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Space-borne mass spectrometer instrumentation

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Abstract

In-situ space-borne mass spectrometers are applied in different fields of space physics. These instruments observe the solar wind plasma, solar energetic particles and cosmic rays, the atoms of the local interstellar medium, the gas and dust of the coma and tail of comets or planetary atmospheres and magnetospheres. The flux intensity, mass, energy and charge of the particles is measured in-situ and density, bulk velocity and temperatures of the particle populations are derived. The interplanetary space is a very large plasma physics laboratory and with in-situ instruments one is able to observe and learn to understand the physical phenomena in this plasma. A future application of high precision mass spectrometers is the in-situ measurement of the elemental, isotopic and molecular composition of samples of planetary bodies and comets. (Int J Mass Spectrom 215 (2002) 113–129) © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Instruments such as mass spectrometers are used for in-situ particle and ion observations in space. Energetic rays and particles have been observed since the end of the 19th century. First radioactivity of ground minerals was identified as the source of radiation, but it become clear with the advent of balloon experiments and the decisive experiments and discovery in 1912 that there was also an energetic radiation called "cosmic rays" from space [1]. The instrument was an electroscope and it discharged more rapidly as the balloon ascended. The radiation was initially believed to be electromagnetic in nature, but during the 1930s, it was found that cosmic rays must be electrically charged because they are affected by the Earth's magnetic field. While cosmic ray research is still carried out also with ground or balloon based instrumentation, it is the atmosphere and the Earth's magnetic field, which cut off the lower energetic ions of the space plasma. The advent of space age with the launch of SPUTNIK in 1957 and EXPLORER I in 1958 triggered the research of in-situ space plasma physics and the development for suitable detectors. The Geiger counter instrumentation measurements on the Explorer satellite lead to the discovery of the enormous number of high-energy particles trapped in the Earth's magnetic field, known as the Van Allen Radiation Belts. The existence of the solar wind was predicted in 1951 from remote observations of the inclination of the comet ion tails off the radial comet-Sun direction and the solar coronal source was modelled in 1958. But it was not before LUNIK II in 1960 and finally MARINER II in 1962 that the existence of the solar wind was proven by direct in-situ observations [2–6]. In-situ space plasma instrumentation was not the driving factor to move

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into the space age, this was the competitive race to the moon, i.e., manned space flight. However, to the end of the last millennium, all solar system planets except Pluto have been visited by spacecrafts and space plasma parameters were measured in-situ from 0.3 AU to beyond 80 AU.

Particle space research is spanning the whole field of in-situ plasma observations and the exploration of planetary bodies including their magnetospheres, atmospheres and surfaces. The first generation of particle instruments was focusing mainly on the energy distribution of the ions and electrons in the space plasma. The instrumentation became more mature and presently flying mass spectrometers have mass resolutions resolving elements and isotopes, determine energy and charge of the particles. The questions to be answered in the next decades ask for mass resolutions and sensitivities for very precise isotopic ratios and quantitative measurements of trace elements, presently only achieved with ground based laboratory instruments. Returning samples from space, such as the silicate minerals of the lunar regolith and igneous rocks returned by the APOLLO and LUNA spacecrafts, and analyse the probes in laboratories on Earth is one possibility. Then the rocket not only has to launch the instruments required for sampling and storage, but also the Earth Return Vehicle. This was exercised with the probes from the moon, it was envisaged for the cancelled MARS SAMPLE RETURN 2005 mission and will be realised onboard the STARDUST or GENESIS mission. Samples of cometary dust or the solar wind plasma will be collected in-situ and returned to Earth. The sampled material can then be thoroughly analysed in terrestrial laboratories and be compared to the known terrestrial and meteorite abundances [7]. The precise mineral, elemental and isotopic compositions of the samples of lunar rocks and regolith have been determined as well as the cosmic radiation exposure ages and geochronical ages. The drawback of this approach is the possible terrestrial contamination, i.e., the lunar rocks, stored on Earth, contain traces of water vapour from the Earth's atmosphere [8]. Future explorations should therefore include very sensitive and high-resolution in-situ space-borne instruments, in the long term capable to derive results comparable to the precision of ground based laboratory measurements.

Besides mass spectrometer type instrumentation, other in-situ instruments measure the magnetic fields and waves in the space plasmas such as solar wind or planetary magnetospheres. These measurements are crucial for the interpretation and understanding of the observed ion and electron fluxes and their temporal variations.

In the following, we will present the principles of space borne mass spectrometers and some examples (by far not all) and discuss their capabilities and applications. For space-borne instrumentation, the available resources, such as mass, volume, power and telemetry budget restrict the designs of instruments. The thermal and radiation environments are very different from the terrestrial environment and are unique for each space mission. The goal is to design and built instrumentations for exquisite scientific data return within the given resources.

2. Space plasma, planetary bodies and magnetospheres

The solar wind is a steady flow of highly ionised plasma out of the solar atmosphere. The average solar wind is composed of electrons and approximately 95–97% protons, 2–4% α-particles (He^{2+}) and 1% minor ions. The most abundant minor ions are the elements C, N, O, Ne, Mg, Si and Fe. At Earth's orbit the solar wind plasma is very dilute and hot. The plasma density is about 1–10 ions/cm^3 and the bulk speed is supersonic and about 300–800 km/s, but under some conditions can exceed 1000 km/s. The energy of solar wind ions is between 0.5 and 2.0 keV/nuc. The flux intensity of the solar wind is about 2×10^8 ions/cm^2 s. The kinetic temperature is between 10^4 and 10^6 K and the interplanetary magnetic field strength is about 5 nT. Despite the absence of collisions this plasma behave much like collisional gases or fluids, with coherent behaviour induced by their electric and magnetic fields. The electrical conductivity of the solar wind plasma is very high, as the plasma is nearly fully ionised, i.e., main ions are protons, He^{2+} or α-particles, O^{6+} or O^{7+} or Fe^{7+} to Fe^{16+}. A second temperature, referred to as the coronal temperature, is used to characterise the solar wind. It is derived from the relative charge state distributions of the elements in the solar wind and is typically of the order of the temperature of the solar corona, 10^6 K. The charge distributions are "frozen-in" in the solar corona, and are a "ion-thermometer" to measure in-situ the temperature in the distant solar corona. The solar magnetic field lines are tied to the plasma due to the high conductivity. As the solar wind flows outward from the rotating Sun, the field patterns take on the general form of a spiral, the so-called Parker's spiral. The knowledge of the solar wind elemental and ionic charge composition, the kinetic temperature and the variability is essential for our understanding of the physics of the solar wind, the solar atmosphere and heliosphere and the Sun itself. One fundamental question is how the solar wind is accelerated in the vicinity of the Sun and why the solar corona is so extremely hot compared to the relative 'cool' photosphere (millions degree Kelvin compared to a few thousand degree Kelvin) [9].

