral part of the LISM can enter the heliosphere as it is not affected by the heliosheath (Todo). Inside the heliosphere the neutrals are guided only by the gravitational force and radiation pressure of the sun. The neutral particle's species determines how deep it can travel into the heliosphere before it becomes ionized. Species with a higher First Ionization Potential will be able to approach the sun much closer without being ionized. This results in He<sup>+</sup> being the dominant PUI species at a solar distance of 1 AU even if in the LISM the abundance of hydrogen is about 10 times the one of helium.

- ionisation process is also dependent on the species
- radiation pressure only important for H (and He?). Kepler orbit...
- Spatial distribution:  
gravitational force and radiation pressure lead to two regions of enhanced density of neutrals (in the ecliptic): Focusing cone and crescent. Focusing cone: For species with high FIP (as the others are ionized before and do not reach the downwind side of the sun)
- variation of He<sup>+</sup> with the solar cycle: Rucinski 2003
- H, O and N are depleted in the filtration region (Baranov Malama 1995), Wimmer Skript: even before ionization: density is determined by ratio of gravitational force and photon pressure
- neutral density determines PUI production rate

## 2.4 Inner-source Pickup Ions

The idea of an additional source for the PUI's neutral seed population was born when Geiss, Gloeckler, Fisk, et al. (1995) measured a global distribution of C<sup>+</sup> PUIs with the SWICS instrument on Ulysses. Interstellar carbon exists almost exclusively in a single charged state (Frisch et al., 2011) in the LISM. As only neutral atoms can enter the heliosphere it was not expected to find a distinct signature of C<sup>+</sup> pickup ions. However, pickup carbon was observed with about the same ratio as oxygen, of which, in contrast, 80% is in a neutral charge state in the interstellar medium. These findings suggested that there must be another source for neutrals that has its origin somewhere inside the heliosphere.

In following studies (e.g. Geiss, Gloeckler, and Steiger, 1995) there were found also other species like O<sup>+</sup> and Ne<sup>+</sup> of these, so called, inner-source PUIs.

Inner-source PUIs show a composition that is similar to the one of the solar wind (Gloeckler et al., 2000; Allegrini et al., 2005) as well as a velocity distribution function that is centered around  $w_{SC} \approx 1$  (Schwadron et al., 2000) and seems to have thermalized with the solar wind.

Beneath those two characteristics there are other aspects concerning inner-source PUIs, that are still under debate. In particular that is the production mechanism of their neutral seed population. Allegrini et al. (2005) has summarized current candidates for possible scenarios. Two of those give an explanation for the ion's composition as they directly incorporate solar wind ions in the process:

- Solar wind recycling (Gloeckler et al., 2000; Schwadron et al., 2000): Absorption of solar wind ions by heliospheric grains and subsequent reemission of neutral atoms
- Solar wind neutralization (Wimmer-Schweingruber and Bochsler, 2002): Solar wind ions penetrate sub-micron-sized dust grains and undergo (partial) neutralization by charge exchange

(As this work does not focus on inner-source PUIs in particular...)

## 2.5 VDF

After the particle has been ionised it is forced onto a gyro motion about the local field line of the heliospheric magnetic field due to the Lorentz force.

To examine the velocity distribution of PUIs after they have been ionized we need to consider the initial speed  $v_{ini}$  of the neutral particle. For neutrals from the LISM this is mainly given by the inflow speed  $v_{ISM}$  of the local interstellar medium with which they enter the heliosphere. As we don't exactly know about the production mechanism of inner-source PUIs, the following considerations mainly relate to interstellar PUIs. Schwadron et al. (2015) obtained  $v_{ISM} \approx 25 \text{ km s}^{-1}$  with the IBEX satellite for helium. Considering the acceleration by the sun's gravitational force we have a maximum initial speed of  $v_{ini} \approx 50 \text{ km s}^{-1}$  at 1 AU. Compared to an average solar wind speed of  $v_{sw} \approx 400 \text{ km s}^{-1}$  one can neglect this initial speed in a first step.

