Measurement of the Composition of the Local Interstellar Cloud with the Interstellar Probe Mission

Peter Wurz
Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern Switzerland
peter.wurz@unibe.ch

Rico Fausch
Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern Switzerland
rico.fausch@unibe.ch

Daniele Piazza
Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern Switzerland
Daniele.piazza@unibe.ch

Jonathan Gasser
Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern Switzerland
jonathan.gasser@unibe.ch

Martina Föhn
Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern Switzerland
m.foehn93@gmail.com

André Galli
Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern Switzerland
andre.galli@unibe.ch

Audrey Vorburger
Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern Switzerland
audrey.vorburger@unibe.ch

2024 IEEE Aerospace Conference | 979-8-3503-0462-6/24/$31.00 ©2024 IEEE | DOI: 10.1109/AERO58975.2024.10521348

Abstract—**The proposed Interstellar Probe (IP) spacecraft will travel through the heliosphere and advance into the local interstellar medium (LISM) within roughly 16 years, i.e., with twice the speed as the Voyager spacecraft. IP will enable the dedicated exploration of the heliospheric boundary by imaging the heliosphere from inside and outside the heliopause, and by directly sampling the unknown LISM. IP will also enable in situ measurements in the undisturbed LISM beyond the heliospheric bow shock or bow wave. The measurement of the chemical composition of the neutral gas in the local interstellar cloud is an important element of the scientific investigations of IP. So far, the chemical composition of the LISM was mostly inferred from pickup ions in the solar wind, from anomalous cosmic rays, and from spectroscopic observations of nearby stars. We are designing a highly specialized mass spectrometer to measure the neutral gas at these extremely low densities. The expected species to be recorded are H, He, C, N, O, Ne, Na, Mg, Al, Si, P, S, Ar, Ca, and Fe. In addition, this mass spectrometer will measure the isotope composition of D/H, ^{3}He/^{4}He, ^{22}Ne/^{20}Ne, and ^{36}Ar/^{38}Ar of the LISM with unprecedented accuracy. These measurements will take advantage of the long duration of the IP mission, allowing for long integration times.**

TABLE OF CONTENTS

1. INTRODUCTION

The proposed Interstellar Probe spacecraft (IP) of NASA shall reach the undisturbed interstellar medium well beyond 300 AU within 50 years of travel time [1, 2], i.e., with 6.8 – 7.0 AU/year, which is twice the speed of the Voyager spacecraft. The IP mission is organized in three steps. First, the Heliosphere phase, where IP will travel through the heliosphere up to the termination shock, to about 90 AU, within roughly 16 years. Second, the Heliosheath phase, where IP will continue on its trajectory and fly through the heliosheath within about 9 years up to the heliopause at about 150 AU [3]. Third, the Interstellar phase, where IP will enter the very local interstellar medium (VLISM), reaching about 350 AU in 50 years. IP will enable the dedicated exploration of the heliospheric boundary, imaging the vast heliosphere, and direct sampling of the unknown LISM for the first time. IP will also enable the first situ measurements in the undisturbed LISM far beyond the heliospheric bow shock or bow wave [4].

A European contribution at the level of medium-size mission opportunity (equivalent to a M-class mission of ESA) was proposed, referred to as STELLA [5], with contributions of scientific instruments and contributions to the spacecraft.

The foreseen payload of IP includes 87 kg for the scientific instruments, consuming 87 W. The scientific instruments are a Magnetometer, Plasma Wave Instrument, Plasma Sub-system, Pick-up Ion Instrument, Energetic Particle Spectrometer, Cosmic Rays, Interstellar Dust Analyzer, Neutral Mass Spectrometer, Energetic Atom Imager, and a Lyman-alpha Spectrograph [1]. Here we present our design for the Neutral Mass Spectrometer (NMS).

The knowledge of the chemical composition of a stellar entity is important to understand its origin and its evolution to the present state. On IP the chemical composition will be measured in all relevant domains namely in the thermal plasma, in the energetic particles, in the neutral gas, and in dust. In addition, measurements will be conducted to learn about the interstellar environment, the local plasma environment, the local dust distribution, high-energy particle populations, and the radiation environment, the large-scale structures of the heliosphere, and the photon environment.

So far, the chemical composition of the LISM was mostly inferred from pickup ions in the solar wind [6, 7], from anomalous cosmic rays [8], and from spectroscopic observations of nearby stars [9]. The Ulysses mission of ESA [10, 11] and the Interstellar Boundary Explorer mission of NASA [12] performed direct measurements of the interstellar neutral atoms flowing into the inner solar system. These data are limited to a few major species of the LISM: H [13, 14, 15, 16], the D/H ratio [17, 18], He [13, 19, 11], O [13], and the Ne/O ratio [20] in the VLISM (see also review in [21]). Moreover, these measurements at 1 AU or other locations in the inner heliosphere are not necessarily representative of the unperturbed LISM [21], and many neutral species of the LISM are completely lost on their travel into the inner solar system due to ionization and other loss processes before they can reach the inner heliosphere [23].

The NMS foreseen for IP has the following measurement requirements: i) mass range 1 – 300 u/e (actually covering H to Fe), ii) mass resolution m/Δm = 100, iii) instantaneous field-of-view of 10°, and iv) viewing in ram direction and co-alignment with the dust instrument. The driver for the instrument design is the composition of the LISM neutral gas that has a total neutral density of $n_0 = 0.2$ cm^{-3}, most of which is hydrogen; the He abundance in the LISM is less than a tenth of that, and heavier species have an abundance between 10^{-3} and 10^{-4} with respect to H [24]. We are designing a highly specialized neutral gas mass spectrometer, referred to as NMS, to measure the neutral gas at these extremely low gas densities. The NMS measurements will take advantage of the long duration of the IP mission, allowing for long integration times for the individual measurements.

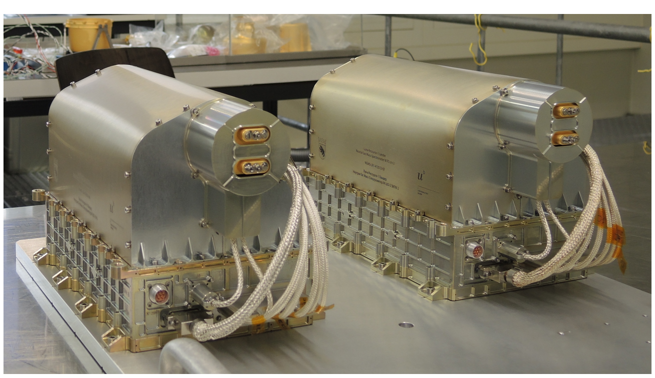


Figure 2: Neutral Gas Mass spectrometer for the Luna-Resurs mission [24, 25], proto flight model (left) and flight spare model (right).