High-energy solar particles are accelerated near the Sun due to flares or coronal mass ejections. Energetic interplanetary particles are accelerated in the heliosphere in so-called co-rotating interaction regions or by interplanetary shocks and at the termination shock of the heliosphere. Cosmic rays and galactic particles have been accelerated to extreme energies far away from our heliosphere, to energies even beyond TeV. Galactic cosmic rays consist of energetic electrons and nuclei, which are a direct sample of material from far beyond our solar system. They could have been accelerated by shock waves of supernova explosions. The origin and transport processes for these particle populations and the underlying acceleration mechanisms, for example plasma cyclotron wave resonances for solar particle acceleration or Fermi's acceleration process in the vicinity of a supernova, are studied with the data of the in-situ particle instruments. The high-energy cosmic and galactic rays are modulated by the interplanetary field, i.e., with the 11 or 22 years solar activity cycle.

All planets and comets explored to date have magnetospheres [10]. They are the regions above the atmosphere and ionosphere where magnetic phenomena and the high atmospheric conductivity caused by ionisation are important in determining the behaviour of charged particles. In the 1960, this research was not limited to observing the energetic particle naturally occurring in the Earth radiation belts, but within the frame of the 'Starfish' programme H-bombs were detonated in the upper atmosphere and the resulting energetic electrons lasted for about 5 years in the Earth's radiation belts. Magnetospheric plasma physics studies the magnetospheres of planets, asteroids and comets and the structure of the magnetospheres due to the interaction of the solar system bodies with the solar wind. The solar wind carries with it a magnetic field and a frame dependent electric field (Lorentz force). This electric field is very important for the depletion or even removal of planetary atmospheres from an unmagnetised planet, such as Mercury or Mars [11,12], as well as sweeping out of the heliosphere the so-called pick-up ions. These are formerly neutral atoms, ionised by charge exchange with the solar wind plasma or solar UV radiation. The major source for neutral atoms in the solar system is the interstellar local medium, which is due to the local dilute gas cloud our solar system is presently passing through. This interstellar local medium has a density of about 0.1 atoms/cm^3, a relative velocity of 26 km/s and a temperature of about 5000 K. Resulting pick-ion populations have been measured in-situ, i.e., H^+, $^3He^+$, $^4He^+$ or O^+ originating from the local interstellar medium [13,14]. Another source of neutral atoms is atoms sputtered of solar system body surfaces, such as the moon. These lunar pick-up ions such as O^+, Al^+ or Si^+ have been observed [15,16].

The dust grains in the solar system have been known before the space age due to the observed zodiacal light. The elemental composition of interplanetary dust particles (asteroidal and cometary) is one of three major types: chondritic (60%), iron–sulfur–nickel (30%), and mafic silicates, which are iron–magnesium-rich silicates (10%). Since dust and especially interstellar dust is believed to be composed of primordial matter of the time of the formation of the solar system, the determination of the composition of individual grains is of interest to planetary science and the science of the early solar system development. To understand the process of dust transport in the solar system and its interaction with the interplanetary magnetic field, not only the grain mass and orbital elements, but also the charge of the dust grains must be measured in-situ.

As comets (or "dirty snow balls") approach the Sun, they develop a coma consisting of gas and dust grains. The observable coma, the ion and dust tails of the comets are up to 10^8 times larger than the nucleus of the comet. Comets are the grand, most tiny cheaters in our solar system. The gas contains not just atoms or simple molecules such as CO or H_2O, but also more complex organic molecules such as formic acid or acetonitrile. The composition of planetary atmospheres, i.e., the isotopic abundances of the traces of noble gases such as Ne and the identity of the molecular species such as O_2, N_2 or CO_2 has been measured [17]. The geological age of lunar rocks was determined in samples returned to Earth. Radioactive decay measurements of lunar samples show that the highlands formed about 4 billion years ago and the lowlands about 3.5 billion years ago. This is in marked contrast to surface rocks on Earth, which show a wide distribution of ages, from very young to about 4 billion years. Lunar rocks are old; and it was concluded that the Moon is not geologically active. All lunar rocks are igneous (solidified lava). Lunar rocks are depleted in elements with low boiling points. This suggests that the material in the lunar crust was subjected at some point to higher temperatures than rocks in the crust of the Earth. The origin of the Moon is still unknown. Before the advent of space age theories have included simultaneous formation of the Earth and Moon which is ruled out by the observed chemical composition differences [8,18].

Different in-situ mass spectrometers should be capable to measure the mass of particles in space such as ions, atoms, molecules and dust grains. Some must be capable to observe particle fluxes from different directions and determine the trajectory path of the incoming particles. In-situ space plasma instrumentation must be capable to observe an energy range of the space plasma ions ranging from eV to beyond GeV. The flux intensities vary from 10^{14} ions/cm^2 s sr (MeV/nuc)$^{-1}$ for solar wind protons to 10^{-14} ions/cm^2 s sr (MeV/nuc)$^{-1}$ for galactic cosmic rays.

3. Space plasma in-situ measurements and instrumentation

There are different types of in-situ space plasma instruments, such as stacks of solid state particle detectors, magnetic field combined with solid state particle detectors, electrostatic analysers with a charge detector, magnetic velocity filters combined with electrostatic energy analysers and electrostatic energy analysers combined with time-of-flight mass spectrometers. The design of these instruments is driven by the science requirements, which define the energy range, the required sensitivity, and the spatial and time resolution. The instruments must be capable to analyse, classify and compress the observed particle events before the data is transmitted by the telemetry to an antenna on Earth. The limited telemetry data rate resources are a major design factor of in-situ space instruments. The available resources of the specific space missions in mass, volume and power and the expected extraterrestrial environment define the envelope of possible instrument developments. The expected radiation and thermal environment are major design factors. The properties of an in-situ instrument are defined by their energy, mass and charge range and resolution as well as the sensitivity, expressed by the geometrical factor (detector area and solid angle of field of view) and detection efficiency.