For simplicity we thus consider a neutral particle at rest that becomes ionized by one of the aforementioned processes. The freshly created ion now is subjected to the electromagnetic forces of the solar wind plasma. In particular, it finds itself at a velocity  $v_{sw}$  relative to the magnetic field which is convected outwards by the solar wind that is assumed to flow radially outwards. Due to the Lorentz force the PUI starts to gyrate about the magnetic field line on an orbit that is perpendicular to it. When we further consider a magnetic field's orientation that is perpendicular to the solar wind flow,  $\vec{B} \perp \vec{v}_{sw}$ , the ion's gyration speed is  $v_{sw}$  while its guiding center moves together with the field line at a speed of  $v_{sw}$  as well. Thus, the total speed of the PUI ranges between  $0 v_{sw}$  and  $2 v_{sw}$  in a sun frame of reference.

As the heliospheric magnetic field lines are shaped like an Archimedean spiral, the so called *Parker spiral*, the assumption of a perpendicular magnetic field only applies when solar wind speed  $v_{sw}$  and solar distance  $r_{\odot}$  follow the relation

$$90^\circ \approx \arctan \left( \frac{2\pi}{T_{\odot} \cdot v_{sw}} r_{\odot} \right)$$

with sun's sidereal period  $T_{\odot} \approx 25 \text{ d}$  (Prölss, 2004). In other cases, e.g. for solar distances about 1 AU, at which the angle between solar wind and magnet field direction is approximately  $45^\circ$ , the maximum speed in a sun frame of reference is decreased. In general, the gyration speed is given by

*todo*

with ... .

The velocity space for a pickup situation with a non-radial magnetic field orientation is shown in figure *todo* on the right. The PUI's total velocity consists of the

movement of the guiding center (...) and the gyration velocity (...). We note, that in this case there is a relative velocity between the motion of the solar wind bulk and the PUI's guiding center movement.

However, independent on the magnetic field orientation, every possible velocity space trajectory is part of a sphere with the radius  $v_{sw}$  centered around  $\vec{v}_{sw}$ . That means that, in the frame of the solar wind, the freshly created PUI always moves with a speed that is as fast as the solar wind itself. (todo: Hier w einführen?)

Instead of a single PUI we can consider an ensemble of PUI's that is injected into the solar wind while the magnetic field orientation is not changing much. For that we expect the VDF to form a ring shape in velocity space, commonly called the "PUI torus VDF" (Oka et al., 2002). The expected orientation of this highly anisotropic torus VDF depends on the local magnetic field direction and is sketched in figure todo for three different angles.

...thickness that is related (associated) to the neutral's velocity and is very small compared to the radius...

Spatial diffusion: chalov Fahr 1998. Signature of plasma parcel in which is was produced doesn't match with the one it is measured in

After the injection, the PUI population is radially carried away with the solar wind. During phase space transport through the heliosphere the PUIs are subjected to multiple processes that are expected to modify the shape of the initial toroidal VDF. However, it is not completely understood how the VDF evolves in detail.

A fast isotropization of the VDF due to pitch-angle scattering was suggested by Vasyliunas and Siscoe (1976) in a theoretical work. However, observations by e.g. Möbius et al. (1998) on  $He^+$  or Gloeckler et al. (1995) on  $He^+$  have shown clear anisotropic features in the measured VDFs. Following studies (todo) explained these findings with the assumption that the ions would be injected into the sunward hemisphere of velocity space more likely. Ineffective pitch-angle scattering into the anti-sunward hemisphere thus would result in a radial anisotropy.

