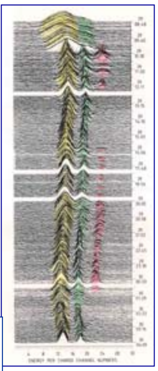
Particle Detectors for Space Application

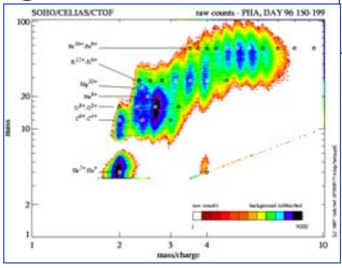
Thermal Plasma Analyzers

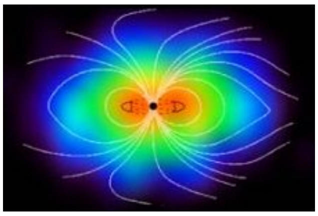
- Electrostatic Analyzers (E/Q Analyzer)
- Analyzers with mass separation (Time of flight instruments)

Energetic Particle Telescopes

Energetic Neutral Atom Imagers





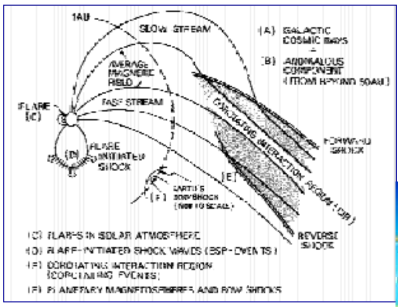


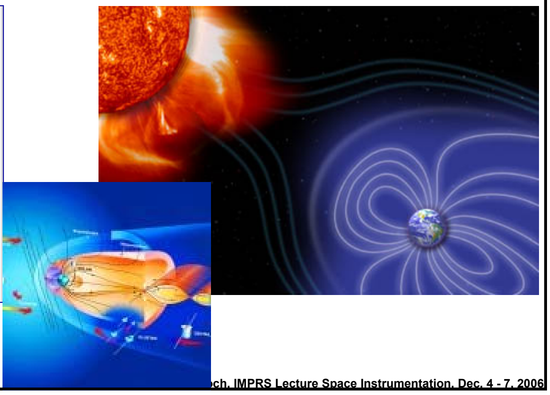
Particle Detectors – What are they good for

>99% of matter in universe is in the plasma state

gas consisting of charged particles (electrons, ions) with or without an admixture of neutral particles

dynamics and properties of such a plasma you can fully determine only by measuring the properties of the individual particles

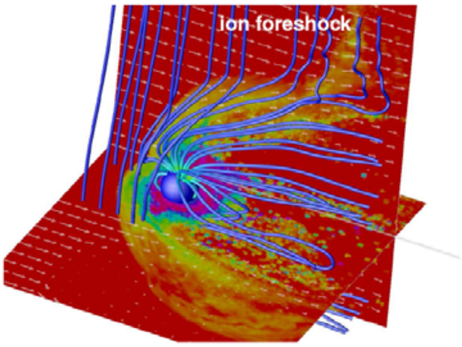


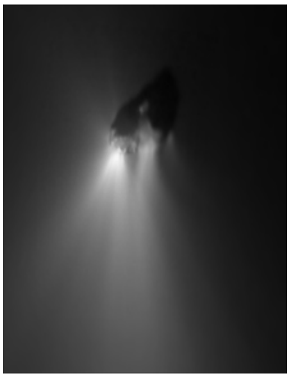


Particle Detectors – What are they good for

as probes for plasma physics: space as huge plasma laboratory

for exploratory purposes: derive properties of planetary surfaces and atmospheres





Particle Detectors – What are they good for

a very large parameter space has to be covered

e.g. particle energies in space physics range from thermal energies (few eV) to cosmic ray energies (GeV)

with very different demands

- high temporal resolution (<1s) for plasma physics
- high mass resolution ($M/\Delta M \sim 1000$) for exploration of a comet's coma

Particle Spectrometers – General Design Aspects

Ideally particle analyzers have to determine the plasma's

- density
- flow velocity
- temperature and any anisotropies in that temperature,
- organization relative to the magnetic field,
- whether its distribution function, f(v), differs from a maxwellian distribution,
- elemental and isotopic composition and charge states.

In the design you have to worry about

- the accommodation that the spacecraft provides
- the limited power available for the instrument
- the mass and volume available in the payload
- the stabilization of the spacecraft (spinning / non-spinning)
- the electrostatic cleanliness of the spacecraft
- telemetry rate to transmit all this information back to Earth

One must understand what plasma environment will be encountered.

- will there be a cold beam like the solar wind or a hot plasma such as the Earth's plasma sheet
- will there be an intense radiation belt (false counts, decrease the life of the instrument)
- what is the resolution required in time, angle, energy and mass per charge to achieve the scientific objectives?
- what is the range required in energy and density to measure the plasmas encountered

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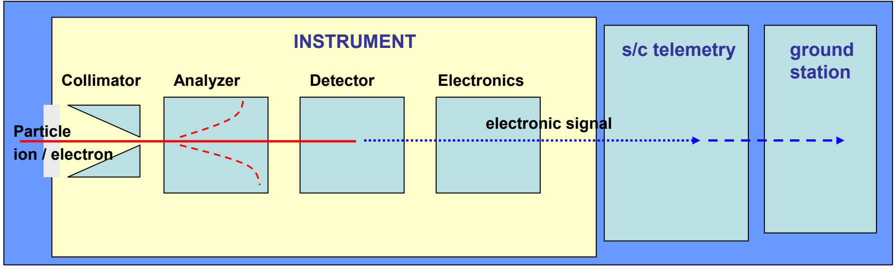
Particle Spectrometers – Parts

Collimator: **(mechanical) device to limit the incoming particle beam to a small spatial opening angle and simultaneously provides a large aperture surface**

Analyzer: **filters particles with pre-selected values of the particle parameters out of the beam for further analysis**

Detector: **counts particles (eventually with energy determination)**

Electronics: **includes power supplies, analog electronics to amplify the detector signal and to transform them for further analysis, DPU (interface to s/c and control unit)**