3.1. Plasma and suprathemal particle instruments

Since the advent of space age, a lot of plasma analysers and suprathermal particle instruments have been launched to explore the solar wind plasma and the plasma of planetary magnetospheres. Some examples are launched onboard PIONEER, HELIOS, VOYAGER, ULYSSES or WIND [19–23].

The first in-situ observations of the solar wind plasma were carried out onboard MARINER II, which headed towards Venus in 1962 [24,25]. The Solar Corpuscular Radiation Electrostatic Particle Analyser consisted of a curved plate analyser with variable electric field to determine the energy/charge and the detector was a sensitive vibration-reed electrometer to measure the charge of the ions. This instrument allowed to measure the energy ranges of the impinging solar wind in a temporal sequence by stepping through the high voltage applied to the curved plate analyser. The instrument determined the density, velocity and temperature of the solar wind. It observed the pattern of slow and high speed streams and determined that the α-particles had about the same velocity as the protons. The first space-based composition measurements were carried out of the α-particle to proton ratio. These measurements relied on the fact that the mean energy/charge of the α-particles is twice that of the protons, i.e., in first order all ions have about the same velocity in the solar wind plasma. The α-particle to proton ratio varied substantially with solar wind conditions. The solar wind is only observed within a few degrees off the satellite-Sun line. For this first observations great care in the instrument design was taken prior to launch to suppress and block the solar photon radiation and suppressing photoelectrons due to UV photons such as Ly-α by means of a black gold coating of the analyser plates. This interference of the solar photon radiation is an ongoing design factor for in-situ space instrumentation and had become more important as the sensitivity, field of view and effective geometrical factor of the instruments increased.

More modern instrument types measure ion velocity and energy/charge separately and from these measurements the mass/charge is derived. This instrument type needs to scan over the full ranges of both velocity and energy/charge. The result is a disadvantageously low duty cycle, that can only in part be overcome with adaptive scanning schemes. Another limitation is overlapping values of mass/charge of space plasma ions. For example, the common solar wind ions He^{2+} and C^{6+} have the same mass/charge and cannot be separated with such an the instrument. The abundance of C^{6+} can only be inferred from measurements of the other charge states of carbon, i.e., C^{5+}. This is done by assigning a value of coronal ion temperature to the solar wind and extract the abundances via modelling. For cases where the most abundant charge state of an element is obscured, a large uncertainty in the abundance of the element is introduced.

To overcome this instrumental design restriction, an electrostatic analyser combined with time-of-flight spectrometers was introduced in the 1980 to in-situ mass spectrometers [26,27]. Three parameters are measured for each ion: energy/charge, velocity and total energy of each ion in a triple coincidence scheme. From this information, mass, charge state and energy of each ion is derived. These instruments can cover a wide range of energies and have a very low background due to the triple coincidence detection scheme. The effective duty cycle for these instruments is a function of the number of energy/charge steps needed to cover the full energy/charge range. The principle of operation of these instruments is: The ion passes an electrostatic analyser. The ion is or might be “post accelerated” in a high potential field in the order of 20–30 kV and then penetrates through a thin carbon foil to enter the time-of-flight section. On leaving the foil, secondary electrons are released which are accelerated towards a micro channel plate (MCP) or channeltron detector, triggering the start of the time-of-flight measurement. The ion passes through the field-free time-of-flight section and hits a solid state particle detector. Emerging from the detector surface on ion impact are secondary electrons and these are accelerated towards another detector and the time-of-flight measurement is stopped. The post acceleration is necessary as the solid state detectors have a low energy threshold due to the front-end detector deadlayer and the nuclear defect. Such type of instrumentation with three coincidence detection of the ions have been very successfully applied as in-situ mass spectrometers [28,29].

The entrance systems or electrostatic analysers of the instruments have been developed from the cylindrical to the sperical and “top hat” analyser. Variations of the latter allow spatial 3D sampling of the particles in the space plasma [30–32].

For isotope abundance measurements it is necessary to be able to distinguish ions differing in mass by 1 amu for masses as large as 100 amu. Isochronous time-of-flight instruments have been developed for space application [33,34]. These type instruments use electric deflection fields shaped in such a way that the time-of-flight is independent of the ion's kinetic energy and only a function of the ion's mass/charge.

An example is the isochronous mass spectrometer of the CELIAS (Charge, Element and Isotope Analyser System) instrument package onboard the SOHO mission, shown in Fig. 1 [35]. SOHO is the Solar and Heliospheric Observatory, launched on December 2, 1995 and positioned in a halo orbit at Lagrange point L1. The mass determining time-of-flight sensor (MTOF) is a high mass resolution ($m/\Delta m > 100$) system to measure the solar wind composition. The sensor consists of a wide angle, variable energy/charge passband deflection system and the isochronous time-of-flight spectrometer. The latter is based on the principle that the time-of-flight of an ion of a given mass/charge, m/q, is proportional to $(m/q)^{1/2}$ in the presence of an electric field that increase linearly with distance (harmonic oscillator). The measurement of the time-of-flight gives unambiguous values of m/q for individual ions. The required electric field is produced by a combination of a hyperbolic plate set at a large positive voltage (20–30 kV) and a V-shaped plate at ground potential. The high mass resolution of the sensor is due to the fact that the time-of-flight is independent of the ion energy and angle at which the ion enters. The value of the high voltage determines the maximum ion energy that can be deflected, but it does not affect the mass resolution. The time-of-flight range is up to 500 ns. The practical implementation required a conversion of the multiple charged solar wind ions into singly charged ions. This is accomplished with a thin carbon foil at the entrance. Ions passing through the foil undergo a large number of collisions with the carbon atoms, resulting in

