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Measurement of neutral atoms and ions in Mercury's exosphere

M. Mildner *, P. Wurz, S. Scherer, M. Zipperle, K. Altwegg, P. Bochsler, W. Benz, H. Balsiger

Physikalisches Institut, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland

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Abstract

The Mercury apparatus for ions and atoms (MAIA) is a linear time-of-flight mass spectrometer operating in two modes, a neutral mode and an ion mode, which are used alternatively. MAIA is designed to determine the composition of Mercury's exosphere and possibly its crust. The mass resolution of MAIA is sufficient to resolve all elements up to mass 300 amu. In both optional modes the mass range extends from 1 to 100 amu, and, if required, it can be increased up to 300 amu by changing the data acquisition mode. Even isotopes could be resolved, however, the partial pressures at Mercury are most likely too low for identification.

1. Introduction

Mercury, the innermost planet of the solar system, is the least well known of the terrestrial planets. Because of its proximity to the Sun, ground-based observations are difficult. Furthermore, it is very difficult to reach with a spacecraft because the planet is small and located very deep in the Sun gravitational well (Racca, 1997). Nevertheless, Mercury is the most interesting planet in our solar system to study and it is highly desirable to carry instruments capable of investigating this planet's tenuous atmosphere and its interactions with the magnetosphere (Slavin et al., 1997). Therefore, Mercury is the target of ESA's space mission BepiColombo (Balogh et al., 2000). The Mercury Apparatus for Ions and Atoms (MAIA) could address two main questions; the first one is the investigation of the composition of Mercury's exosphere. The second one is the composition of the surface.

The Hermean atmosphere is technically an exosphere, which is characterised by rare collisions of atoms (Hunten et al., 1988). The existence of H, He, O, Na, K and Ca in the Mercury atmosphere has been established. There may be water ice in craters on the polar caps (Killen and Ip, 1999), which might result in water molecules in the atmosphere. The day-side particle density at the planet surface is estimated to be between 100 and 2×10^6 cm^{-3} with probable large night-side enhancements for hydrogen and helium (Kumar, 1976). The total pressure at the surface is thought to be 10^{-12} mbar. The average surface temperature varies between 100 and 700 K (Chase et al., 1976). Using data from several orbits, two-dimensional maps of the atmosphere will be constructed at a resolution of approximately $20^\circ \times 5^\circ$ for the more abundant atmospheric constituents. By recording the exospheric ions that have been sputtered from the Hermean surface, we will infer the elemental composition of the surface. Sputtering from the surface will be induced by energetic magnetospheric ions and sometimes by solar wind ions (Wurz and Blomberg, 2001). The energy range of MAIA will be sufficiently wide to record most of the sputtered ions, since the energy distribution of sputtered ions peaks around 10 eV. No energy determination of the ions will be performed because these are of sputtered origin and therefore the energy information is not very important. Integration over the energy spectrum of the ions will improve the sensitivity for abundance determinations. Thus, information about elements from the Hermean surface such as Na, K, Fe, S, Mg, Si, and Al (Ti, O) can be obtained.

2. Experimental details

MAIA, shown in Fig. 1, is a linear time-of-flight mass spectrometer with an overall length of 400 mm. The instrument design is based on the ROSINA-RTOF sensor (Balsiger et al., 2001), which is currently developed for the ESA Rosetta mission. A time-of-flight mass spectrometer

* Corresponding author. Tel.: +41-31-631-4426; fax: +41-31-631-4405.

E-mail address: mildner@phim.unibe.ch (M. Mildner).

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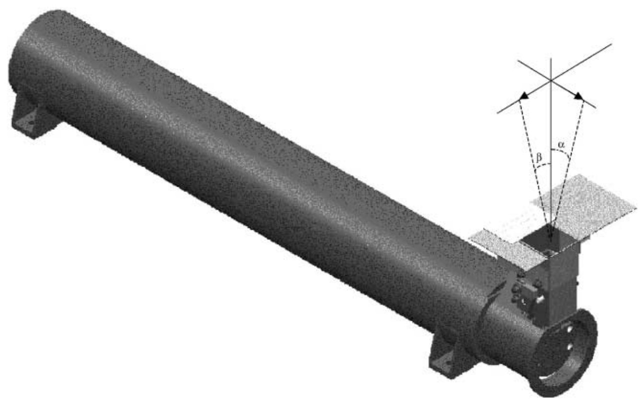

Fig. 1. Schematic view of the Mercury apparatus for ions and atoms MAIA. On the right-hand side the orthogonal extraction ion source is plotted. MAIA has an overall length of 400 mm with an estimated mass of 4 kg including electronics (not shown).