Measurement Techniques used in Particle Spectrometers

For non-relativistic particles techniques are based on two principles:

the deflection of charged particles in electric and magnetic fields ($E/Q < 40$ keV)

- Analyser with static electric and/or magnetic fields. Measured quantities ***E/Q, P/Q, E/M*** or ***M/Q,***
- Analyser with oscillating electric or magnetic fields. Measured quantity: ***E/M, M/Q.***

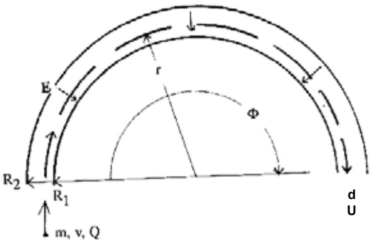
interaction of fast (energetic) particles with matter *(or deflection in 'atomic fields')*

- Detector systems in telescope arrangements. The mass dependence of the specific energy-loss process is used in combination with different algorithms. Measured quantity:MZ^2.
- Time-of-flight technique with secondary-electron emission (SEE) in combination with solid-state energy detectors. Measured quantity: *E/M* and *E,* allowing the unique determination of *M* and *E.*

Based on first-order detection principles a number of different approaches have been developed to identify heavy particles, characterised by the parameters energy ***E,*** momentum ***P,*** ionic charge ***Q,*** nuclear charge ***Z*** and mass ***M***

Generally speaking, instruments using deflection of charged particles in macroscopic fields are only sensitive to ion particle parameters such as *E/Q* (energy per charge) or *M / Q* (mass per charge), with Q denoting the ionic charge of a particle. The principle of 'interaction with matter' allows, on the other hand, the measurement of quantities related to nuclear particle parameters such as nuclear charge *Z* and atomic number ***A.*** A complete description of an ion, therefore, requires instruments which use a combination of both detection principles.

Electrostatic Analyzer



uses an electric field between two curved plates to guide the flight path of a charged particle around a bend to a detector.

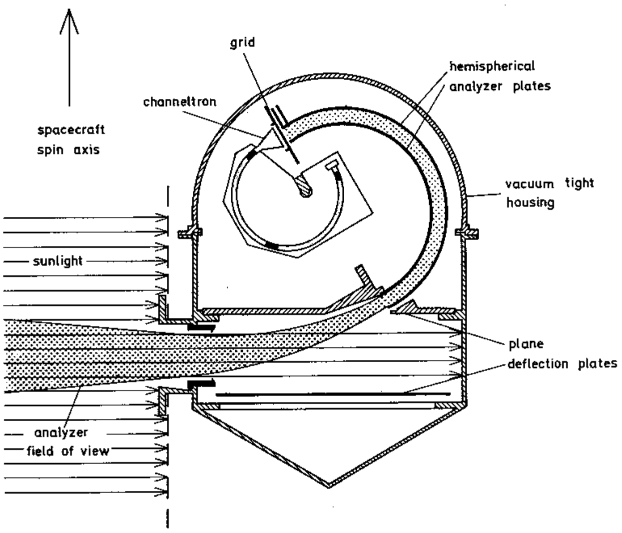
The particle orbit through the curved plate analyzer is given by the force balance between the electric field force and the centripetal force.

The electric field exerts a force qE on the particle that causes it to move in a great circle with radius r equal to mv^2/qE.

particles pass if their energy/charge (E/q) fits, i.e., if

$$E/q\ (= m/2 * V2/q) = UR/2d.$$

The flux of plasma that enters the instrument is determined by the size of the aperture, A. The size of the detector, the voltage range and the polarity affects the energy and species detected.



Scheme of the Helios E1 electron instrument (I2), invented by H. Rosenbauer.
The trick: no photo electron could ever make it to the detector!

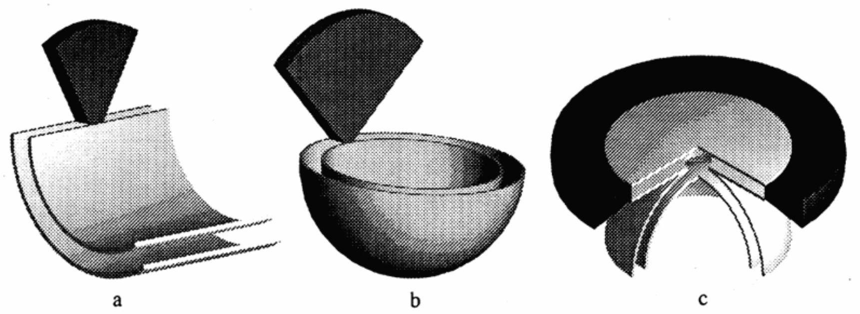
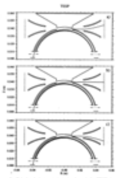


Fig. 1. Evolution of the electrostatic analyzer used in space plasma diagnostics: (a) cylindrical analyzer, (b) spherical analyzer, and (c) top-hat analyzer. The dark regions illustrate the field of view.

On the left is a pair of cylindrical plates. In the middle are spherical plates and on the right is a so-called top hat design leading into a pair of spherical plates. Particles are admitted into the first two detectors over a limited path length. This length together with the size of the detector at the end of the curved plate defines a geometric window. The top hat analyzer views a full 360 degrees in azimuth with a narrow fan in the orthogonal direction.