Recent observations have emphasized the influence of the magnetic field direction on the measured anisotropy. Utilising 2D analyses of the velocity space, Oka et al. (2002) and Drews et al. (2015) found that the measured VDF of PUIs is systematically oriented about the direction that is perpendicular to the magnetic field. Thus, it is believed that the VDF's anisotropic features are remnants of the initial toroidal VDF. (and the pa scattering didnt have enough time to isotropize the distribution)

Furthermore, there are different acceleration and deceleration processes that change the PUI's initial VDF and lead to a diffusion in velocity space. Under the assumption of an isotropic VDF the PUI population is often treated as an adiabatic gas that is consequently cooled when expanding with the solar wind. This picture, initially suggested by Vasyliunas and Siscoe (1976), however, must be reviewed due to the doubtful fact of a fully isotropic VDF. Another cooling mechanism, called the *magnetic cooling*, is due to the magnetic field weakening with solar distance. As the PUIs are swept outwards both their ... and their ...invariant have to be conserved which leads to a decrease in both velocity components (parallel and perpendicular to the magnetic field) and thus to a decrease in total velocity (in the frame of the solar

wind).

(focusing (adiabatic invariant) & Ginzberg Landau (Fahr2008): "magnetic cooling" (auch gute Erklärung: Fahr&Fichtner2011))

Acceleration of PUIs can be caused by acceleration: first and second order fermi (verstehen, gründe): eher außen bzw. eher innen. Außerdem ein Mechanismus, der nicht an einzelne Events gebunden ist, sondern immer vorhanden: Mechanismus für alle Teilchen, power law -5...

man kann in der 1D Verteilung beobachten, dass  $2v_{sw}$  exceeded wird

Instrument that is capable of measuring this distribution: large acceptance in absolute velocity, large variation and resolution in angles

### 2.5.1 1D reduced VDF, aim of this work...?



## Chapter 3

# Instrumentation

### 3.1 ULYSSES

sfsf

### 3.2 SWICS

sffsf





## Appendix A

# Frequently Asked Questions

### A.1 How do I change the colors of links?

The color of links can be changed to your liking using:

```
\hypersetup{urlcolor=red}, or  
\hypersetup{citecolor=green}, or  
\hypersetup{allcolor=blue}.
```

If you want to completely hide the links, you can use:

```
\hypersetup{allcolors=.}, or even better:  
\hypersetup{hidelinks}.
```

If you want to have obvious links in the PDF but not the printed text, use:

```
\hypersetup{colorlinks=false}.
```