Table 1
Summary of the characteristics of the MAIA instrument

Assignment	Measurement of Mercury's exosphere
Objective	Ions and atoms
Mass range	1–100 amu
Mass resolution	$m/\Delta m \geqslant 300$
Field-of-view	$20^\circ \times 5^\circ$
Accepted particle energy	Neutral mode: $\leqslant 0.26$ eV
	Ion mode: $\leqslant 50$ eV
Power consumption	Neutral mode: 5 W
	Ion mode: 3 W
	Standby mode: 0.5 W
Mass	4 kg

has inherent advantages with respect to other concepts. The principle offers an opportunity to record a complete mass spectrum for each measurement cycle without the necessity of scanning over the entire mass range. Therefore, it is very easy to establish an absolute mass scale calibration. Additionally, the mechanical design of a time-of-flight instrument is very simple.

The MAIA instrument consists of one orthogonal extraction ion source, a 300 mm field-free drift path, and one fast MCP detector (Schletti et al., 2001). The orthogonal extraction ion source consists of an ion-optical entrance channel and an acceleration region into the time-of-flight section, which is oriented orthogonal to the initial ion propagation direction (Willey and McLaren, 1955; Dawson and Guilhaus, 1989). In Fig. 2 a sectional drawing of the orthogonal extraction ion source of the MAIA prototype. Depending on the operation mode MAIA will measure either neutral gas (neutral mode) or external ions (ion mode). Measurements will be performed alternatively. The geometrical field-of-view of MAIA is $20^\circ \times 5^\circ$ and it is mainly limited by the geometrical layout of the entrance channel of the orthogonal extraction ion source. A ceramic metal compound technology is used for the construction of the ion source, which guarantees a lightweight design with high reliability and functionality (Scherer, 1999).

The neutral channel of MAIA will be used for the determination of the composition of Mercury's atmosphere. The neutral gas is ionised by an electron impact ionisation unit inside the ion source. In addition, the electron beam facilitates a storage of ions, which results in a high sensitivity of 10^{-4} A/mbar. The neutral channel has very high detection efficiency for neutral gas at temperatures up to approximately 3000 K(0.26 eV). This will cover the anticipated temperatures of the exospheric gas, but will exclude the measurement of sputtered atoms from Mercury's surface, because the energy distribution of sputtered atoms peaks around 2–3 eV and ions of this energy cannot be stored in the ion source. With the neutral channel of MAIA only the

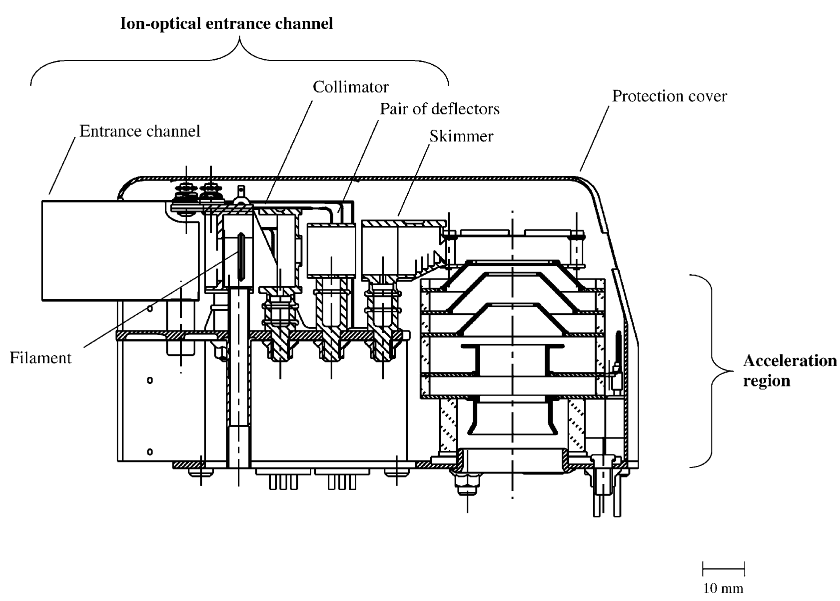

Fig. 2. Sectional drawing of the orthogonal extraction ion source of the MAIA prototype in side view.

neutral volatile elements escaping from Mercury's crust will be investigated.