2. INSTRUMENT CONCEPT AND DESIGN

The Neutral gas Mass Spectrometer (NMS) for IP has to measure gas densities at very low levels with an instrument that requires low resources from the spacecraft. NMS is a time of flight (TOF) mass spectrometer based on the design of our previous TOF instruments for space research, such as RTOF/ROSINA/Rosetta [26], P-BACE/MEAP [27] NGMS/Luna-Resurs [24, 25] shown in Figure 2, and NIM/PEP/JUICE [28] shown in Figure 1. Compared to other mass spectrometer types, TOF mass spectrometers allow measuring the whole mass spectrum instantaneously instead of scanning over the mass range, which increases the sensitivity significantly and reduces the needed measurement time. In a time-of-flight instrument ions are produced continuously in the ionization region of the instrument. With a high-voltage extraction pulse these ions are accelerated into the analyzer section. In our instrument these ion extractions are done at 20 kHz. The pulsed extraction causes a duty cycle in the use of the produced ions. To overcome the duty cycle of the ion extraction we use an ion storage ion source [29, 28], which collects and stores the continuously produced ions in the ionization region until the next extraction pulse subjects these ions to the time-of-flight mass analyzer. This improves the sensitivity significantly, for example for mass spectra recorded in the low 10^{-10} mbar range, mass peaks down to $1\cdot10^{-16}$ mbar were identified in the mass spectra for a recording period of only 5 s [24].

Quadrupole mass spectrometers (QMS) have a long history in space research, see review in [30]. QMS, and the related

Figure 1: NIM instrument of PEP/JUICE. Left, the golden structure is the sensor head unit, and right is the electronics box.

ion trap mass spectrometers, are scanning instruments, thus a full mass spectrum is obtained by scanning across the desired range of m/z values, where the resulting duty cycle has an adverse effect on the sensitivity of the instrument. When collecting full mass spectra, the advantage in sensitivity of a TOF MS with an ion storage source over a scanning instrument (e.g., a QMS) is of the order of (10 * mass range). Moreover, the need for high voltages at radio frequency makes QMS instruments power hungry that is a problem for the IP mission which is severely power limited.

The mass resolution $R = m/\Delta m$ of a TOF instrument is calculated by $R = t_{tof}/(2\Delta t)$ with t_{tof} the time of flight of an ion and Δt the full width at half-maximum (FWHM) of the mass signal peak. The longer the drift path, the longer the drift time t_{tof}, which results in a better mass resolution. Size limitations of the instrument imposed by the spacecraft limit the length of the drift path length, though, and typically our instruments are about 30 cm in the long dimension. Therefore, our ion-optical design of the TOF analyzer includes an ion mirror to almost double the drift path length, with the added advantage for energy focusing which improves the mass resolution. Even though the requirement for mass resolution is modest, $m/\Delta m = 100$, the better the mass resolution the better is the signal-to-noise ratio. In a TOF mass spectrometer the ions of an ion packet of a certain mass u/e are focused to shorter

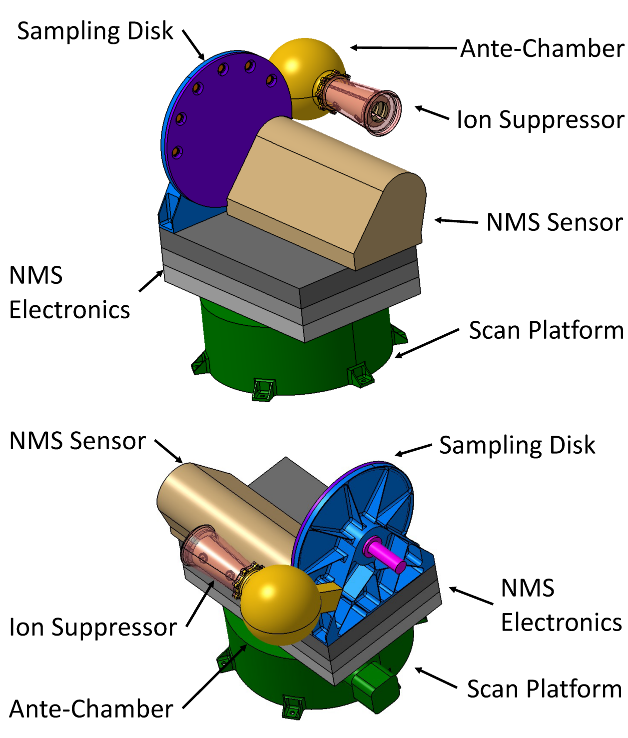


Figure 3: Schematic views of the NMS instrument with major elements identified: top panel shows side from approaching LISM gas flux; bottom panel shows the rear side of NMS.

widths in time when increasing the mass resolution, but keeping the total number of ions in that packet, i.e., keeping the ion-optical transmission. Thus, the narrower the mass peaks the higher the peak amplitudes by keeping the same number of ions; the better mass resolution in a TOF instrument improves the S/N ratio proportionally. With previous instruments of this size, we routinely achieve $m/\Delta m = 1000$, which improves the S/N compared to the NMS requirement by a factor of about 10.

Mass range of NMS is m/z 1 – 150 (regular mass range), where m is the mass of the species under analysis and z charge of the ion, and m/z 1 – 300 u/e (high mass range); earlier instruments of this type have a mass range up to m/z 1000 [24, 28]. The mass range of a TOF instrument is easily expandable as it basically is only limited by the length of the memory recording the TOF spectra. Instead, the upper limit of the mass range is given by the science requirements, which here only warrant an upper limit of 300 u/e. For our previous 30 cm instruments, recording 16 bits horizontally was sufficient for this mass range, including margin, when using a 2 GHz ADC [28, 32].

NMS uses electron impact ionization of neutral gas with a typical electron energy of nominally 70 eV (50 eV to 150 eV are possible) to produce the ions for mass spectrometric analysis [33]. Two thermionic cathodes, a main and a redundant filament, serve as electron emitters in the NMS instrument. Electron impact ionization is a simple and the classical ionization source, which we have used in all previous mass spectrometers for space flight. The two filaments will be enhanced yttrium oxide filaments, Y_2O_3e, to minimize the power consumption while increasing their lifetime [33].

The relative speed of the spacecraft with respect to the interstellar gas of about 59 km/s results from the speed of the spacecraft of about 33 km/s and the flow velocity of the interstellar gas with respect to the Solar System of about 26 km/s [34, 19]. Direct measurement of neutral gas at these relative speeds is not possible, as discussed in reference [35], because these high speeds correspond to energies of the formed ions that cannot be handled by such an ion-optical system of the mass analyzer. Instead, we have to use an ante-chamber to thermalize the gas stream before subjecting the gas to the ion source of NMS. We already used an ante-chamber for the NIM/PEP instrument on JUICE, see Figure 1 and reference [28]. The additional advantage of an ante-chamber is the ram pressure enhancement of the density inside the cavity of the ante-chamber n compared to the outside density n_0 thanks to the thermalization of the hyper-velocity gas stream of the interstellar gas entering the ante-chamber [31]. Because of the high relative velocity of the spacecraft and the LISM gas stream, the density enhancement is more than a factor of 100 for the heavier species of the LISM, as can be seen in Figure 4.

For power reasons the NMS instrument cannot be turned on all the time during a 50-year mission. Also, the filaments and the detector have a limited lifetime. Thus, NMS will be operated at regular intervals, which has to be studied against resources from the spacecraft and consumables of NMS components.

The outward trajectory of IP, after the Jupiter gravity assist maneuver, will be near the upwind direction of the LISM gas flow. To maximize the signal strength the NMS instrument pointing should be in the ram direction within 2˚ accuracy, which might make a scanner platform for NMS necessary, depending on the spacecraft pointing during the outward trajectory and the NMS accommodation on the spacecraft.

Table 1. Summary of NMS instrument specifications.

