Particle Detectors for Space Application

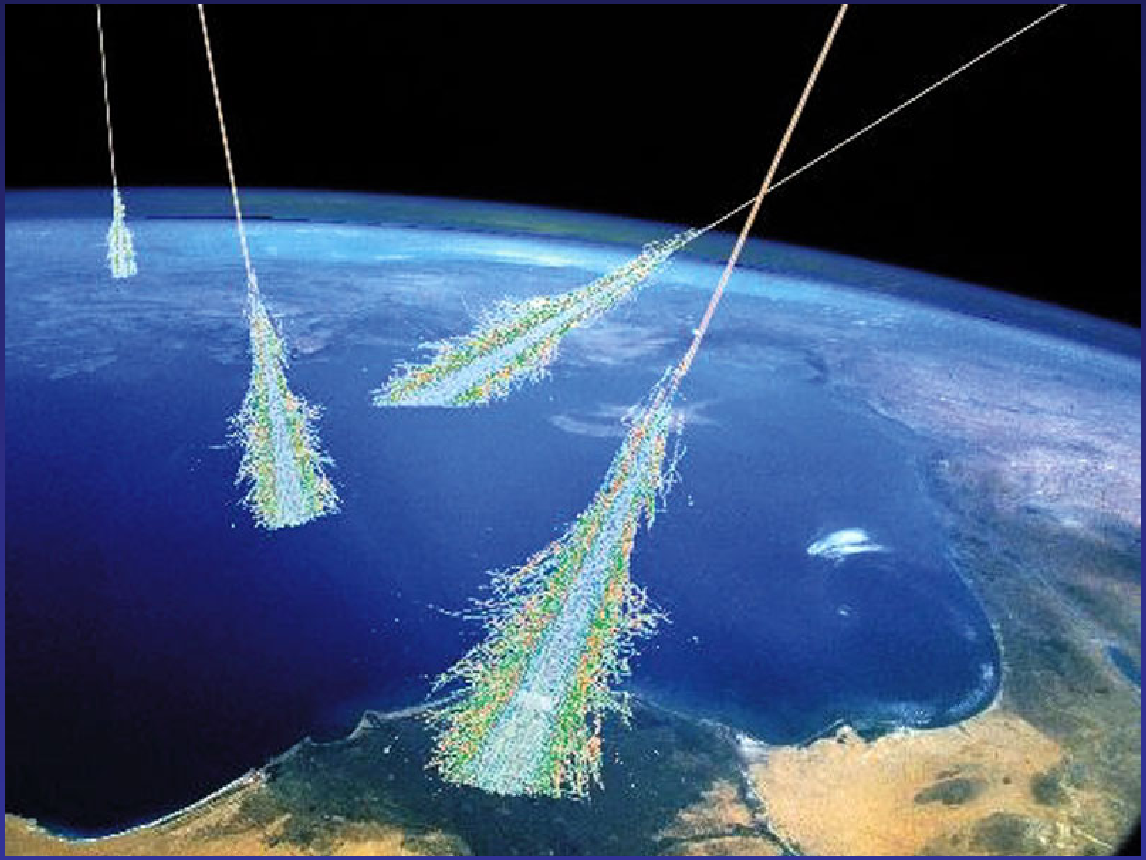
by Markus Fränz and Joachim Woch

1. Particles in Space -

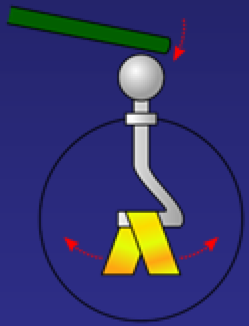
   History of discovery and properties
2. Meaning for solar system science
3. Particle measurement techniques