The ion channel will record most of the sputtered ions from Mercury's surface. The acceptance of the instrument at the low-energy end of the spectrum is determined by spacecraft charging. With a favourable placement of the sensor on the spacecraft as well as efficient spacecraft potential control the limit of 5 eV might be pushed to even lower values, thus increasing the sensitivity of the ion channel. A software-based self-adjustment of the electrodes of the entrance channel of the orthogonal extraction ion source will increase the accepted ion energy range.

A light and very fast MCP detector will detect the particles. It is able to record very fast pulses with a single ion pulse width of 500 ps (Wurz and Gubler, 1996). In Table 1 is a summary for the main characteristics of the MAIA instrument given.

3. Experimental results

Fig. 3 shows a mass spectrum of residual gas in the calibration chamber recorded with a prototype of MAIA in neutral mode using the ionisation assembly of the ion source. The mass spectrum is typical for this large vacuum chamber at modest bake-out. The mass resolution in this mode is at mass 18 amu (H_2O) about $m/\Delta m = 460$ (FWHM) and at ^{136}Xe it is $m/\Delta m = 520$ (FWHM). The dynamic range extends over five orders of magnitudes after integration for 4 h. For the MAIA prototype, the ionisation assembly is placed in the orthogonal entrance channel. Therefore, no storage effect for ionised ions is in effect and explains the low sensitivity of 6×10^{-9} A/mbar of the MAIA prototype. As a next step, we will implement ion storage in the ion source in a similar way as on the ROSINA-RTOF sensor (Balsiger et al., 2001) to increase the sensitivity in this mode by several orders of magnitude. An alternative way to improve the sensitivity (neutral mode) and the efficiency (ion mode) of the MAIA instrument is to introduce a pseudo-random time-of-flight mass method (Hadamard transformation), which can improve the duty cycle up to 50% (Brock et al., 2000), but it limits probably the recordable mass range.

The MAIA instrument is able to detect exospheric ions when operating in the ion mode. The mass spectrum of an external xenon ion beam for a mass range up to 150 amu is shown in Fig. 4. The total count rate versus mass-per-charge is plotted. External ions with energy of 10 ± 1.5 eV are supplied from our low-energy ion accelerator (Ghielmetti et al., 1983). The depicted count rate corresponds to a detected ion flux of 4.2 ions/(cm^2 s).

From the accumulated counts, we derive an overall efficiency for the MAIA prototype of 4×10^{-3}. This overall efficiency is determined by three factors: an ion optical transmission of 0.27; a duty cycle of 0.025 for xenon from the orthogonal extraction principle; and 0.6 from the ion detector. Xenon ions of different charge states can be identified as well as some residual gas ions. Individual isotopes are clearly resolved. The mass resolution for MAIA operation in the ion mode is about $m/\Delta m = 400$ (FWHM).

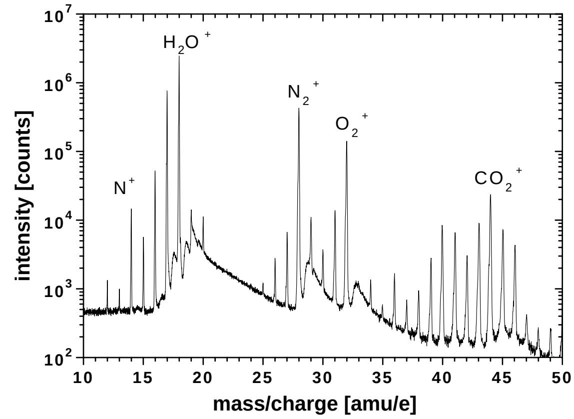

Fig. 3. The neutral mode of the MAIA instrument: mass spectrum of residual gas at a chamber pressure of 1×10^{-6} mbar. The integration time is 4 h.