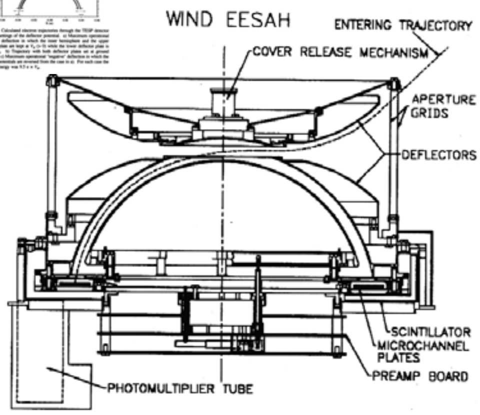
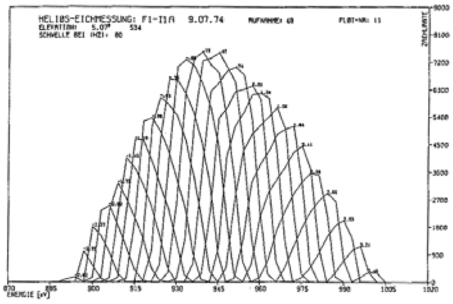


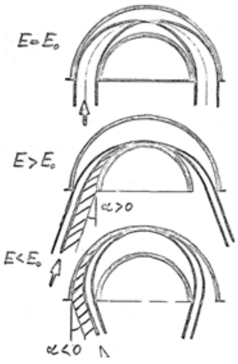
Fig. 7. The large electron analyzer, EESA-H, for the Wind 3-D Plasma Instrument. Deflection plates are used to deflect the analyzer field of view by +/- 45°. This figure also illustrates the anti-coincidence scintillator used to reject penetrating particle background counts.

Top Hat Analyser

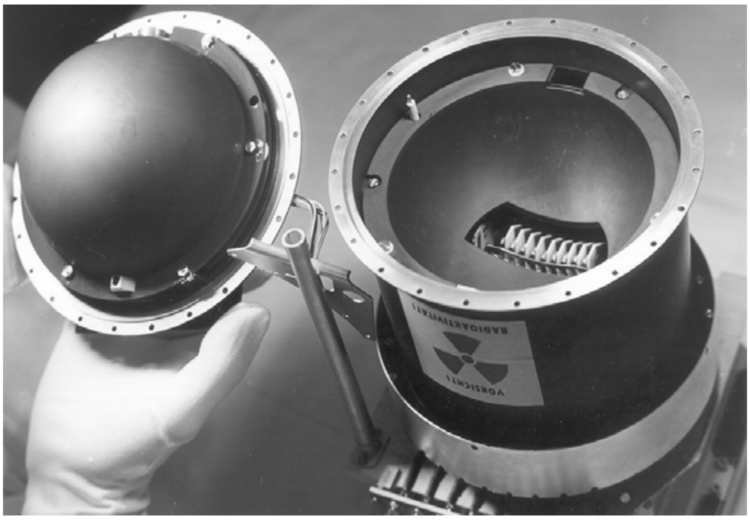
design to overcome the limited field of view of the classical electrostatic analyzer. This design has hemispherical plates but the particles enter at the top of the plates and are bent less than 90 degrees. The top plate above the entrance to the analyzer helps guide the particles into the slit. A sample trajectory is shown by the dashed line. The resulting field of view is a narrow fan that extends completely around the detector. A segmented collector at the bottom of the detector provides angular resolution. If the spacecraft spins about an axis that lies in the plane of the fan beam then the fan will sweep out all of solid angle space each rotation. If the spacecraft is three-axis stabilized then another means must be adopted to provide that sweeping. A partial solution is the use of deflection plates along the entrance path. If two top hat analyzers are mounted on a three-axis stabilized spacecraft with their fans orthogonal, deflector plates can enable the detector to scan above 70% of the solid angle around the spacecraft.

The calibration facilitiy at MPS





The energy-angle dependence requires careful calibrations!



The ion instruments on Helios 1&2, built at MPE Garching (H. Rosenbauer, PI).

The detector on the back end of an analyzer returns counts. In order to convert the count to physically useful quantities we must apply calibration factors. The basic quantity we wish to compute is the distribution function that gives the number of particles at the detector per unit volume in configuration space and per unit volume in velocity space. This can then be used to calculate moments such as the density, temperature and velocity. The number of counts, c, measured by a detector in time τ, is:

$$C = A\tau\varepsilon \int v f(\mathbf{v})\, d^3\mathbf{v} \qquad (1)$$

where v is the velocity, f(v) is the distribution function d3v is the velocity space element sampled by the analyzer in time τ, A is the entrance aperture area, and ε is the detector efficiency. The integral is over the instantaneous acceptance of the analyzer. We can rewrite d3v as:

$$\cos\theta v^2 dv d\theta d\phi.$$

For a given analyzer the product <(dvdΦ)/v> is a constant, W. If the resolution of the analyzer in energy and angle is good compared to the scale size for changes in the distribution function, then W can be removed from inside the integral. We define the geometric factor of the detector as AW so that the counts as a function of speed and angle can be written:

$$c(v,\phi)/\tau = G\varepsilon v^4 \int f(v,\phi,\theta) \cos\theta d\theta \qquad (2)$$

If the plasma is hot then the distribution function varies little over the θ - acceptance of the analyzer and

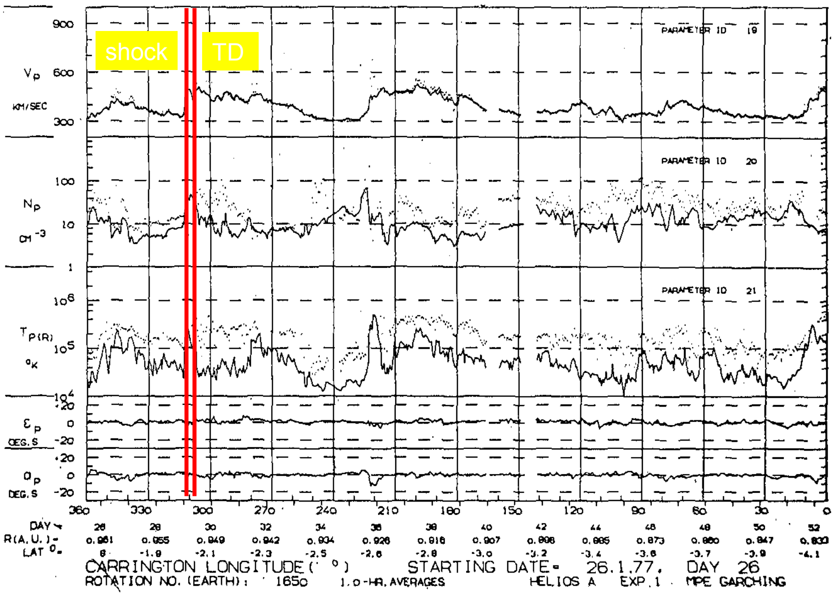
$$f(v,\phi) = c(v,\phi)/\tau v^4\, G\varepsilon \int \cos\theta d\theta \qquad (3)$$

We can now calculate the moments of the distribution function

Density: $n = \int f(\mathbf{v}) d^3\mathbf{v}$

Velocity $\mathbf{v} = n^{-1} \int f(\mathbf{v})\, v d^3\mathbf{v}$

Temperature: $\mathbf{T} = 0.5\, mn^{-1} \int f(\mathbf{v})(\mathbf{v}-<\mathbf{v}>(\mathbf{v}-<\mathbf{v}>)d^3\mathbf{v}$ where **T** is a tensor.