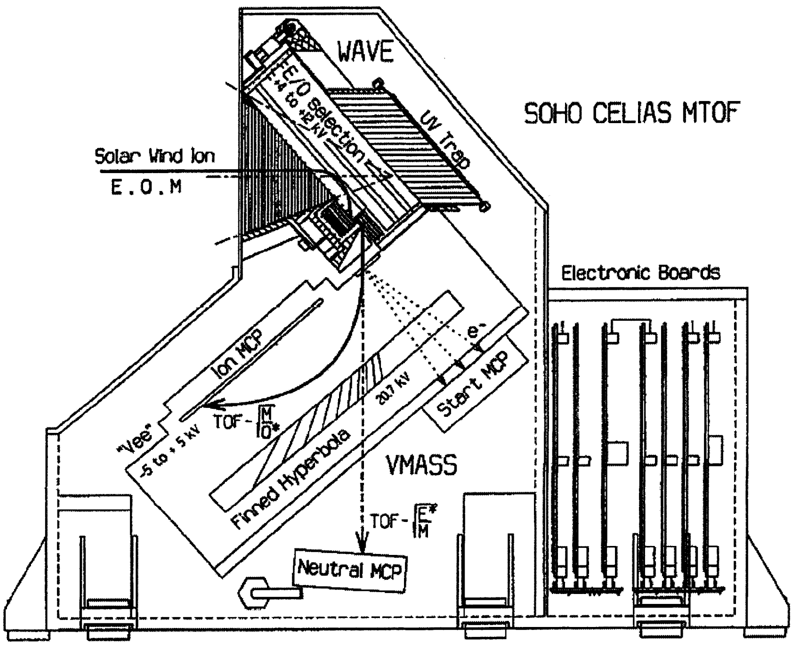

Fig. 1. The isochronous time-of-flight mass spectrometer CELIAS/MTOF onboard SOHO. The time-of-flight TOF of the ions is only a function of their mass/charge $(m/q^{*})^{1/2}$ in the linear increasing electrical field (harmonic oscillator).

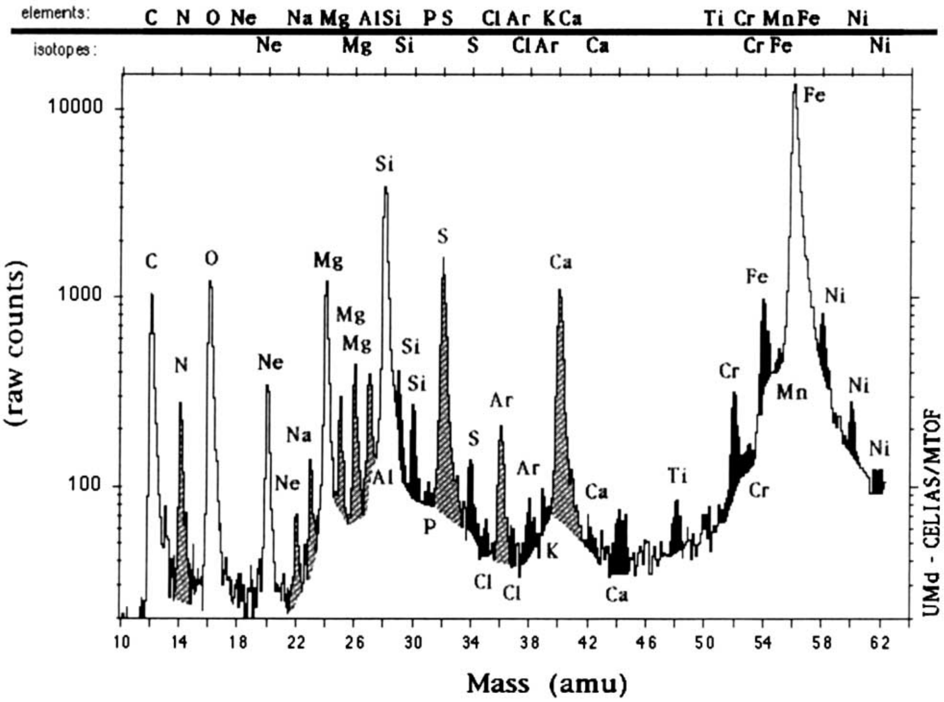

Fig. 2. Solar wind elements and isotopes observed by CELIAS/MTOF (raw counts). The dark shaded isotope peaks were observed in the solar wind for the first time.

some energy loss, scattering and charge exchange [36,37]. Most ions emerge from the foil as neutrals, a few percent are singly ionised and a fraction has more than one charge. As the ions leave the foil, secondary electrons are produced and accelerated towards the time-of-flight start detector (microchannel plate). The stop signal is created by the ions at the end of the time-of-flight region. An example for the resulting time-of-flight spectrum is shown in Fig. 2 [38]. This spectrum was accumulated over a 3-day period. The MTOF sensor was set in a mode that was optimised for observing solar wind species with masses above that of sulfur. This is why the peaks for Ca (mass 40) and Fe (mass 56) are so dominant. The O (mass 16) is actually the most abundant heavy element in the solar wind, and the true Fe (mass 56) abundance would be roughly 10% that of O. For example, the Si, S and Ni isotopes were measured for the first time in-situ in the solar wind.

An example for an in-situ mass spectrometer for the suprathermal energy regime of the space plasma is shown in Fig. 3. The Suprathermal Time-Of-Flight (STOF) instrument is also part of the CELIAS package onboard SOHO [35]. STOF is a particle telescope for the measurement of ionic charge states of particles with suprathermal energies in the range of 50–4000 keV/nuc or above the solar wind to low energy flare and shock accelerated particle energies. It has a stacked multiple-segment electrostatic analyser with a large area time-of-flight and a pixeled energy measuring system. STOF combines the electrostatic analysis with the time-of-flight and the determination of the residual energy in a solid state detector. The solid state detector covers an area of about 105 cm^2. It consists of 12 detector chips mounted on six ceramic hybrids. Each hybrid carries two detectors and a special amplifier chip with the associated analogue and digital electronics for signal processing.

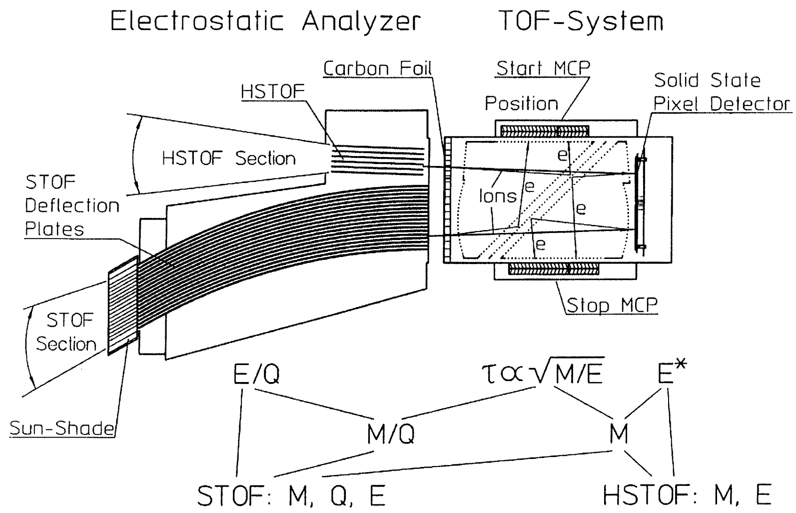

Fig. 3. Suprathermal particle instrument STOF onboard SOHO. From the measurement of the energy/charge E/q, time-of-flight $\tau \sim (m/E)^{1/2}$ and residual energy E^* the mass/charge m/q, mass m and energy E of the ions are determined.