Parameter	Current Best Estimate/Comments
Mass (kg)	10 kg, instrument 5 kg, scanner
Volume (cm^3) Witch scanner	L x W x H = 30 cm x 45 cm x 35 cm L x W x H = 30 cm x 45 cm x 45 cm
Thermal requirements	Non-Op: –40°C to +60°C Op: –20°C to + 40°C
Data Volume (compressed)	Direct meas.: 1.12 Mbyte per day Foil read-out: 5.03 Mbyte per foil
Field-of-view	10° full angle
Pointing of FoV center	2°
Current TRL	5, some sub-units 7–8
Duration of Experiment	Entire IP Mission

To increase the sensitivity of NMS further, it will employ the foil collection technique where LISM atoms are implanted in a suitable collection foil for later analysis. The foil collection technique was used for collecting solar wind ions during the Apollo missions [36] and later for the Genesis mission [37], and for collecting interstellar gas atoms on the Mir space station [38]. NMS will have 50 foil collectors accommodated on the sampling disk to be exposed to the LISM gas flow, one collection foil at a time. Typical collection periods on a single foil will be about one year. This corresponds to a spatial averaging of 6–7 AU along the IP trajectory, which is acceptable for most mission phases given the spatial dimensions of the heliosphere [3]. To release the implanted species from the foil it will be heated stepwise to temperatures of 1500ºC – 2000ºC to release all elements up to Fe into the gas phase. There will be 128 temperature steps, optimized for the release temperatures for the different species implanted into the foil. Most likely, the heating will destroy the collection foil, thus, each foil can only be used once. The foil to be analyzed is rotated into the ionization region of the ion source of the mass spectrometer so that the species released from the foil will be directly placed in the

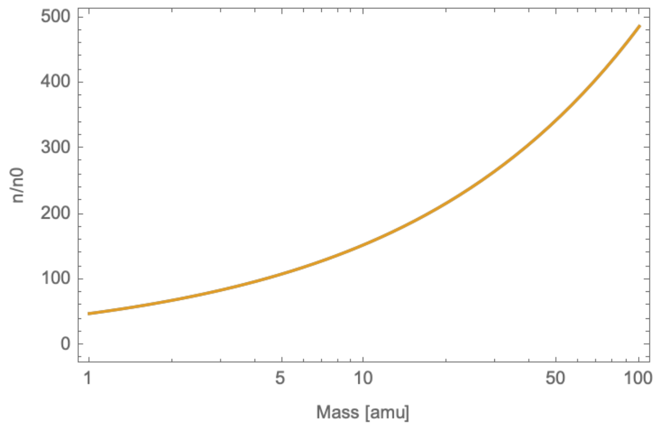


Figure 4: Calculation of the density enhancement in the ante-chamber because of the ram pressure enhancement for a relative gas speed of 59 km/s, based on [31].

ionization volume of the NMS ion source for efficient ionization and detection of the material collected in a foil.

Figure 3 shows a schematic drawing of the NMS instrument with its major components, the NMS sensor unit (the actual mass analyzer), the electronics box, the ante-chamber, the sampling disk with the collection foils, the ion suppressor, and the scanner in case that it is needed. Figure 5 shows a detail of the ion source design with one of the collection foils placed at the ion source ionization region for read-out of the material implanted in the foil during its exposure to the LISM gas flow. For read-out of the implanted material, the collection foil will be heated in temperature steps until complete destruction of the collection foil. As evaporation temperatures are typically material specific, chemical species will be released in a sequence, simplifying their analysis during post-processing.

The NMS instrument will be operated in two different modes. One mode is the direct (ante-chamber) measurement of the LISM gas along the IP trajectory at regular intervals, in

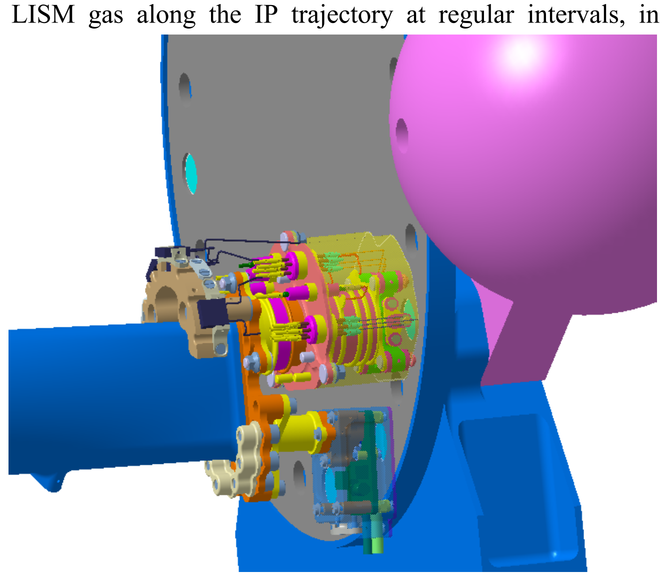


Figure 5: Detail showing the ion source, the detector, the sampling disk with the foil collectors, and the ante-chamber.

current planning once per month, which gives 600 measurement days during the 50-year mission. Such a direct measurement takes 1 full day (24 hours), and produces 1.12 Mbyte of data (compressed). The other mode is the read-out of the collection foil, which takes about 1 week, including cleaning the ion source, cleaning the collection foil, background measurements, and the actual foil read-out. This mode produces 5.03 Mbyte of data (compressed) per foil read-out. The collection foil read-outs add an additional 350 measurement days. In total the NMS operation is close to 1000 measurement days, which is compatible with the expected lifetime of filaments and detector. Currently, two filaments are foreseen, but if necessary, even four filaments can be accommodated in the ion source to have more reserves for the long mission duration. The detector is the more severe limitation. Using micro-channel plate detectors (MCP) their lifetime is given by the total extracted charge which results in the 1000 operation days. Implementing redundancy in the detector is not straight forward, but might have to be considered given the long duration of the IP mission. A summary of the key facts of the NMS instrument for IP is given in Table 1.

The temperature of the LISM gas of about 7400 K [34, 19] together with the ram speed of the LISM gas result in an angular width of the gas flow of up to 1.5° (half angle) at the IP spacecraft. To cover the full angular distribution of the gas flow and allow for moderate pointing requirements of the spacecraft for the NMS instrument, the resulting field-of-view of NMS is 10° full angle.

The radiation environment for the Interstellar probe mission has been estimated for several mission scenarios [39]. The total accumulated radiation dose behind 10 mm Al is about 30 krad considering the following contributions: 1. About 0.2-year launch and checkout; 2. About 0.6-year cruise to Jupiter; 3. Jupiter gravity assist (JGA) maneuver; 4. About 12-year (inner) heliosphere phase; 5. About 5-year heliosheath phase; 6. About 35-year interstellar phase in the very local interstellar medium (VLISM); and the 7. background gamma rays from the radioisotope thermoelectric generator (RTG). This total radiation dose can easily be handled by passive shielding and suitable radiation tolerant components (e.g. at the 100 krad level).

3. EXPECTED PERFORMANCE

NMS will have to measure the neutral gas of the LISM at very low number densities. Two measurement modes are foreseen, the direct measurement of the flux of neutral gas into the ante-chamber, and the collection of the neutral gas in the collection foils and the later read-out of these foils.

To estimate the signals that will be recorded with NMS during the mission we start with an estimate of the abundances of species in the local interstellar medium [40]. Table 2 shows the densities of the elements in the LISM and the expected fluxes at the IP spacecraft in the Interstellar phase.