Carrington routine plot of Helios E1 ion data (1 hr averages)

Plasma Composition Measurements

The plasma composition is often quite variable and is an important diagnostic for the origin of that plasma.

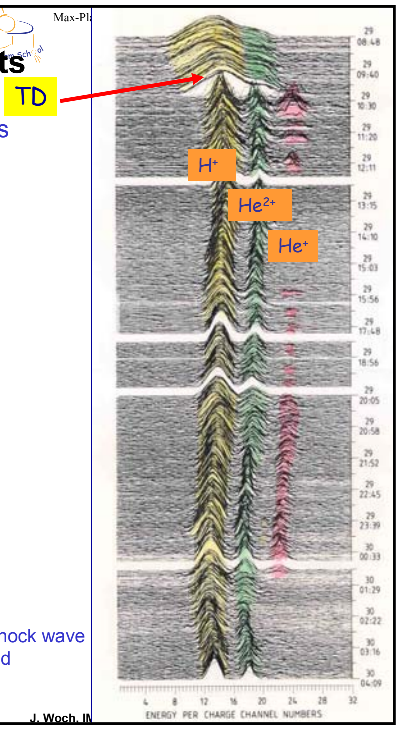
The passage of an interplanetary coronal mass ejection (ICME). The counts as a function of energy per charge are shown for this interval.

Before TD, high temperature solar wind

⇒ protons and He++ distributions are not clearly separated

After TD, cold solar wind

⇒ protons and He++ distributions are clearly separated



Discovery of singly ionized Helium ions
in the driver gas following an interplanetary shock wave
by **Helios 1** in January 1977: remnants of cold
prominence material.

Some detector types which provide mass/charge resolution

electrostatic analyzers

separation only when the thermal velocity of the ions is much less than the bulk velocity

magnetic (sector) spectrometers

provide good mass resolution, but complex, slow, massive, limited field-of-view stray magnetic fields that may affect other measurements.

time of flight instruments

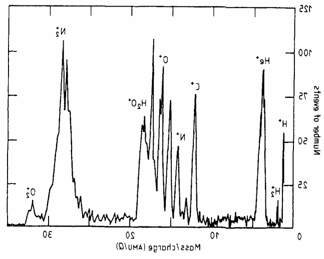
good sensitivity, all species simultaneously measured, broad field of view but only modest M/Q resolution (M/∆M < 10).

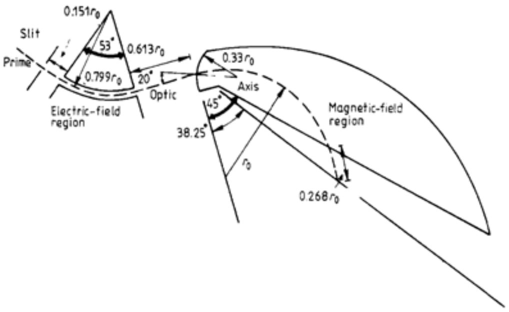
Quadrupole (oscillating electric fields)

compact design, but em-noise, low effective sensitivity

Magnetic Spectrometers

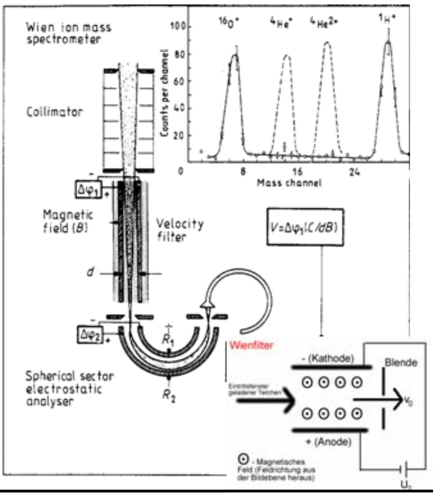
Combinations of electrostatic and magnetic sector fields can be used for a determination of the mass-per-charge *(M / Q)* ratio of ions by combining the ***(E /** Q)* information from the deflection in an electrostatic analyser with the momentum-per-charge ***(P/**Q)* ratio obtained from a gyroradius measurement in a magnetic field





A double-focusing modified Mattauch-Herzog field configuration with good mass focusing over a wide range of gyropaths (0.1 – 10keV, 1 - 200 AMU) M/∆M ~ 14 (allowing to resolve the crirtical carbon-nitrogen-oxygen group)

An ion spectrometer composed of an electrostatic energy analyser **(ESA)** and a velocity filter (e.g. Wien Filter) allows the particle quantities, energy per charge *(E* / Q) and velocity V = (2 E/ *M)"',* to be determined independently. These measured quantities can be combined to yield the two 'ionic' parameters *(E I Q)* and *(M/Q),* the energy and mass per charge ratio



Incident ions first pass through the velocity filter with crossed electric and magnetic fields oriented such that the corresponding forces on the particle are directed in opposite directions. For a particle velocity

$$V_0 = \Delta\varphi \frac{C}{dB}$$

the forces balance exactly and the particle can pass the analyser. Here $\Delta\varphi$, B and *d* denote the electric potential difference, the magnetic-field strength and the gap width, respectively. The constant C corrects for field distortions caused by the finite size of the plates. Particles within a narrow velocity band centred at V_0, are passed through the velocity filter and transmitted to the particle detector (channeltron) if the energy/charge ratio *W/ Q* matches the passband of the spherical sector electrostatic analyser following the velocity filter. The mass-per-charge ratio can then be obtained from

$$M/Q = \left(\frac{2}{V_0^2}\right)\left(\frac{W}{Q}\right) = \left(\frac{W}{Q}\right)\frac{2}{C^2}\left(\frac{B}{E}\right)^2$$

$$E = \Delta\varphi / d.$$

The so-far discussed ion spectrometer composed of an electrostatic energy analyser **(ESA)** and a velocity filter (e.g. Wien Filter)

allows the particle quantities, *(E/Q)* and *(M/Q),* the energy and mass per charge ratio to be determined