   current and future designs

Everything started with cosmic rays

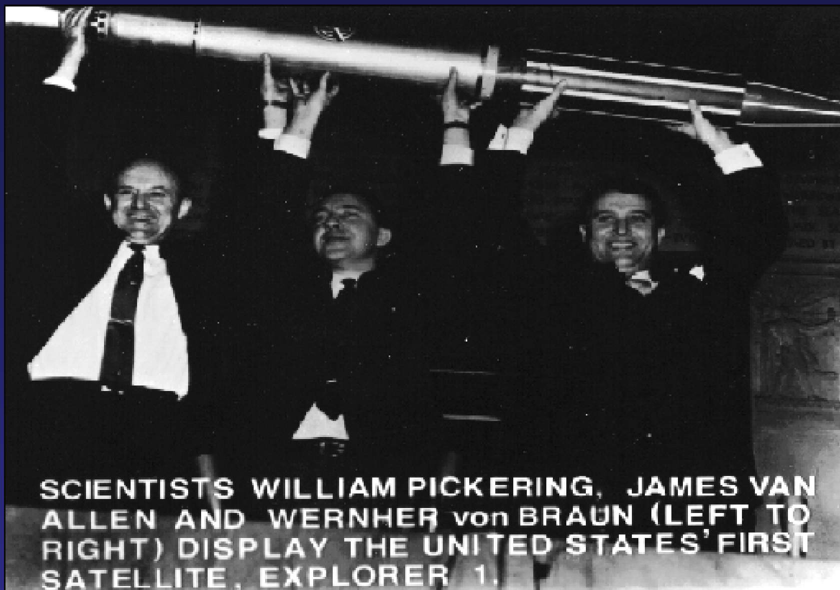


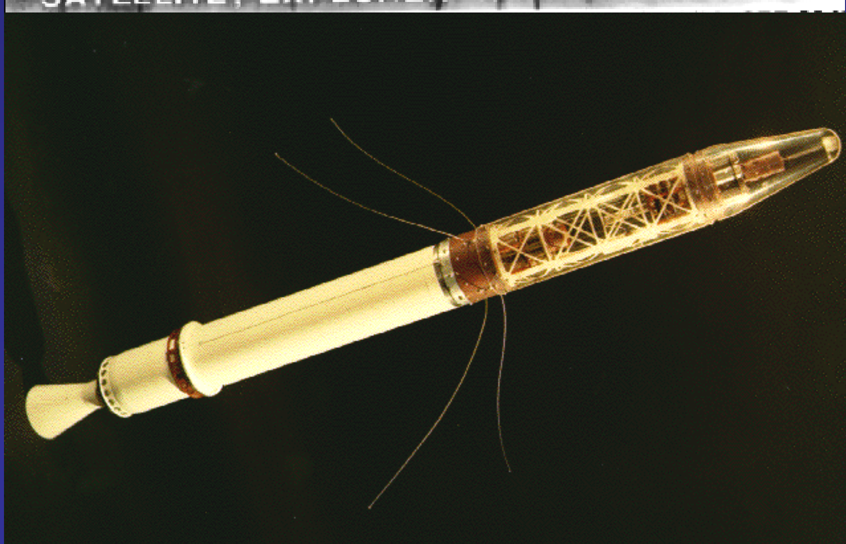
Discovered by Theodor Wulf of Göttingen University in 1910 using an ***Electroscope*** **on the Eiffel tower**

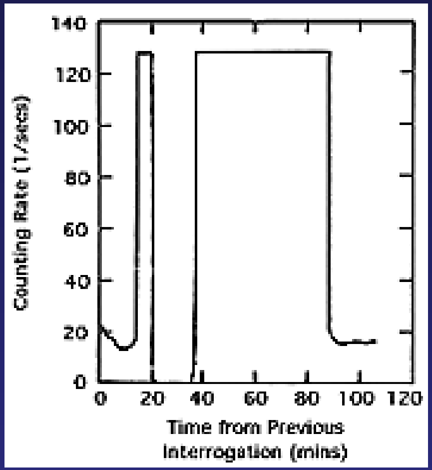


The discovery of particles with energies higher than we can produce on Earth had a huge impact on fundamental physics and the evolution of qunatum theory.