For the estimate of signal from the direct mode we start with the density of a species in the interstellar medium. For each species we consider the density enhancement in the ante-chamber because of the ram pressure effect of gas at an incoming speed of 59 km/s (see Figure 4), and the overall detection efficiency [41]. The ion source is a so-called storage ion source, which overcomes the duty cycle losses of conventional ion sources for TOF mass spectrometers [42, 28]. NMS measures a complete mass spectrum with a cadence of 20 kHz. These mass spectra are added to form a histogram for a selected period, depending on the need of S/N and data reduction. After NMS turn-on, the integration period is shorter, 10–100 s, to evaluate outgassing of the instrument and of the ion source. After about an hour we will switch to integration times of 1 h. The longer integration time will increase the sensitivity and reduce the data rate at the same time. Since the interstellar signal is expected to be constant on much larger time scales [43] hence, long integration times will not be a problem. Table 2 shows the expected counts for some integration times, 1-s to estimate the efficiency of the instrument, 1-h as the nominal data product, and 1-d when integrating all measurements of a 24-h measurement day. Numbers printed in green have a sufficiently high S/N to be evaluated scientifically. In direct mode we can measure the major species and the noble gases He, Ne, and Ar. This will give a data set of 600 measurements along the IP trajectory for these species.

To estimate the signal from the foil collection mode we start with the flux of interstellar species as seen on the IP

Elements	**H**	**He**	**C**	**N**	**O**	**Ne**	**Na**	**Mg**	**Al**	**Si**	**P**	**S**	**K**	**Ar**	**Ca**	**Fe**
n_X / n_H [*1e6]	1.00E+06	1.00E+05	661	46.8	331	123	2.04	6.61	0.0794	8.13	0.219	15.8	0.304	2.82	0.000407	2.51
n [cm^-3]	0.25	0.025	1.65E-04	1.17E-05	8.28E-05	3.08E-05	5.10E-07	1.65E-06	1.99E-08	2.03E-06	5.48E-08	3.95E-06	7.60E-09	7.05E-07	1.02E-10	6.28E-07
flux [cm^-2 s^-1]	1.46E+06	1.46E+05	9.62E+02	6.81E+01	4.82E+02	1.79E+02	2.97E+00	9.62E+00	1.16E-01	1.18E+01	3.19E-01	2.30E+01	4.42E-02	4.11E+00	5.93E-04	3.65E+00
Ante-Chamber																
Ram enhancement	48.7	97.38	168.7	182.2	194.8	217.8	233.5	238.5	253	257.7	271.1	275.4	304.1	292.2	307.9	364.3
Counts [s-1]	1.22E+02	2.43E+01	2.79E-01	2.13E-02	1.61E-01	6.70E-02	1.19E-05	3.94E-05	5.02E-07	5.24E-05	1.48E-06	1.09E-04	2.31E-07	2.06E-03	3.13E-09	2.29E-05
Counts [h-1]	4.38E+04	8.76E+03	1.00E+02	7.67E+00	5.80E+01	2.41E+01	4.29E-03	1.42E-02	1.81E-04	1.89E-02	5.34E-04	3.92E-02	8.32E-05	7.42E-01	1.13E-06	8.23E-03
Counts [d-1]	1.05E+06	2.10E+05	2.41E+03	1.84E+02	1.39E+03	5.79E+02	1.03E-01	3.41E-01	4.34E-03	4.53E-01	1.28E-02	9.40E-01	2.00E-03	1.78E+01	2.71E-05	1.98E-01
Foil collection																
LISM flux [s^-1]	1.46E+06	1.46E+05	9.62E+02	6.81E+01	4.82E+02	1.79E+02	2.97E+00	9.62E+00	1.16E-01	1.18E+01	3.19E-01	2.30E+01	4.42E-02	4.11E+00	5.93E-04	3.65E+00
Counts [wk-1]	8.81E+06	8.81E+05	5.82E+03	4.12E+02	2.91E+03	1.08E+03	1.80E+01	5.82E+01	6.99E-01	7.16E+01	1.93E+00	1.39E+02	2.68E-01	2.48E+01	3.58E-03	2.21E+01
Counts [mo-1]	3.77E+07	3.77E+06	2.49E+04	1.77E+03	1.25E+04	4.64E+03	7.70E+01	2.49E+02	3.00E+00	3.07E+02	8.26E+00	5.96E+02	1.15E+00	1.06E+02	1.54E-02	9.47E+01
Counts [yr-1]	4.59E+08	4.59E+07	3.04E+05	2.15E+04	1.52E+05	5.65E+04	9.37E+02	3.04E+03	3.65E+01	3.74E+03	1.01E+02	7.26E+03	1.40E+01	1.30E+03	1.87E-01	1.15E+03

Table 2: Estimated counts for the expected elements for the two NMS modes, direct mode with the ante-chamber and the foil collection mode. Densities for the LISM are from [40]. See main text for further details.

spacecraft in the Interstellar phase. The species are implanted in the foil with some efficiency, thermally released during the read-out process, ionized in the ion source and registered after mass analysis. Table 2 shows the expected counts for selected integration times, 1-week to estimate the efficiency of the collection process, 1-month for e.g. around the heliopause, and 1-year as the nominal data product. Numbers printed in green have a sufficiently high S/N to be evaluated scientifically. In the foil collection mode, we can measure all expected species except for Ca, which will give a data set of 50 measurement points along the IP trajectory for these species.

The estimates for the abundance of elements in the LISM [40] include neutral species and ions (with charge states 1 to 4). Both the direct channel with the ante-chamber and the foil collection technique do not distinguish between neutral and ionized species, they measure neutral and ionized particles together, independent of their charge state. Since neutral and ionized particles are present in the LISM in comparable amounts, their separation to make a statement on the ionization state of the LISM (which is relevant for plasma models of the LISM-heliosphere interaction) is required. This separation is accomplished by an ion suppressor added in front of the ante-chamber (and possibly in front of the exposed collection foil). By switching the ion suppressor on or off we will measure the neutral flux and the total flux, respectively. The technical implementation of an ion-suppressor is straight forward (see Figure 3), the scientific need for it must be evaluated in future studies, as it would present a duty cycle for total flux measurements.

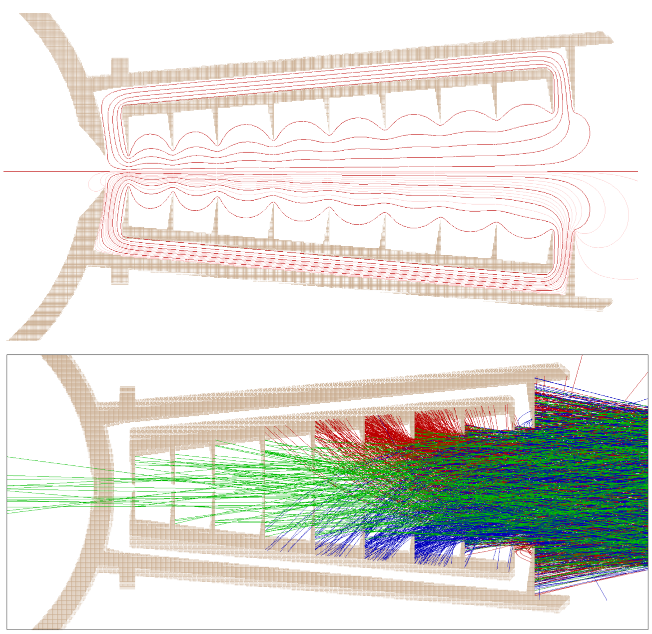


Figure 6: SIMION calculation of the potential distribution in the ion suppressor (top panel) and the trajectories of positive (red) and negative (blue) ions and neutral atoms (green) of up to 3 keV (bottom panel). Deflection electrode potentials are at +1kV and –1kV.