- However not *E*, *Q* and *M* independently, ⇒ e.g., no direct information on charge state of the measured ions and the mass distribution

  This imposes severe limitations on science in plasmas containing atomic species with different charge states

  e.g., solar wind where knowledge of charge stage distribution allows to derive freezing-in temperatures, knowledge of mass distribution resolves FIP effect

  magnetospheric plasmas where charge states tells you something on the source of the particles

- Only applicable to E / Q < 40 keV/q

solved by e.g. ***Time of flight spectrometers in combination with an Energy determination by a Solid State Detector***

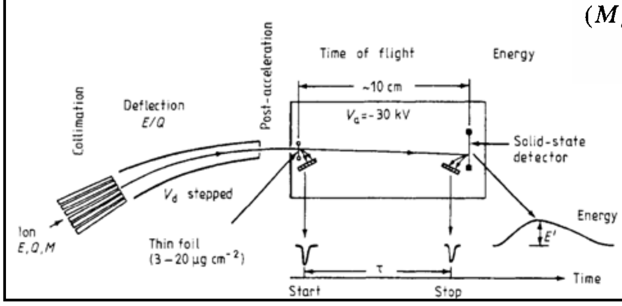
Time of flight spectrometer – Functional Principle

ESA selects ions according to E_0/Q according to deflection voltage V_d

exiting ions are post-accelerated by potential drop V_a

accelerated ions enter into the TOF – E system

- ions enter through a thin Carbon foil
- secondary electrons emitted from the foil and detected by an MCP provide start time
- stop time is provided by secondary electrons emitted from the surface of a Solid State Detector
- SSD measures the residual energy E (based on E - ΔE technique, or PHA)



$$(M/Q) = 2[V_a + (E_0/Q)](d/T)^{-2}$$

$$M = 2(E\alpha)(d/T)^{-2}$$

$$Q = M(M/Q)^{-1}$$

$$E_0 = Q(E_0/Q).$$

parameter *α* accounts for energy losses in the carbon foil and in the entrance window of the detector, as well as for non-ionising collisions (nuclear defect) in the detector bulk material

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The flight time of non-relativistic ions (in ns cm-1) is $T=22.8 * W^{-0.5}$ with the energy *W* in keV/nucleon.

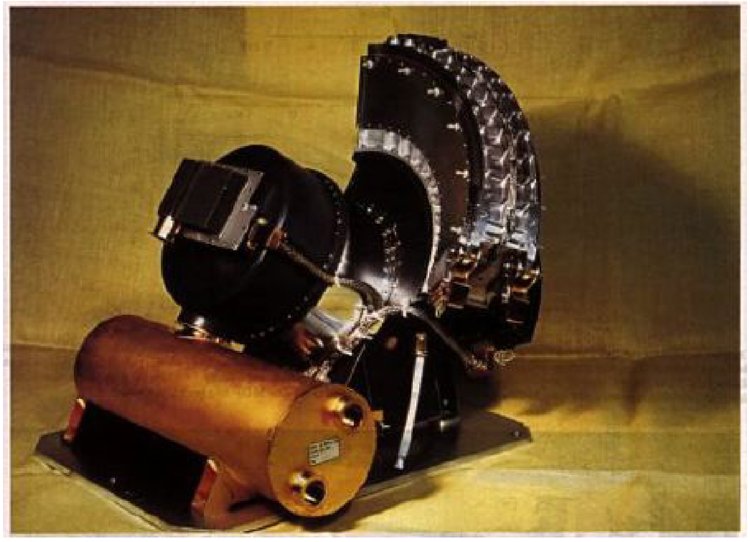
for a typical *d* of 10cm

W (solar wind)
~ 1 keV/nuc ⇒ T ~ 200 ns

d

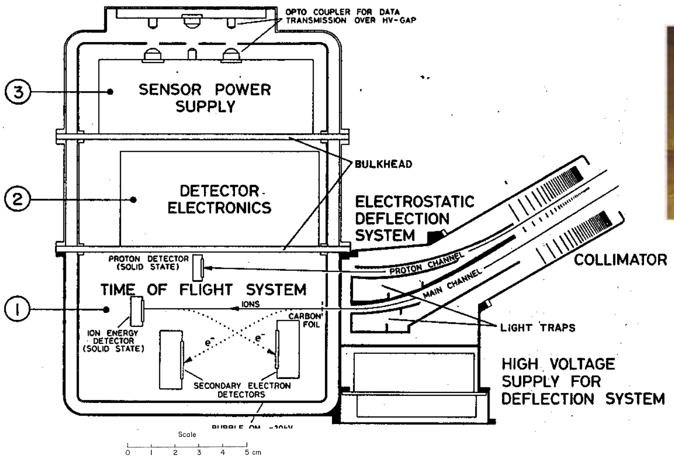
W (magnetosphere)
~ <100 eV/nuc – >100 keV/nuc