Space Science started with cosmic rays





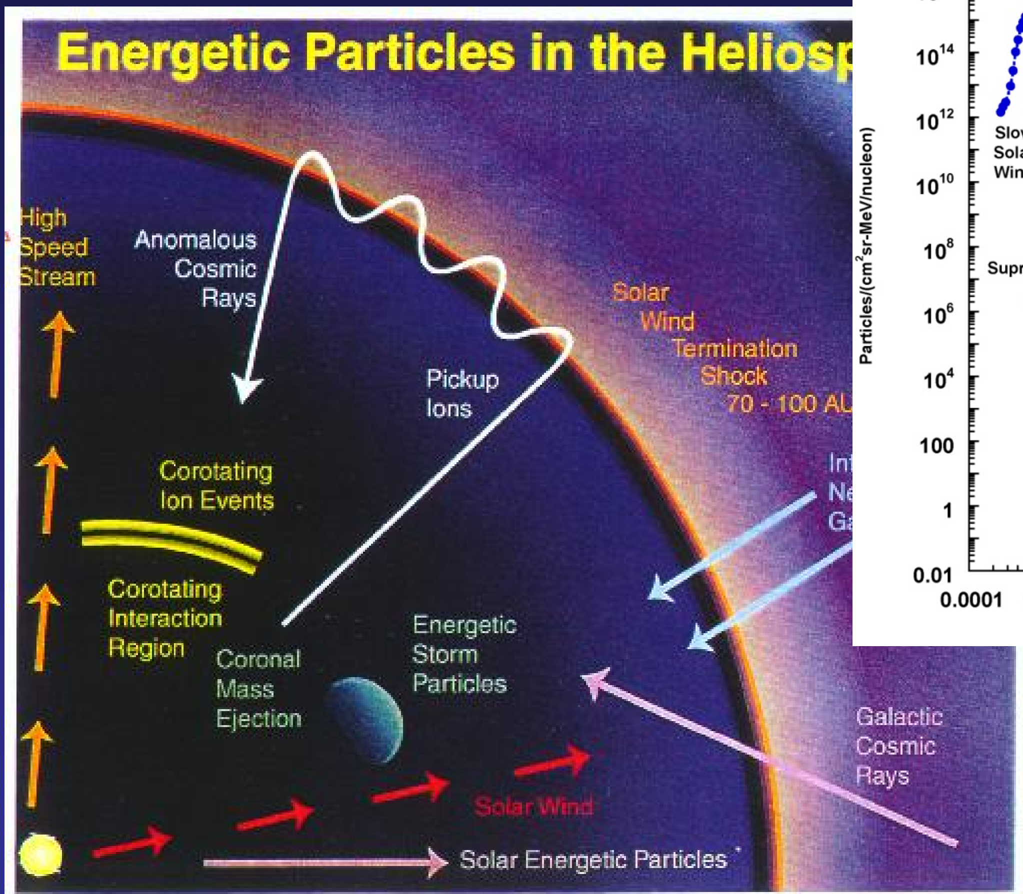


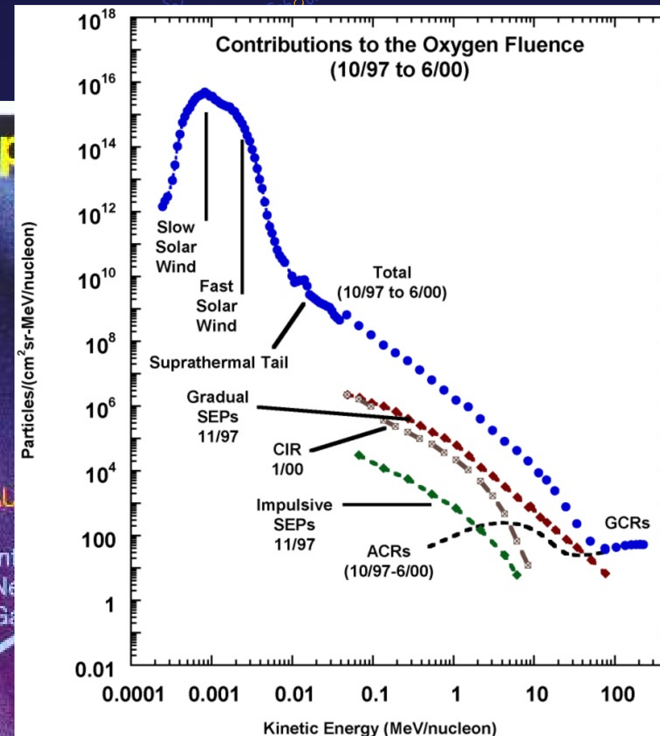
tape recorder read-out from Explorer 3

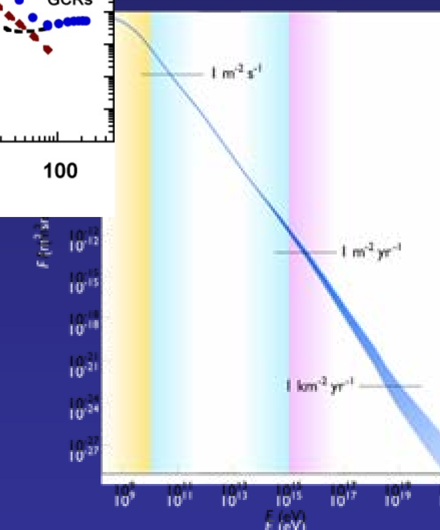
Explorer 1 (Jan 31, 1958) carried a Geiger Counter to study the latitudinal distribution of low-energy cosmic ray it failed in that

instead it discovered Earth's radiation belts (by saturation of counters)