The detector is divided in 192 pixels, each can be pulse-height analysed separately. The purpose of the separating the large area of the detector is to reduce the effective capacity noise of the full detector area for a single pulse height event to about 8 keV as only the capacity of a single pixel of 0.5 cm^2 is contributing to the detector noise. The solid state detector is shown in Fig. 4 [39].

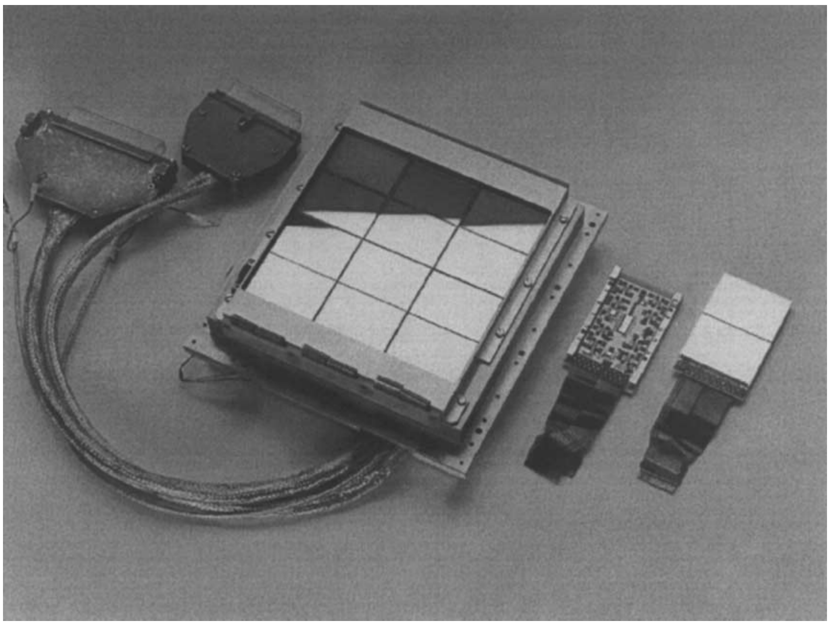

Fig. 4. The 105 cm^2 pixeled solid state particle detector of STOF. It consists of six ceramic hybrids. On the right-hand side two single hybrid units are visible, the bottom side with the electronic components including the amplifier chip and the topside with the two detector chips.

STOF has an additional section, HSTOF, for high-energy ions and neutrals. The entrance system of HSTOF consists of flat deflection plates. The HSTOF section determines the mass and energy of an incoming energetic particle. At low energies, the HSTOF section of the instrument is a detector of energetic neutral atoms, i.e., atoms with energies below the cut-off of the HSTOF entrance systems deflection plates [40,41].

In the STOF section, from the energy/charge and the time-of-flight, the mass/charge of the ions is obtained. In both sections, from the residual energy and the time-of-flight the mass of the particle is derived. The STOF instrument measures the mass, charge and energy of each ion. Typical STOF observations in the energy versus time-of-flight, the energy/charge versus the time-of-flight and the derived mass and mass/charge of the ions are shown in Fig. 5(a, b and c) for June 8, 2000, as an interplanetary shock was passing across the satellite towards Earth. The mass resolution of the instrument is about 5 and the energy/charge resolution about 0.1. The elemental ratios of He/H and Fe/O and the charge state ratios for He as determined by STOF for suprathermal ions since launch to the end of the year 2000 are shown as an example in Fig. 6. During this period, the solar activity was increasing from solar activity cycle minimum in 1996 towards solar activity maximum in 2000.

3.2. Energetic particle detectors

Energetic particle detectors are in-situ instruments developed to measure high energetic ions beyond the solar wind and up to the cosmic and galactic ray energies. Examples of these instruments were launched onboard GALILEO, ULYSSES and ISEE [42–45]. In 1951, it was found that not only gas-filled Geiger-type counters but semiconductor devices were suitable "solid state" detectors for high energy particles and allowed the precise measurement of the particle energy [46–48]. Some high-energy spectrometers utilised an inhomogeneous magnetic field for separation of the charged particles. Protons (and heavier particles) traverse the magnetic field almost unaffected and are detected in a semiconductor detector. Electrons are deflected and detected on another semiconductor detector. Positrons (if present) are deflected in the opposite direction and detected in another detector. These instruments are cable to distinguish ions, electron and positrons and were applied in an energy range from about 50 keV to several hundred MeV. Due to the cosmic ray radiation background (about 1 particle/cm^2 s at 1 AU or Earth's orbit), these instruments need some kind of anti-coincidence to distinguish traversing cosmic ray particles from particles of lower energy being stopped within the detector. Another type of high energy or cosmic ray particle detector consists of a detector telescope containing a stack of semiconductor detectors of increasing thickness surrounded by an anti-coincidence scintillation detector. The principle of observation is based on the energy loss measured in the front detectors (ΔE) and the residual energy measured in the (thick) back detector (E). Since the energy loss is a function of the nuclear charge, Z, and the residual energy a function of the kinetic energy or mass, A, the ΔE versus E plot allows the identification of the particle mass. These type of instruments are capable of measuring protons and heavier nuclei from below 1 MeV/nuc to GeV/nuc. Recent examples are instruments onboard SAMPEX and ACE [49–51]. For the observation of minor ions and resolving the charge states in the energy range from about 0.2–3 MeV/nuc, larger geometrical factors were necessary [52,53]. Such instruments achieve the charge resolution by focusing of the incoming ions through a multi-slit mechanical collimator and an electrostatic analyser with a deflection voltage and the measurement of the impact position in the detector system. To determine the nuclear charge, Z, and energy of the incoming ions the combination of thin-window flow-through proportional counters filled with a counter gas, e.g., isobutane, and ion implanted solid state detectors provide for an ΔE (energy loss) versus E (residual energy) telescope with a large geometrical factor. The multi-wire proportional counter simultaneously determines the energy loss ΔE and the impact position of the ions. Suppression of background from penetrating cosmic radiation is provided by an anti-coincidence