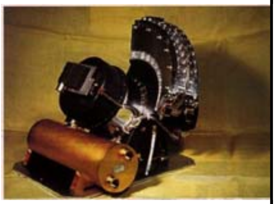
⇒ 1000 ns – 10 ns

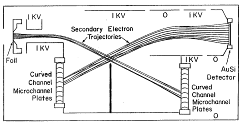


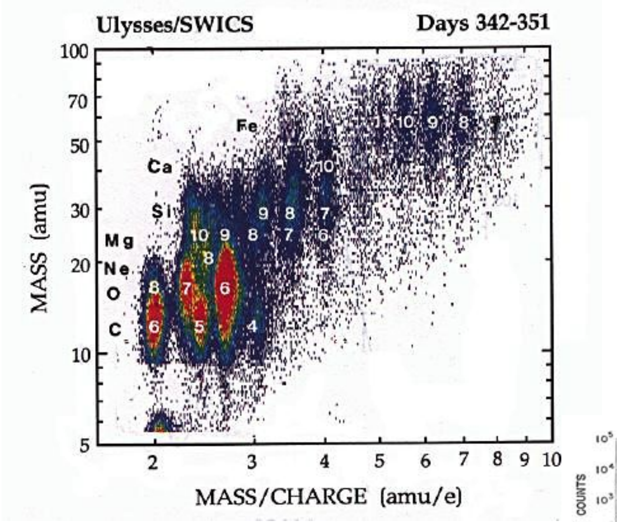
The SWICS Instrument on Ulysses

Concept of the SWICS/Ulysses TOF Spectrometer

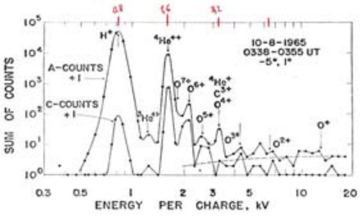




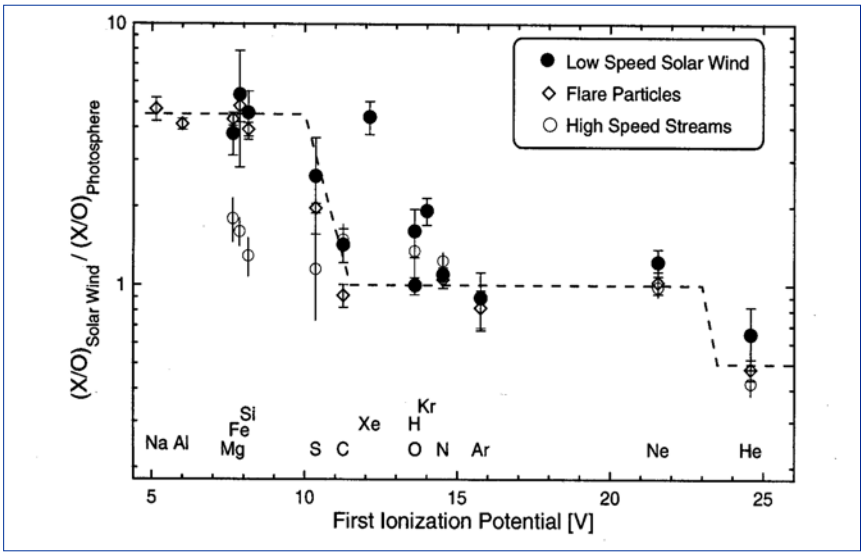




'mass' spectrum from an electrostatic analyzer

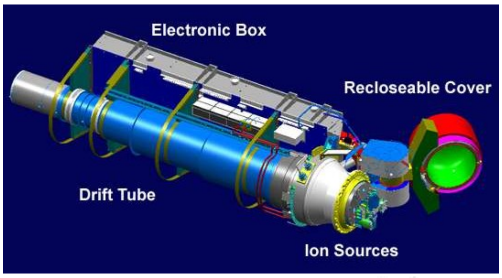


The solar wind element composition as revealed by modern TOF instrumentation



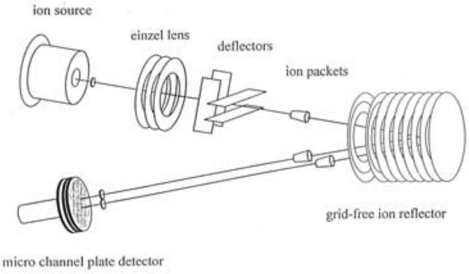
Elemental abundances and the FIP effect

ROSINA/RTOF auf ROSETTA
Reflectron-Time-of-Flight-Spektrometer



Instrument parameters

- Mass range: 1-1000 amu
- Mass resolution M/ΔM=500 (1% Level)
- High time resolution by simultaneous mesurement of different masses



ROSINA/RTOF auf ROSETTA
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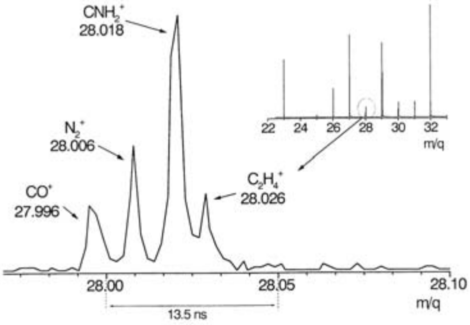
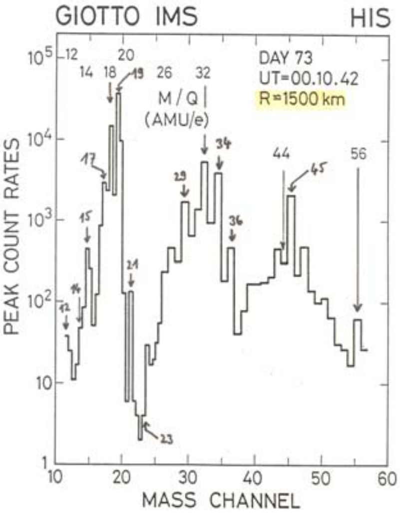
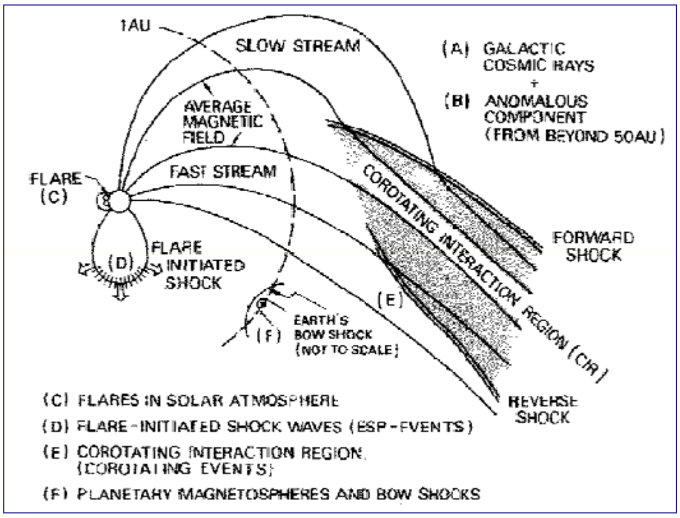




Comparison of a mass spectrum obtained with the IMS-HIS sensor at comet Halley with a laboratory spectrum obtained by RTOF on the Rosetta mission

Energetic particles in the solar system

The heliosphere is flooded with energetic (10s of keV to GeV) particles, from at least 6 different sources!