This was confirmed by Sputnik 3 in the same year.



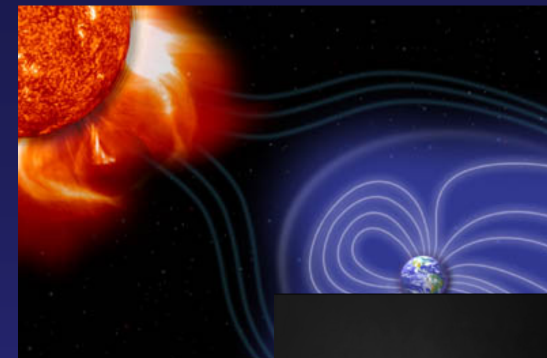


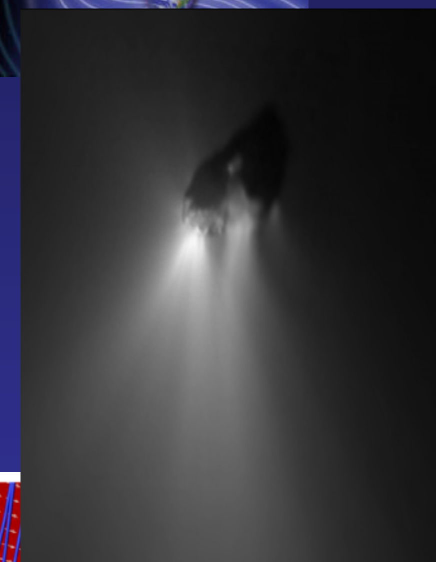


Energetic particles in the heliosphere can be of extra-galactic,galactic, solar or planetary origin and cover an energy range from 1eV to more 10^{20}eV

(eV=electron volt=energy gain of electron in 1 Volt potential)

Particles in Solar System Science





- Types of particles:

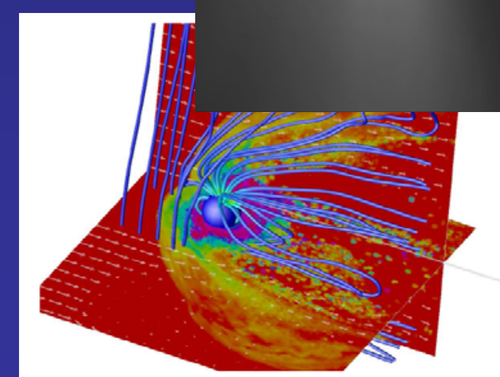
  Electrons, charged atoms, charged molecules, neutral atoms, neutral molecules, dust

- Sources:

  Extra-galactic, galactic, interstellar, termination shock, solar corona, solar flares, interplanetary shocks, planetary bowshocks, planetary magnetospheres, cometary tails, dust rings, planetary surfaces, planetary atmospheres

- Science targets:

  Fundamental physics, plasma physics, acceleration mechanisms, geochemistry and solar system evolution, atmospheric composition and evolution, magnetospheric dynamics...



Particle Detectors – What they are good for

a very large parameter space has to be covered

- **12 orders of magnitude in energy**
- **from electron mass to a few hundred amu (atomic mass units)**

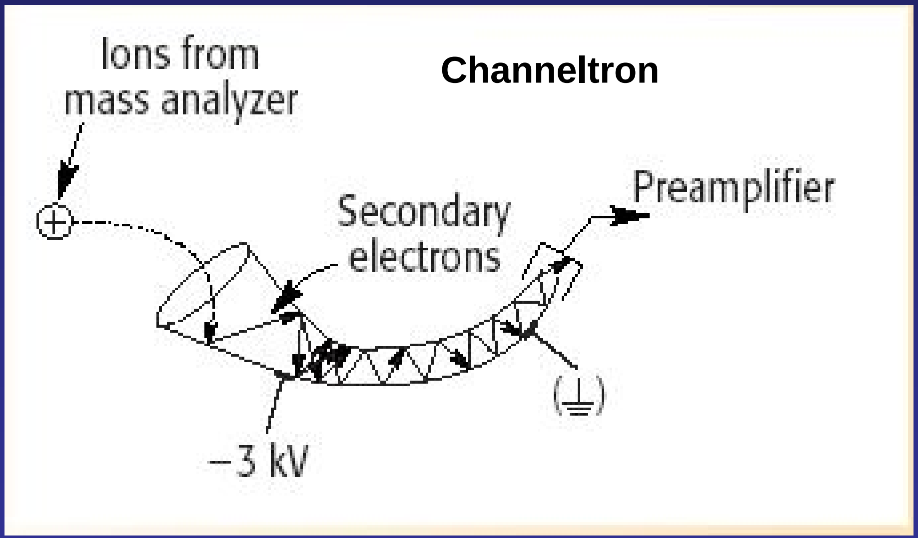
with very different demands

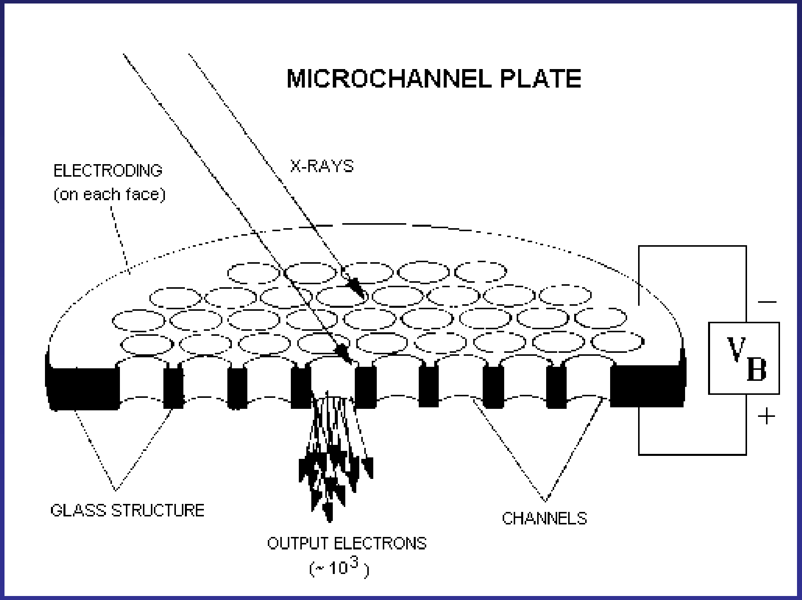
- **high temporal resolution (<1s) for plasma physics**
- **high mass resolution (M/ΔM ~ 1000) for exploration of a comet's coma**