The ion suppressor design is based on an electrostatic deflection scheme, see Figure 7, top panel. To simulate its effectiveness a SIMION ion-optical calculation was performed with a total of 160’000 ions covering a wide energy range entering the ion suppressor within the nominal field of view (see Figure 7, bottom panel). Figure 7 shows the incident ion energy as function the location along the symmetry axis where they hit the suppressor surfaces. Deflection voltages were at +1 kV and –1 kV deflection voltage on the upper and lower electrode, respectively. The ante-chamber is to the left with the entrance at x=111 mm. Typical ion energies of solar wind H^+ and He^{++} are indicated by the horizontal lines, although IP will fly in the the solar wind and thus it is very unlikely that these ions can enter the instrument. Also, interstellar Fe^+ at 1 keV, the highest-mass component of the LISM expected to be measured, is indicated. No ions below 5 keV energy can get through the

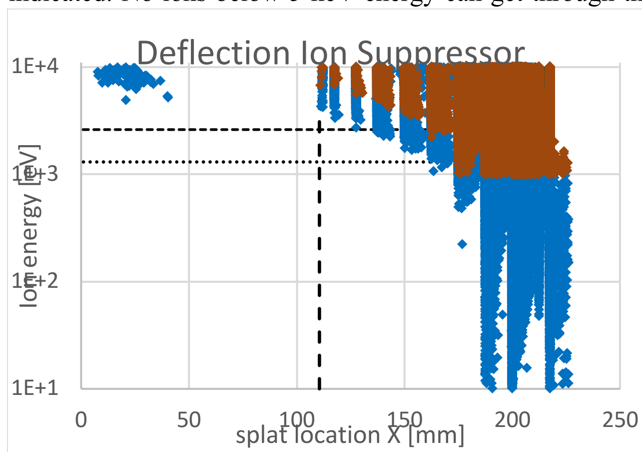


Figure 7: SIMION calculation of the ion impact location in the ion suppressor at a deflection voltage of +/– 1 kV (blue dots) and +/– 2 kV (red dots). Vertical dashed line indicates the entrance into the ante-chamber, horizontal dotted line is for solar wind H^+, and the horizontal dashed line is for solar wind He^{++} and for LISM Fe^+.

system (transmission < 10^{-5}). Remaining ions that make it into the antechamber are all above 5 keV initial energy (top left dots in Figure 7). The overall simulated transmission of 5 – 10 keV ions through the ion deflector into the antechamber is $1.01 \cdot 10^{-3}$. If necessary, the deflection electric field can be increased to also suppress those higher-energy ions. This is shown in Figure 7 (red dots), where 10^5 ions above 5 keV were flown through the ion suppressor with the deflection electrodes at +/– 2 kV. In this case, no ions at energies below 10 keV made it into the antechamber.

The expected signal levels given in Table 2 for the two NMS modes are for the trajectory outside the heliopause. Inside the heliopause filtration effects occur, where the neutral density of an element is reduced because of charge exchange processes between the neutral atoms and ions [44, 23]. Furthermore, inside the heliopause, the ions will be deflected by the electromagnetic fields in these locations and thus the ion density will be reduced. No LISM ions will pass through the termination shock of the heliosphere, thus only the neutral

LISM signal will be recorded by NMS during the heliosphere phase. Thus, with NMS measurements along the IP trajectory passing the termination shock, and the heliopause, the measured signal will reflect these different plasma entities directly. Figure 8 shows the expected density profile along the IP trajectory for H and He atoms using $n_H = 0.127\ cm^{-3}$ at the heliospheric termination shock, and $n_H = 0.195\ cm^{-3}$ and $n_{He} = 0.016\ cm^{-3}$ at 1000 AU [45, 46, 47, 48]. LISM He atoms hardly interact with the heliospheric plasma, thus they enter

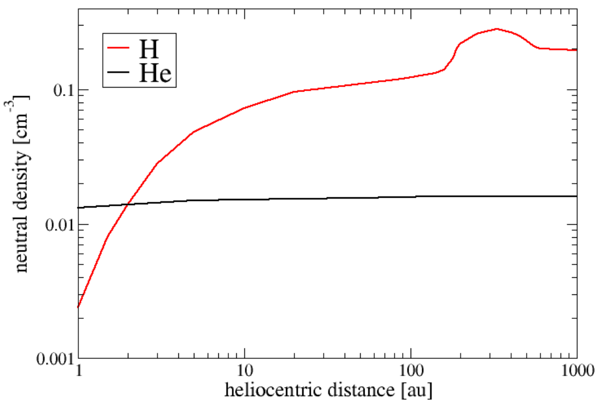


Figure 8: Expected density profile for LISM H and He atoms along the IP trajectory.

into the solar system unaffected and only in the inner solar system their density reduces somewhat because of ionization by solar photons and solar wind electrons. In stark contrast, LISM H atoms strongly interact with the heliospheric plasma, mostly via charge exchange between H atoms and protons. This interaction leads to a density enhancement in front of the heliopause by about a factor 2, the so-called hydrogen wall, and a continuous reduction of LISM H inside the heliosphere because of photo-ionization and charge exchange processes. Such density profiles will be recorded for all mentioned LISM species, which will allow to study the interaction of the LISM and the heliospheric plasma in unprecedented detail.

Measuring the composition of neutral gas in the interstellar gas flow is also a challenge for testing and calibration because the gas arrives at a speed of 59 km/s. This speed translates to a specific energy of 18 eV/nuc, or an energy range from 18 eV to about 1 keV for the elements from H to Fe. Since the detection in NMS is either via implantation in the collection foil or via the ante-chamber one can use an ion beam for the calibration. Since ion beams can be characterized very well, calibration of NMS will allow for accurate measurements of the densities of the different species in the LISM.

4. Conclusions

We presented an advanced design for a very sensitive mass spectrometer for the IP mission. The primary science goal of NMS is the measurement of the composition of the very local neutral interstellar gas, sufficiently outside the influence of the heliosphere, with measurements foreseen for the entire trajectory. Possibly, the trajectory of IP allows for flybys of trans-Neptunian objects like Quaoar, Ixion, Orcus, or others to be identified in the future, which might also provide opportunities for mass spectrometric investigations if the flyby distance is close enough.

The measurement requirements for NMS are composition and density of the interstellar gas i) the major species, H and He, ii) of the heavy species, C, N, O, Ne, Na, Mg, Al, Si, P, S, Ar, Ca, and Fe, iii) and isotopes of the more abundant species: D/H, $^3He/^4He$, $^{20}Ne/^{22}Ne$, $^{36}Ar/^{38}Ar$, and possibly others. This list of species to be measured allows to derive some astrophysical important element ratios, like the Ne/O ratio that provides information on the evolution of our Milky Way [20]. Making the ISM composition measurements along the trajectory of IP, from the inner Solar System all the way to the undisturbed interstellar medium. Their densities are extremely low and a challenge for in situ investigations. NMS high sensitivity is the result of the combination of several factors: i) the high sensitivity of the mass spectrometer itself, ii) the significant ram-pressure enhancement in the ante-chamber resulting from the high velocity of the IP spacecraft, iii) long integration times for the direct measurements, iv) extremely long integration times by using the foil collection technique.