Spectrometers based on the deflection of particles in macroscopic electric and/or magnetic fields are limited for various reason to particle energies up to several 10 keV

How to measure particles with energies above that?

Interaction with matter (or deflection in ‘atomic fields’).

- Detector systems in telescope arrangements. The mass dependence of the specific energy-loss process is used in combination with different algorithms. Measured quantity: MZ^2.
- Time-of-flight technique with solid-state detector systems. Measured quantity: MZ^2, *EIM,* and *E,* allowing the separation of mass *M* and energy *E.*

3 processes are of importance for energetic particle spectroscopy

- **specific energy loss *(dE/dx)***
- **secondary-electron emission (SEE)** (mainly of importance for TOF measurements)
- **pulse shape analysis (PSA) based on a waveform analysis of the signal a particle leaves in a SSD** (not of great practical importance low resolution)

The specific energy loss (dE/dx)

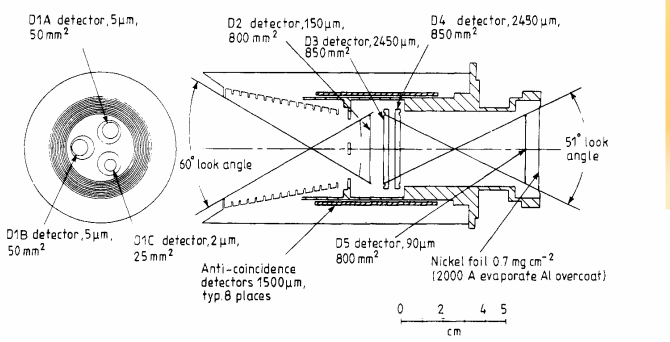
Energetic particles traveling through matter lose energy continuously by Coulomb interaction with electrons and nuclei in the absorbing material. The amount of energy lost per unit path length is referred to as the electronic and nuclear specific energy loss $(dE/dx)_e$, and $(dE/dx)_n$, respectively. The energy loss due to nuclei collisions becomes significant only for particle energies below a few keV/nucleon, leaving $(dE/dx)_e$ in the energy range of interest as the dominant process. For particles with sufficiently large velocities the electronic energy loss is adequately described by the equation

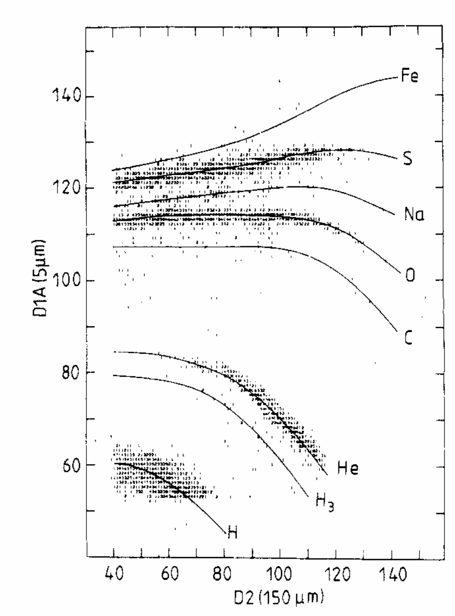
$$-(\mathrm{d}E/\mathrm{d}x)_{\mathrm{e}} = k_1(MZ^2/E_0)f(E, k_2).$$

Here *M, Z* and *Eo* denote the mass, charge and energy of the particle. The parameters $\boldsymbol{k_1}$ and k_2 depend only on the target material. The function *f(E,k2)* varies only slowly with particle energy *E.*

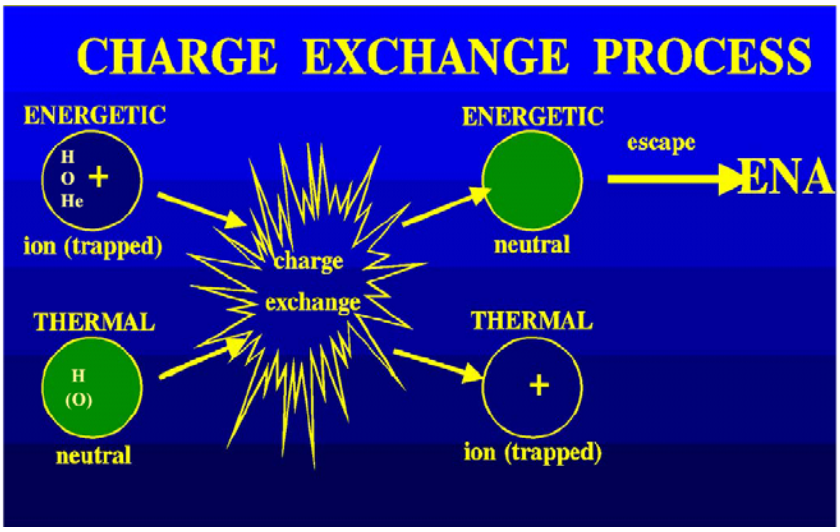
How to extract mass information from a (dE/dx) and *E* measurement?

The general concept of such an instrument is to arrange two suitable detectors, such as proportional counters or solid-state detectors, in a telescope configuration. If the thickness ΔX of the front element is chosen to be short compared to the range of the incident particle the energy loss ΔE is approximately equal to $(dE/dx)\Delta X$. The back detector of the telescope must be thick enough to absorb the entire residual energy E. The ΔE and *E* signal provided by the telescope can then be used to determine the incident particle energy E_o ($E_o = E + \Delta E$) and to establish mass information by applying an appropriate algorithm or particle identifier function to the signal amplitudes.