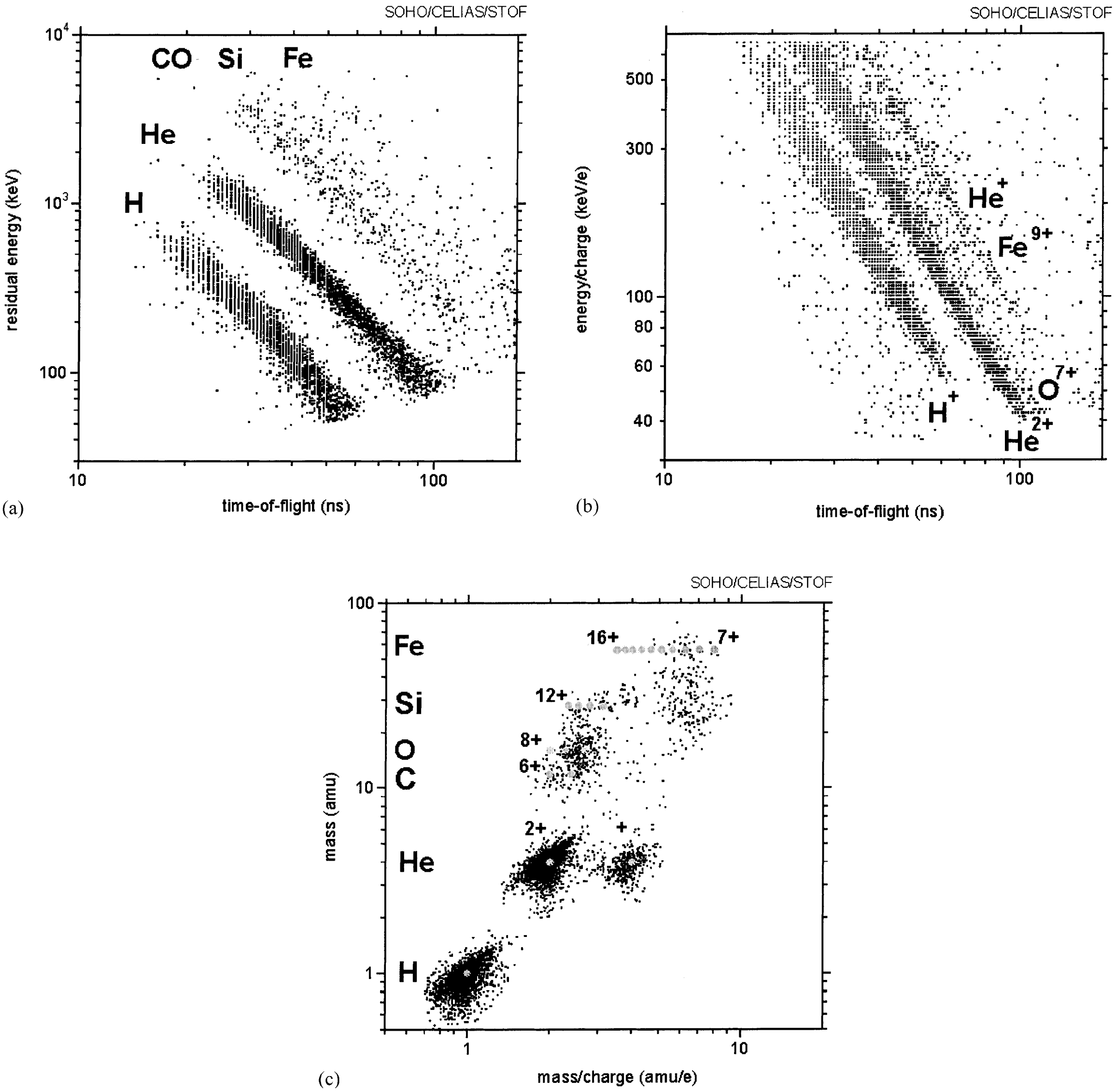

Fig. 5. The pulse-height data of STOF from June 8, 2000. (a) The particle mass tracks in the residual energy versus time-of-flight plane. (b) The particle mass/charge tracks in the energy/charge versus time-of-flight plane. (c) The calculated mass versus the calculated mass/charge (background subtracted).

system such as a CsI scintillator and Si-photodiodes. For the determination of the charge of energetic ions the Earth's magnetic field was used as well. The trajectories of the detected ions are traced back, i.e., their passage in the Earth's magnetic field is modelled. Then one can derive limits on the possible charge state of the detected ion and analyse the charge state distribution by statistical methods [54]. The very high energetic particles will be measured onboard ISS [55]. This instrument relies on micro calorimeters that measure directly the energy deposited in an absorber. These instrument detectors make use of a

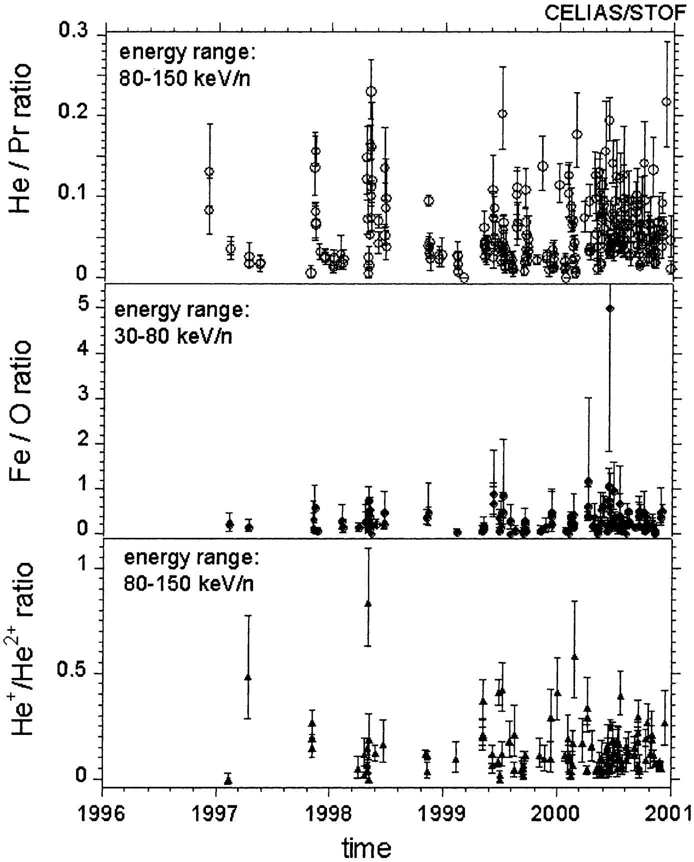

Fig. 6. Observations of STOF of the elemental helium/hydrogen He/Pr and iron/oxygen Fe/O ratios, and the He charge state ratios of suprathermal ions from Febuary 12, 1996 to December 31, 2000.

superconducting quantum interference device (SQUID) and must be operated at temperatures of about 0.1 mK.