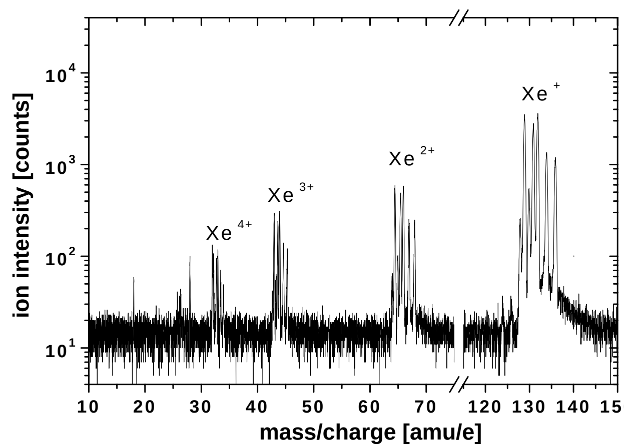

Fig. 4. The ion mode of the MAIA instrument: mass spectrum of external xenon ions with energy of 10 ± 1.5 eV. The drift voltage is -2500 V. The pressure in vacuum chamber is 1×10^{-7} mbar. The incoming ion flux is approximately 5000 ions/(cm^2 s). The integration time is 12.5 h.

The geometrical acceptance range is one of the key parameters for MAIA's mapping tasks. In Fig. 5 the total count rate of xenon ions is shown as a function of the angle α and β with respect to the geometrical axis of the entrance of the MAIA prototype.

Our low-energy ion accelerator produces the external ion beam. The energy of the external ions is 8 ± 1.5 eV. The angular acceptance range is $\pm 3.5^\circ$ at FWHM. The goal of a high-resolution two-dimensional mapping for the more abundant atmospheric constituents is achievable.

Fig. 6 shows the total ion count rate of xenon ions as a function of the beam energy of the external ion beam. The accepted energy range for external ions has been determined as 5–50 eV. The curve peaks at 10 eV, which was the design goal and this maximum can be slightly shifted by adjusting

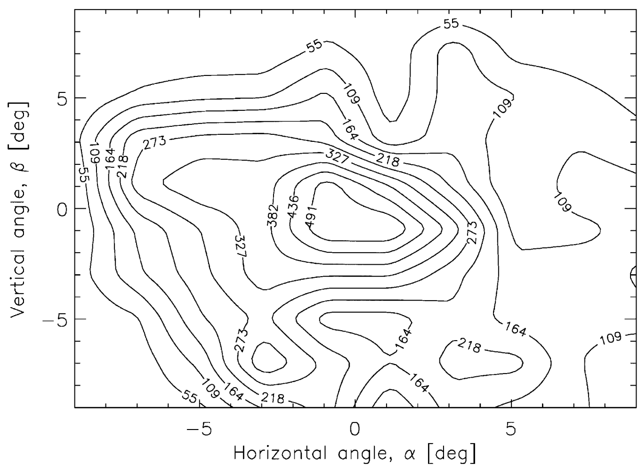

Fig. 5. Geometrical acceptance range of MAIA-prototype for external low-energy ions with energy of 8 ± 1.5 eV. Data acquisition time is 600 s.

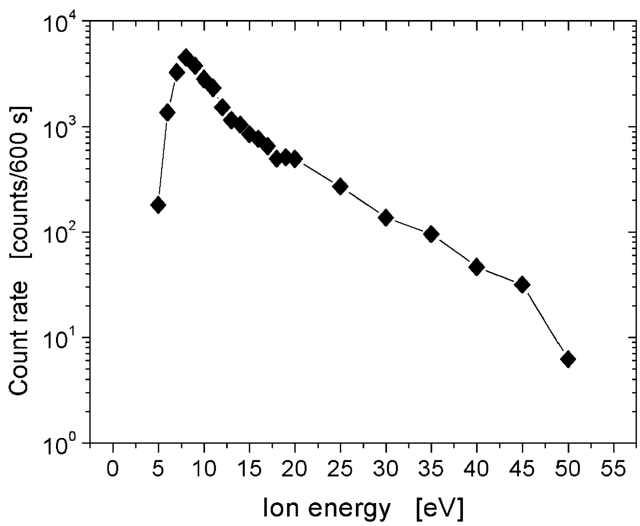

Fig. 6. Accepted energy range of the MAIA instrument for external ions. Data acquisition time is 600 s for each energy setting.

the potentials applied to the orthogonal entrance channel. This result proves that sputtered ions from the Mercury surface can be detected.

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