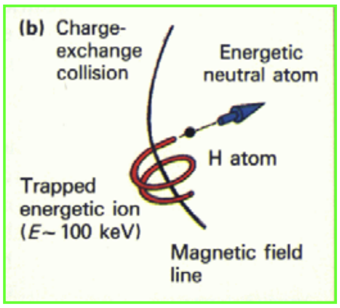




Energetic Neutral Atom (ENA) Detection – the transition from in-situ particle measurements to imaging



ENA Imaging – The Principle



The co-existence of an energetic charged particle population (solar wind, magnetospheric plasma) and a planetary neutral gas leads to interaction, e.g., through charge-exchange:

$$A^+(\text{energetic}) + P(\text{cold}) \Rightarrow A(\text{energetic}) + P^+(\text{cold})$$

Little exchange of momentum → conserve velocity
ENA are not influenced by E- and B-fields; they travel on straight ballistic path like a photon
Directional detection of ENAs yields a global image of the interaction and allows to deduce properties of the source populations.

ENA production mechanism in space plasmas

- **Charge - exchange reaction with atmospheric / exospheric gases**
- Sputtering of planetary atmospheres
- Backscattering from the planetary atmospheres (ENA albedo)
- Sputtering from planetary surfaces
- Ion neutralization / sputtering on dust particles
- Recombination (CMI)

ENA Imaging – How to do it ?
Measurement Techniques

it‘s tough !

ENAs are dilute and have to be measured against a `foreground´ of charged particles and UV photons

→ imposes difficulties even when doing `White Light Imaging´

ENAs are not influenced by em-fields

→ How to do spectral analysis ?

ENA Imaging Instruments
The Recipe

step 1: prevent ions and electrons to enter the instrument

→ electric and magnetic deflection systems

step 2: reduce UV and EUV

→ foils, grates

step 3: convert neutral particle into ion

→ ionizing foils, grazing incidence on surfaces

step 4: perform spectral, mass analysis

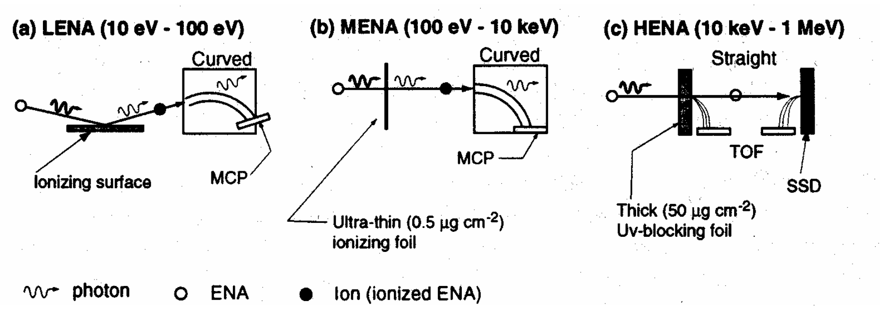
→ E + B fields, TOF system, E-PHA

step 5: perform imaging

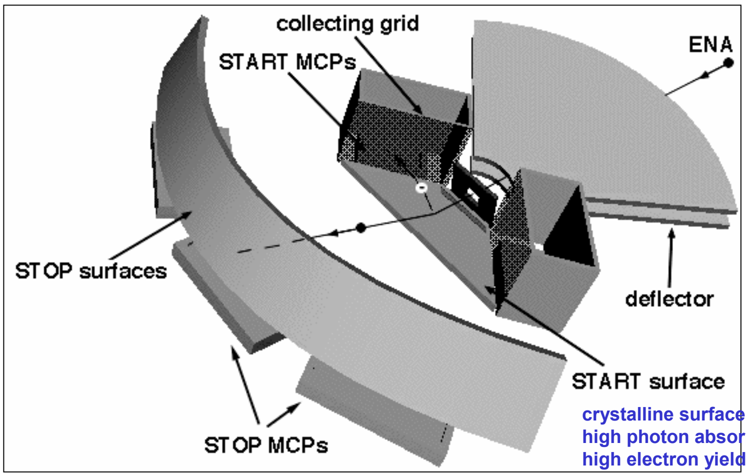
→ direction-sensitive detection (MCP, SSD)

conserve velocity and directional information
and *combine it with a high geometric factor !*

ENA Imaging Instruments
The Principle

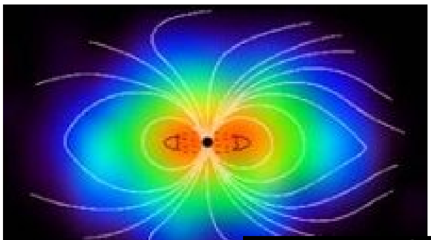


Schematics of a real ENA Instrument
ASPERA for MEX and VEX

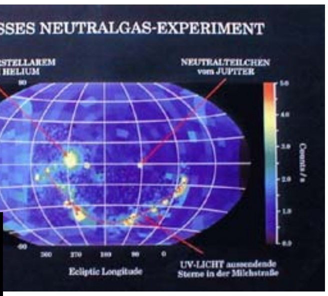


crystalline surface with high photon absorption, high electron yield, high conversion efficiency with which neutrals loose or capture electrons e.g. tungsten

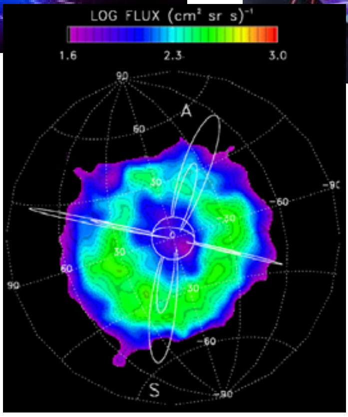
energy range several 10 eV to 10 keV
can distinguish H from O
moderate imaging capabilities



the Io torus viewed with MIMI on Cassini



the interstellar neutral gas detected by GAS on Ulysses



ring current injections in Earth’s magnetosphere viewed by HENA on IMAGE