3.3. Neutral particle detectors

In-situ instruments have been launched in the last decade with the capability to observe neutral atoms and the interaction of space plasma, radiation and the neutral atoms, originating from of the local interstellar medium, interplanetary and interstellar dust grains, planetary bodies and atmospheres [56]. In-situ mass spectrometer type instruments designed to detect neutral atoms are presently onboard IMAGE and CASSINI [57,58]. In the plasma-neutral reaction processes, such as charge exchange, the so-called pick-up ions as well as energetic neutral atoms can be created. In the latter process, an energetic ion captures an electron of a neutral atom and moves on as an energetic neutral atom on ballistic trajectories, unaffected by the interplanetary or planetary magnetic fields. Detection of the neutrals and reconstruction of their flight path makes the "imaging" of planetary magnetospheres or even the heliosphere with in-situ instruments possible. Some of the in-situ neutral detectors operate like conventional ion-type detectors, just diverting the charged particles in front of the detector. This is applicable to energies down to about 1 keV [59–62].

For lower energies of about several eV the design approach is the implementation of target converting the atom in a negative ion. The negative ion is accelerated and detected as in an convential ion instrument (applicable for atoms such as H, O, F or Cl, but not He) [56].

The very challenging direct in-situ observation of the He atoms of local interstellar medium, their density, bulk velocity and temperature was accomplished with the neutral-gas instrument onboard the ULYSSES mission [63,64]. The neutral He of the local interstellar medium was detected via secondary ions or electrons, which are emitted upon particle impact from a freshly deposited lithium-fluoride (LiF) layer. The solar gravitational field is employed as a natural velocity analyser and so the density, velocity and temperature of the He gas were derived. A collimator and an electrical field in front of the detector unit suppress the charged particles of the space plasma. The suppression of the photoelectrons due to Ly-α photons is achieved by the LiF-coated target. The latter is transparent to Ly-α photons and therefore, has a very low photoelectron yield, provided the surface is clean. The ion yield on He atom impact is comparatively high since LiF is an ionic crystal and most sputtered atoms leave the surface ionised. Due to the better momentum transfer, the yield of Li^+ is higher than F^- on He bombardment. The Li^+ ions are accelerated in an electric field towards the detector. The detector is positioned in such a way that no photons can hit the front plane of the detector directly. The sputtering yield is a function of impinging atom energy and reaches about 1% at 80 eV. The LiF evaporation system is an essential subunit to evaporate layers of fresh LiF on the conversion plates. This was achieved with a tiny furnace, filled with LiF. The effective temperature was about 600 °C and the evaporation was monitored with a quartz crystal (shift of resonance frequency). A possible successor to the described experiment is shown in Fig. 7. The design principles are very similar to the original instrument, but the overall geometrical factor and therefore the sensitivity is increased by a factor of about 10 due to the larger detector area.

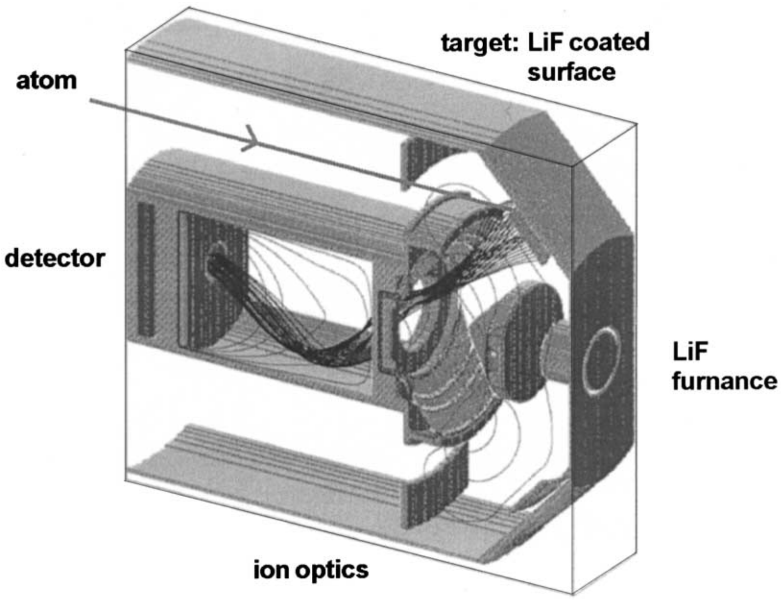

Fig. 7. Design study of a low energy He detector with large geometrical factor for the observation of the helium atoms in the interplanetary medium. The neutral He atoms impact on the target covered with LiF and the sputtered Li^+ ions are guided by the ion optics to the detector.

3.4. Dust detectors

Dust grains are measured in-situ or collected with highflying aircrafts and analysed in ground based laboratories. In-situ dust detectors are instruments capable to determine the orbital elements, i.e., arrival direction and velocity, and flux of dust particles. Examples for this type of instruments have been launched onboard HELIOS, STARDUST and CASSINI [65–67]. Some of them are also capable to determine the charge and/or mass of the dust grain particles. The grain masses are detected in a range of 10^{-19} to 10^{-9} kg. Furthermore, some dust detectors determine as well the composition and charge of the grains. The dust analyser could consist of three subsystems: The dust velocity sensor measures speed, direction and, if possible, the charge of the dust grain. The impact plasma sensor measures mass and speed or momentum of the grain, which on impact on the detector surface is converted into a plasma plume and the resulting charge is proportional to the momentum of the grain. A mass spectrometer measures the composition of the emerging plasma.