The measured particle density profiles of individual species along the S/C trajectory will also serve to derive the filtration of the species at the interface between the heliosphere and the interstellar medium. By adding an ion-suppressor to the ante-chamber and possibly to the collection foil the ionization state of the LISM can be measured.

5. Acknowledgements

The financial support by the Swiss Space Office and the Swiss National Science Foundation is gratefully acknowledged.

6. References

[1] P.C. Brandt, E. Provornikova, S.D. Bale, A. Cocoros, R. DeMajistre, K. Dialynas, H.A. Elliott, S. Eriksson, B. Fields, A. Galli, M.E. Hill, M. Horanyi, T. Horbury, S. Hunziker, P. Kollmann, J. Kinnison, G. Fountain, S.M. Krimigis, W.S. Kurth, J. Linsky, C.M. Lisse, K.E. Mandt, W. Magnes, R.L. McNutt, J. Miller, E. Moebius, P. Mostafavi, M. Opher, L. Paxton, F. Plaschke, A.R. Poppe, E.C. Roelof, K. Runyon, S. Redfield, N. Schwadron, V. Sterken, P. Swaczyna, J. Szalay, D. Turner, H. Vannier, R. Wimmer-Schweingruber, P. Wurz, and E.J. Zirnstein, Future Exploration of the Outer Heliosphere and Very Local Interstellar Medium by Interstellar Probe, Space Sci. Rev., 219:18 (2023), 71 pages, DOI: 10.1007/s11214-022-00943-x.

[2] John Hopkins University/Applied Physics Laboratory: https://interstellarprobe.jhuapl.edu/

[3] Daniel B. Reisenfeld, Maciej Bzowski, H.O. Funsten, J. Heerikhuisen, P.H. Janzen, M.A. Kubiak,

D.J. McComas, N.A. Schwadron, J.M. Sokół, A. Zimorino, and E.J. Zirnstein, A Three-dimensional Map of the Heliosphere from IBEX, The Astrophysical Journal Supplement Series 254 (2021), 40, DOI: 10.3847/1538-4365/abf658

[4] P. Mostafavi, L.F. Burlaga, I.H. Cairns, S. A. Fuselier, F. Fraternale, D. A. Gurnett, T. K. Kim, W. S. Kurth, N. V. Pogorelov, E. Provornikova, J. D. Richardson, D. L. Turner and G. P. Zank, Shocks in the Very Local Interstellar Medium, Space Science Reviews 218 (2022), 27, DOI: 10.1007/s11214-022-00893-4

[24] P. Wurz, D. Abplanalp, M. Tulej, and H. Lammer, A Neutral Gas Mass Spectrometer for the Investigation of Lunar Volatiles, Planet. Sp. Science 74 (2012) 264–269.

[5] R.F. Wimmer-Schweingruber, N. Andre, S. Barabash, P. Brandt, T.S. Horbury, I. Luciano, B. Lavraud, R.L. McNutt, E. Provornikova, E. Quemerais, R. Wicks, M. Wieser, and P. Wurz, STELLA – In situ Investigations of the Very Local Interstellar Medium, Frontiers in Astronomy and Space Sciences, Front. 9:1063849 (2022), 10 pages, DOI: 10.3389/fspas.2022.1063849.

[6] G. Gloeckler, L.A. Fisk, J. Geiss, M.E. Hill, D.C. Hamilton, R.B. Decker, and S.M. Krimigis, Composition of Interstellar Neutrals and the Origin of Anomalous Cosmic Rays, Space Sci. Rev. 143 (2009), 163–175, DOI: 10.1007/s11214-008-9482-5.

[7] G. Gloeckler and J. Geiss, Composition of the local interstellar medium as diagnosed with pickup ions, Advances in Space Research 34 (2004) 53–60.

[8] A.C. Cummings, E.C. Stone, C.D. Steenberg, Composition of Anomalous Cosmic Rays and Other Heliospheric Ions, Astrophys. J. 578 (2002), 194–210, DOI: 10.1086/342427

[10] M. Witte, Kinetic parameters of interstellar neutral helium - Review of results obtained during one solar cycle with the Ulysses/GAS-instrument, Astronomy and Astrophysics 426 (2004), 835–844, DOI: 10.1051/0004-6361:20035956.

[11] M. Witte, H. Rosenbauer, E. Keppler, H. Fahr, P. Hemmerich, H. Lauche, A. Loidl, and R. Zwick, The interstellar neutral-gas experiment on ULYSSES, Astronomy and Astrophysics Supplement Series 92 (1992), 333–348.

[12] D.J. McComas, F. Allegrini, P. Bochsler, M. Bzowski, M. Collier, H. Fahr, H. Fichtner, H. Funsten, S. Fuselier, G. Gloeckler, M. Gruntman, V, Izmodenov, P. Knappenberger, M. Lee, S. Livi, D. Mitchell, E. Möbius, T. Moore, S. Pope, D. Reisenfeld, E. Roelof, J. Scherrer, N. Schwadron, R. Tyler, M. Wieser, M. Witte, P. Wurz, and G. Zank, IBEX – Interstellar Boundary Explorer, Space Science Reviews 146 (2009), 11–33, DOI:10.1007/s11214-009-9499-4

[13] E. Möbius, P. Bochsler, M. Bzowski, G. Crew, H.F. Funsten, S.A. Fuselier, A. Ghielmetti, D. Heirtzler, V.V. Izmodenov, M. Kubiak, H. Kucharek, M.A. Lee, T. Leonard, D.J. McComas, L. Petersen, L. Saul, J. Scheer, N. Schwadron, and P. Wurz, Direct Observations of the Interstellar H, He, and O Flow by the Interstellar Boundary Explorer, Science, 326 (2009), 969-971.

[14] L. Saul, P. Wurz, D. Rodriguez, J. Scheer, E. Möbius, N. Schwadron, H. Kucharek, T. Leonard, M. Bzowski, S. Fuselier, G. Crew, and D. McComas, Local Interstellar Neutral Hydrogen sampled in-situ by IBEX, Astrophys. Jou. Suppl. 198 (2012) 14, doi:10.1088/0067-0049/198/2/14.

[15] L. Saul, M. Bzowski, S. Fuselier, M. Kubiak, D. McComas, E. Möbius, J. Sokół, D. Rodríguez, J. Scheer, and P. Wurz, Local Interstellar Hydrogen's Disappearance at 1AU: Four Years of IBEX in the rising solar cycle, Astrophys. Jou. 767 (2013) 1–7, doi:10.1088/0004-637X/767/2/130.