# Bibliography

- Allegrini, F., N. A. Schwadron, D. J. McComas, G. Gloeckler, and J. Geiss (May 2005). "Stability of the inner source pickup ions over the solar cycle". In: *Journal of Geophysical Research* 110.A5, A05105, A05105. DOI: [10.1029/2004JA010847](https://doi.org/10.1029/2004JA010847).
- Drews, Christian, Lars Berger, Andreas Taut, Thies Peleikis, and Robert F. Wimmer-Schweingruber (Mar. 2015). "2D He<sup>+</sup> pickup ion velocity distribution functions: STEREO PLASTIC observations". In: *Astronomy & Astrophysics* 575, A97, A97. DOI: [10.1051/0004-6361/201425271](https://doi.org/10.1051/0004-6361/201425271).
- Frisch, Priscilla C., Seth Redfield, and Jonathan D. Slavin (Sept. 2011). "The Interstellar Medium Surrounding the Sun". In: *Annual Review of Astronomy and Astrophysics* 49.1, pp. 237–279. DOI: [10.1146/annurev-astro-081710-102613](https://doi.org/10.1146/annurev-astro-081710-102613).
- Geiss, J., G. Gloeckler, L. A. Fisk, and R. von Steiger (1995). "C<sup>+</sup> Pickup ions in the heliosphere and their origin". In: *Journal of Geophysical Research: Space Physics* 100.A12, pp. 23373–23377. DOI: [10.1029/95JA03051](https://doi.org/10.1029/95JA03051). eprint: <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/95JA03051>. URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/95JA03051>.
- Geiss, J., G. Gloeckler, and R. von Steiger (Apr. 1995). "Origin of the solar wind from composition data". In: *Space Science Reviews* 72.1, pp. 49–60. ISSN: 1572-9672. DOI: [10.1007/BF00768753](https://doi.org/10.1007/BF00768753). URL: <https://doi.org/10.1007/BF00768753>.
- Gloeckler, G., L. A. Fisk, J. Geiss, N. A. Schwadron, and T. H. Zurbuchen (Apr. 2000). "Elemental composition of the inner source pickup ions". In: *Journal of Geophysical Research* 105.A4, pp. 7459–7464. DOI: [10.1029/1999JA000224](https://doi.org/10.1029/1999JA000224).
- Gloeckler, G., N. A. Schwadron, L. A. Fisk, and J. Geiss (Jan. 1995). "Weak pitch angle scattering of few MV rigidity ions from measurements of anisotropies in the distribution function of interstellar pickup H<sup>+</sup>". In: *Geophysical Research Letters* 22.19, pp. 2665–2668. DOI: [10.1029/95GL02480](https://doi.org/10.1029/95GL02480).
- Möbius, E., D. Hovestadt, B. Klecker, G. Scholer, and G. Gloeckler (1985). "Direct observation of He<sup>+</sup> pick-up ions of interstellar origin in the solar wind". In: *nature* 318 (6045), pp. 426–429. DOI: [10.1038/318426A0](https://doi.org/10.1038/318426A0). URL: <https://www.nature.com/articles/318426a0>.
- Möbius, E., D. Rucinski, M. A. Lee, and P. A. Isenberg (Jan. 1998). "Decreases in the antisunward flux of interstellar pickup He<sup>+</sup> associated with radial interplanetary magnetic field". In: *Journal of Geophysical Research* 103.A1, pp. 257–266. DOI: [10.1029/97JA02771](https://doi.org/10.1029/97JA02771).
- Oka, M., T. Terasawa, H. Noda, Y. Saito, and T. Mukai (June 2002). "'Torus' distribution of interstellar helium pickup ions: Direct observation". In: *Geophysical Research Letters* 29.12, 1612, p. 1612. DOI: [10.1029/2002GL015111](https://doi.org/10.1029/2002GL015111).
- Prölss, Gerd W. (2004). *Physik des erdnahen Weltraums. Eine Einführung*. Springer Berlin Heidelberg. DOI: [10.1007/978-3-642-18807-7](https://doi.org/10.1007/978-3-642-18807-7). URL: <https://doi.org/10.1007/978-3-642-18807-7>.
- Schwadron, N. A., J. Geiss, L. A. Fisk, G. Gloeckler, T. H. Zurbuchen, and R. von Steiger (Apr. 2000). "Inner source distributions: Theoretical interpretation, implications, and evidence for inner source protons". In: *Journal of Geophysical Research* 105.A4, pp. 7465–7472. DOI: [10.1029/1999JA000225](https://doi.org/10.1029/1999JA000225).

- Schwadron, N. A., E. Möbius, T. Leonard, S. A. Fuselier, D. J. McComas, D. Heirtzler, H. Kucharek, F. Rahmanifard, M. Bzowski, M. A. Kubiak, J. M. Sokół, P. Swaczyna, and P. Frisch (Oct. 2015). "Determination of Interstellar He Parameters Using Five Years of Data from the IBEX: Beyond Closed Form Approximations". In: *The Astrophysical Journal Supplement Series* 220.2, 25, p. 25. DOI: [10.1088/0067-0049/220/2/25](https://doi.org/10.1088/0067-0049/220/2/25).
- Vasyliunas, V. M. and G. L. Siscoe (1976). "On the flux and the energy spectrum of interstellar ions in the solar system". In: *Journal of Geophysical Research (1896-1977)* (7).
- Wimmer-Schweingruber, R. F. and P. Bochsler (May 2002). "On the Origin of Inner-Source Pickup Ions". In: *Geophysical Research Letters* 30.2, pp. 49-1 - 49-4.

# Declaration of Authorship

I, Anne Fischer, declare that this thesis titled, and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

---

Date:

---



# Acknowledgements

The acknowledgments and the people to thank go here, don't forget to include your project advisor...