The dust detector onboard CASSINI uses two inclined entrance grids at the front of the detector. An electrically charged grain flying through these grids will induce charge signals on the grids. This induced charge is directly proportional to the charge of the particle and allows therefore a direct determination of its electric charge. The inclined grid geometry leads to asymmetric signal shapes allowing the measurement of the particle direction in one plane. The particle can impact on an analyser target. The impact generates charged and uncharged fractures (ejecta), atoms and ions. The electrons and ions of this plasma are separated by an applied electric field, the ions are collected and their total charge is proportional to the momentum of the impinging dust grain. A fraction of the ions are diverted by a strong electric field into a time-of-flight mass spectrometer giving information about the elemental composition of the dust grains. The whole measurement scheme relies on a multiple coincidence signal to discriminate against accidental coincidence events [68].

For measuring only the dust flux and grain momentum, a microphone type of instrument can be used. Another approach followed up is a polyvinylidene fluoride (PVDF) sensor, a permanently polarised polymer. The hypervelocity dust particle impacts on the PCDF sensor. This produces a rapid local destruction of dipoles (crater or penetration hole) which results in a large and fast current pulse (ns range). The output pulse amplitude depends on impacting particle mass and velocity [69].

3.5. In-situ instruments observing the soil and atmospheres of planets, comets or other solar system bodies

The first in-situ surface composition measurements of refractory material have been carried out not by mass spectrometer instrumentation but an elegant method for the determination of the major elemental composition, the proton or α-particle Rutherford back scattering and X-ray fluorescence. These observations are carried out during the SURVEYOR missions on the Moon, the VEGA and VENERA missions to Venus and the PATHFINDER mission to Mars [70–73]. The latter instrument was mounted on a mobile rover and therefore capable to measure the surface major elemental composition of different rocks in the vicinity of the lander. In the 1990, it was claimed that, possibly, extraterrestrial organic material might have been found in a meteorite attributed to Martian origin [74]. This triggered again the exobiology research, as 3 decades ago leading to the very ambitious experiments carried out onboard the VIKING landers on Mars in the year 1976. The VIKING experiments on the surface are: (a) gas exchange chamber: introduced water and nutrients, looked for change in composition of gas in a chamber. (b) Labelled-release chamber: used radioactively tagged elements in the nutrients to see if they were turned into gases by organisms and released into the chamber. (c) Pyrolytic-release chamber: radioactive CO_2, otherwise the same as Martian environment (no added nutrients). (d) Gas chromatograph and mass spectrometer (GCMS): analysed the chemical elements in the soil to see what was there and how much.

The results were that the three chamber experiments showed chemical activity, but not of sort expected from life. No organic materials were found in Martian soil analysed by GCMS. It was concluded that the chemical activity was caused by active chemistry of the Martian soil, made more sensitive by UV light [75,76]. The in-situ mass spectrometers on VIKING measured the Martian atmosphere, its elemental, molecular and isotopic composition. These results helped to identify some meteorites found on Earth as to be of possible Martian origin [77]. The enclosed traces of the atmospheric gases were found to be similar to the Martian atmospheric composition found by VIKING observations. The mission MARS EXPRESS will carry a lander to Mars in 2003, the so-called BEAGLE-2 [78]. Sample analysis by a mass spectrometer will include isotopic analysis of surface material and the quest to search for minute traces of organic material by in-situ detection on Mars will be persued. The composition of the coma of comets have been measured (21P/Giacobini-Zinner and Halley) and will be measured (46 P/Wirtanen) by in-situ particle instrumentation onboard ICE, VEGA, GIOTTO and ROSETTA [79–82]. Isotopic ratios in the atmosphere of Venus were measured by mass spectrometers onboard VENERA 13 and 14 [83]. In-situ surface mass spectroscopy will be carried out by GCMS on the ROSETTA LANDER, a mission to land on the nucleus of comet 46P/Wirtanen in the year 2012 [84]. The goal of the GCMS instrumentation is the measurement of the isotopic ratios of the elements and the molecular composition of the cometary matter. This is achieved with a drill to sample the probes from the cometary surface, pyrolysis ovens with temperatures up to 800 °C and a gas chromatograph operated with helium gas and high resolution time-of-flight multi-reflectron. With this approach, the volatile components of the cometary matter such as organic matter and gases can be measured, but not the refractory matter such as silicates.

4. Future prospects

The observations of space-borne mass spectrometers have allowed new insights in the physics, chemistry and geology of our solar system. The next generation of detectors might combine the detection ability of neutral atoms and ions. For the solar wind energy range of ions and neutrals, using a linear time-of-flight analyser with a floatable drift tube might be applicable. The potential accelerates the ions, but not the neutrals. Then the ions would be observed in an up-shifted velocity regime while the neutrals would still have their original, lower, speed. A possible extention of this method to, presently not observed, negative ions seems plausible [85]. A mass spectrometer with an electric and parallel magnetic field has been proposed for space application. Then ions are diverted while neutrals travel undisturbed on their original trajectories and could be observed by a second mass spectrometer without interference of the ions [86]. Another approach is a mass spectrometer with a rotating electrical field, the mass/charge is then measured as a function of position and time relative to the phase of the rotation of the electric field. The neutrals would pass again unaffected while ions are deflected and measured [87]. The energy loss and the scattering in foil type time-of-flight instrumentation might be overcome by gated time-of-flight sensors. Without any other means this would result in a very low duty cycle. A solution might be a Hadamard type of time-of-flight instrument which can achieve a duty cycle of up to 50% and very good mass resolution [88]. A new field for in-situ detection would be the direct observation of metastable atoms. The detection principle could be based on the high secondary electron yield of metastable atoms, such as H or He, impinging on a clean target surface [89,90]. The charge detection could gain from the fast improvement associated with the charged coupled device (CCD) technology. First steps of charge detector anodes based on this technology are promising [91]. Still more sensitive charge detectors are based on the quantum dot technology. But these detectors would require cooling to about 40 mK [92]. For in-situ instruments for measuring the composition of soils the laser ablation method combined with a time-of-flight mass spectrometer is promising [93,94]. The laser ablations allows the measure depth profiles of the elemental abundances on a 10^{-5} m scale. The in-situ observation with mass spectrometer instrumentations on extraterrestrial surfaces is one of the most exciting and challenging fields in present instrument development. Generally, the trend is towards highly integrated instruments, where the signal processing electronics is mounted in the vicinity of the detection device or the electronics such as the signal amplifier are already integrated in the detector [95]. The development of the Micro Electro Mechanical Systems (MEMS) and the Lithographic and Galvanic technology (LIGA) makes possible the design studies of very small mass spectrometers and electrostatic lenses [96,97]. These novel techniques and their application to space-borne instruments are promising as one can design and launch very small and precise detectors onboard future space missions.

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