[16] A. Galli, P. Wurz, N.A. Schwadron, K. Fairchild, D. Heirtzler, E. Möbius, H. Kucharek, R. Winslow, M. Bzowski, M.A. Kubiak, I. Kowalska-Leszczyńska, S.A. Fuselier. J.M. Sokół, P. Swaczyna, and D.J. McComas, One Solar Cycle of Heliosphere Observations with the Interstellar Boundary Explorer: Energetic Neutral Hydrogen Atoms Observed with IBEX-Lo from 10 eV to 2 keV, The Astrophysical Journal Supplement Series 261 (2022), 18, DOI:10.3847/1538-4365/ac69c9

[17] D.F. Rodríguez Moreno, P. Wurz, L. Saul, M. Bzowski, M.A. Kubiak, J.M. Sokół, P. Frisch, S.A. Fuselier, D.J. McComas, E. Möbius, and N. Schwadron, Evidence of direct detection of interstellar deuterium in the local interstellar medium by IBEX, Astron. and Astrophys. 557, (2013) A125, 1–13, DOI: 10.1051/0004-6361/201321420.

[18] D.F. Rodríguez Moreno, P. Wurz, L. Saul, M. Bzowski, M.A. Kubiak, J.M. Sokół, P. Frisch, S.A. Fuselier, D.J. McComas, E. Möbius, and N. Schwadron, Signal Processing for the measurement of the Deuterium/ Hydrogen ratio in the Local Interstellar Medium, Entropy 16 (2014) 1134–1168, doi:10.3390/e16021134.

[19] P. Swaczyna, M. Bzowski, J. Heerikhuisen, M.A. Kubiak, F. Rahmanifard, E.J. Zirnstein, S.A. Fuselier, A. Galli, D.J. McComas, E. Möbius, and N.A. Schwadron, Interstellar Conditions Deduced from Interstellar Neutral Helium Observed by IBEX and Global Heliosphere Modeling, The Astrophysical Journal 953 (2023), 107, DOI: 10.3847/1538-4357/ace719

[20] P. Bochsler, L. Petersen, E. Möbius, N.A. Schwadron, P. Wurz, J.A. Scheer, S.A. Fuselier, D.J. McComas, M. Bzowski, and P.C. Frisch, Estimation of the neon/ oxygen abundance ratio at the heliospheric termination shock and in the local interstellar medium from IBEX ob-

servations, Astrophys. Jou. Suppl. 198 (2012) 13, doi:10.1088/0067-0049/198/2/13.

[21] A. Galli, I.I. Baliukin, M. Bzowski, *et al.,* The Heliosphere and Local Interstellar Medium from Neutral Atom Observations at Energies Below 10 keV, *Space Science Reviews* 218 (2022), 31, DOI: 10.1007/s11214-022-00901-7

[22] P. Swaczyna, F. Rahmanifard, E.J. Zirnstein, D.J. McComas, J. Heerikhuisen, Slowdown and Heating of Interstellar Neutral Helium by Elastic Collisions beyond the Heliopause, The Astrophysical Journal Letters 911 (2021), L36, DOI: 10.3847/2041-8213/abf436

[23] A. Galli, S., Redfield, E. Provornikova, H. Kucharek, P. Swaczyna, J.M. Sokół, et al., Measuring interstellar neutrals in-situ: a critical contribution to heliospheric science, Bulletin of the AAS 55 (2023) 3, DOI:10.3847/25c2cfeb.5deec7eb.

[24] P.C. Frisch and J.D. Slavin, The Chemical Composition and Gas-to-Dust Mass Ratio of Nearby Interstellar Matter, The Astrophysical Journal, Volume 594(2), (2003) 844–858, DOI: 10.1086/376689

[25] L. Hofer, P. Wurz, A. Buch, M. Cabane, P. Coll, D. Coscia, M. Gerasimov, D. Lasi, A. Sapgir, C. Szopa, and M. Tulej, Prototype of the gas chromatograph-mass spectrometer to investigate volatile species in the lunar soil for the Luna-Resurs mission, Planet. Sp. Sci., 111 (2015) 126–133.

[26] S. Scherer, K. Altwegg, H. Balsiger, J. Fischer, A. Jäckel, A. Korth, M. Mildner, D. Piazza, H. Rème, and P. Wurz, A novel principle for an ion mirror design in time-of-flight mass spectrometry, Int. Jou. Mass Spectr. 251 (2006) 73–81.

[27] D. Abplanalp, P. Wurz, L. Huber, I. Leya, E. Kopp, U. Rohner, M. Wieser, L. Kalla, and S. Barabash, A neutral gas mass spectrometer to measure the chemical composition of the stratosphere, *Advances in Space Research,* vol. 44(7), (2009), 870–878.

[28] M. Föhn, A. Galli, A. Vorburger, M. Tulej, D. Lasi, A. Riedo, R.G. Fausch, M. Althaus, S. Brüngger, P. Fahrer, M. Gerber, M. Lüthi, H.P. Munz, S. Oeschger, D. Piazza, and P. Wurz, Description of the Ion-optical System of a Mass Spectrometer for JUpiter's ICy Moons Explorer, IEEE Aerospace Conference Big Sky, MT, USA, (2021), 50100, 14 pages, DOI: 10.1109/AERO50100.2021.9438344.

[29] D. Abplanalp, P. Wurz, L. Huber, and I. Leya, An Optimised Compact Electron Impact Ion Source for a time-of-flight mass spectrometer, Int. Jou. Mass Spectrom., 294 (2010), 33–39.

[30] A. Vorburger, P. Wurz, and H. Waite, Chemical and Isotopic Composition Measurements on Atmospheric Probes, Space Sci. Rev. 216(57), (2020) 31 pages, DOI 10.1007/s11214-020-00684-9.

[31] P. Wurz, A. Balogh, V. Coffey, B.K. Dichter, W.T. Kasprzak, A.J. Lazarus, W. Lennartsson, and J.P. McFadden, Calibration Techniques, in Calibration of Particle Instruments in Space Physics, (edt. M. Wüest, D.S. Evans, and R. von Steiger), ESA Communications, ISSI Scientific Report, SR-007 (2007) 117–276.

[32] R. G. Fausch, P. Wurz, M. Tulej, J. Jost, P. Gubler, M. Gruber, D. Lasi, C. Zimmermann, and T. Gerber, Flight electronics of GC-mass spectrometer for investigation of volatiles in the lunar regolith, 2018 IEEE Aerospace Conference, Big Sky, MT, USA, 2018, pp. 1–13, doi: 10.1109/AERO.2018.8396788.

[33] R. Fausch., Föhn, M., Hofer, L., Meyer, S., Wahlström, P., Wyler, S., and Wurz, P., Power-Efficient Electron Emitters for Electron Ionization in Spaceborne Mass Spectrometers. 2024 IEEE Aerospace Conference, (2024) submitted.

[34] M. Bzowski, P. Swaczyna, M.A. Kubiak, J.M. Sokół, S.A. Fuselier, A. Galli, D. Heirtzler, H. Kucharek, T.W. Leonard, D.J. McComas, E. Möbius, N.A. Schwadron, and P. Wurz, Interstellar neutral helium in the heliosphere from Interstellar Boundary Explorer observations. III. Mach number of the flow, velocity vector, and temperature from the first six years of measurements, Astrophys. Jou. Suppl. 220(2), (2015), article id. 28, DOI: 10.1088/0067-0049/220/2/28.

[35] R.G. Fausch, J.A. Schertenleib, and P. Wurz, Advances in Mass Spectrometers for Flyby Space Missions for the Analysis of Biosignatures and Other Complex Molecules. Universe, 8(8), 416 (2022), 8 pages, DOI: 10.3390/universe8080416

[36] J. Geiss, F. Buehler, H. Cerutti, and P. Eberhardt, Solar-Wind Composition Experiment, in Apollo 15: Preliminary Science Report, (1972) NASA SP-289, 25–122.

[37] R.C. Wiens, D. Reisenfeld, A. Jurewicz, and D Burnett, The Genesis Solar-Wind Mission: first deep-space robotic mission to return to Earth, in Sample Return Missions, Elsevier, (2021) 105–122, DOI: 10.1016/B978-0-12-818330-4.00005-7.

[38] F. Bühler, M. Bassi, P. Bochsler, O. Eugster, E. Salerno, G.N. Zastenker, Yu.N. Agafonov, L.G. Gevorkov, N.A. Eismont, A.V. Prudkoglyad, V.V. Khrapchenkov, and N.I. Shvets, First Detection of ^{4}He in a Sample of Interstellar Neutral Gas Collected Onboard Mir Station. Astrophysics and Space Science 274 (2000), 19–24, DOI: 10.1023/A:1026558814412

[39] Interstellar Probe Study Team, Interstellar Probe Study 2019 Report, (2021), NASA Task Order NNN06AA01C.

[40] J.D. Slavin and P. C. Frisch, The boundary conditions of the heliosphere: photoionization models constrained by interstellar and in situ data, Astron. Astrophys. 491 (2008), 53–68, DOI: 10.1051/0004-6361:20078101

[41] P. Wurz, D. Abplanalp, M. Tulej, and H. Lammer, A Neutral Gas Mass Spectrometer for the Investigation of Lunar Volatiles, Planet. Sp. Science 74 (2012) 264–269.

[42] D. Abplanalp, P. Wurz, L. Huber, and I. Leya, An Optimised Compact Electron Impact Ion Source for a time-of-flight mass spectrometer, Int. Jou. Mass Spectrom., 294 (2010), 33–39.

[43] P.C. Frisch, M. Bzowski, C. Drews, T. Leonard, G. Livadiotis, D.J. McComas, E. Möbius, N. Schwadron, and J.M. Sokół, Correcting the Record on the Analysis of IBEX and STEREO Data Regarding Variations in the Neutral Interstellar Wind, The Astrophysical Journal, 801(1), (2015), 15 pages, DOI: 10.1088/0004-637X/801/1/61.

[44] H.-R. Müller, and G. P. Zank, Heliospheric filtration of interstellar heavy atoms: Sensitivity to hydrogen background, J. Geophys. Res., 109, A07104 (2004), 13 pages, DOI: 10.1029/2003JA010269.

[45] G.P. Zank, J. Heerikhuisen, B. E. Wood, N.V. Pogorelov, E. Zirnstein, and D.J. McComas, Heliospheric Structure: The bow wave and the Hydrogen Wall, Astrophys, Jou. 763:20, (2013) 13 pages, DOI:10.1088/0004-637X/763/1/20.

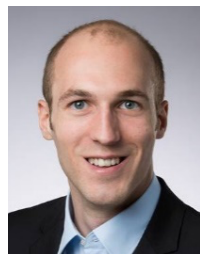
[46] J.M. Sokół, M.A. Kubiak, M. Bzowski, E. Möbius, and N.A. Schwadron, Science Opportunities from Observations of the Interstellar Neutral Gas with Adjustable Boresight Direction, Astrophys. Jou. 245:28 (2019, 22 pages, DOI:10.3847/1538-4365/ab50bc.

[47] P. Swaczyna, D.J. McComas, E.J. Zirnstein, J.M. Sokół, H.A. Elliott, M. Bzowski, M.A. Kubiak, J.D. Richardson, I. Kowalska-Leszczynska, S.A. Stern, H.A. Weaver, C.B. Olkin, K. N. Singer, and J.R. Spencer, Astrophys. Jou. 903:48 (2020) 11 pages, DOI: 10.3847/1538-4357/abb80a.

[48] M. Bzowski, M.A. Kubiak, A. Czechowski, P.C. Frisch, S.A. Fuselier, A. Galli, J. Grygorczuk, J. Heerikhuisen, H. Kucharek, D.J. McComas, E. Möbius, N.A. Schwadron, J. Slavin, J.M. Sokół, P. Swaczyna, P. Wurz, and E.J. Zirnstein, Astrophys. Jou. 882:60 (2019) 15 pages, DOI: 10.3847/1538-4357/ab3462.

7. BIOGRAPHY

Peter Wurz *has a degree in electronic engineering (1985), an M.Sc. and a Ph.D. in Physics from Technical University of Vienna, Austria (1990). He has been a post-doctoral researcher at Argonne National Laboratory, USA. Since 1992 at the University of Bern. He is Professor of physics, 2015–2022 head of the Space Science and Planetology division, and since 2022 director of the physics institute. He has been Co-I and PI for many science instruments for space missions of ESA, NASA, ISRO, CNSA, Roscosmos, and JAXA.*



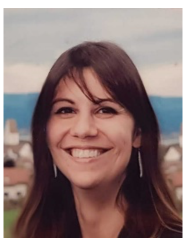
Rico Fausch *completed an apprenticeship as a mechanical design engineer before he received a B.Sc. in Systems Engineering (micro technologies) from NTB University of Applied Science (Switzerland) in 2013 and an M.Sc. in Biomedical Engineering from University of Bern (Switzerland) in 2015. He has been with the Physics Institute of the University of Bern since 2016, where he received his Ph.D. in Physics in 2020 for the finalization of the NGMS / Luna 27. As an instrument scientist, he is involved in the design of several space missions and space instrumentation including NIM / PEP / JUICE (ESA) and CODEX / DIMPLE / CLPS (NASA).*

Daniele Piazza *has more than 20 years of experience in the design and development of space instruments. He has a Ph.D. in mechanical engineering from ETH Zurich and started his career in Formula 1. Since 2005 he leads the mechanical engineering group working on space instruments at the University of Bern. Switzerland.*

Jonathan Gasser *received an M.Sc. in theoretical physics from the University of Bern in 2019, with a thesis on the Axion production from a QCD plasma. He received a Ph.D. in physics in 2023 working on ENA imaging for the IMAP mission, in particular designing, building, and commissioning elements of the ENA calibration facility.*

Martina Föhn *received an M.Sc. in physics from the University of Bern in 2017, with a thesis on the scattering properties of charge state conversion surfaces for space applications for the JUICE and the IMAP missions. She received a Ph.D. in physics in 2021 working on mass spectrometry for the JUICE mission.*

André Galli *received a Ph.D. in Physics from the University of Bern in 2008. After a period as an engineer and technology consultant in Uster and his post-doctoral period at the Netherlands Institute for Space Research in Utrecht, he re-joined in 2012 the University of Bern as a scientist for atmospheric and space research. His research topics cover a broad range from laboratory experiments in the context of icy surfaces in the solar system, data analysis for space missions (Mars Express, Venus Express, IBEX, Rosetta), to project science and management for upcoming space missions (JUICE and IMAP in particular).*



Audrey Vorburger *holds a B.S. and a M.Sc. in Electrical Engineering and Information Technology that she obtained from ETH Zürich in 2008. In 2013 she received her Ph.D. in Physics from the University of Bern. Having spent one and a half years as a post-doctoral researcher at the American Museum of Natural History in NY, USA, she is now back at the University of Bern perusing her teaching certificate. She is a Co-I of SARA onboard Chandrayaan-1 and of PEP onboard JUICE.*