In the following we discuss only electron, ion and neutral atom spectrometers

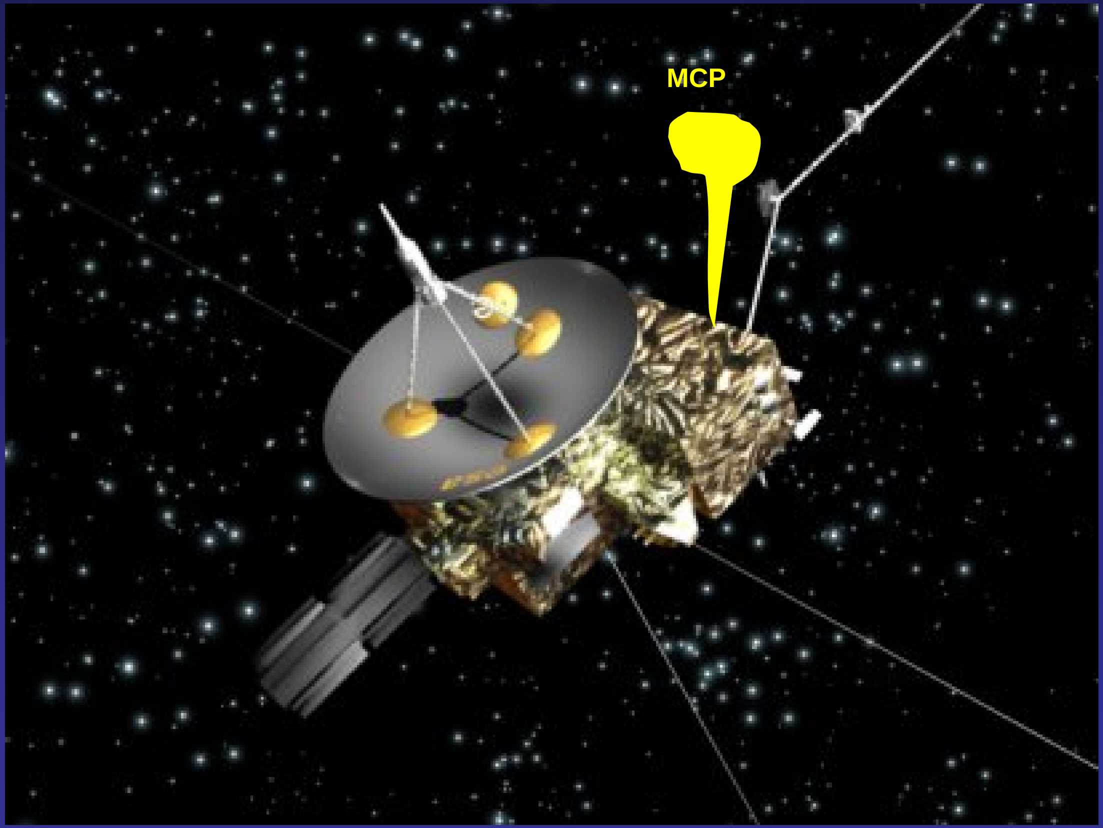
How do you measure a charged particle?

Detecting Particles in Space





Channeltrons and microchannelplates (MCPs) are sensitive enough to detect electrons, ions and neutral atoms with an entrance energy of a few eV



What would you measure if you mount an MCP on a spacecraft – just like that?

Answer:mainly photons, electrons and protons from all spatial directions. The MCP would not survive very long.

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

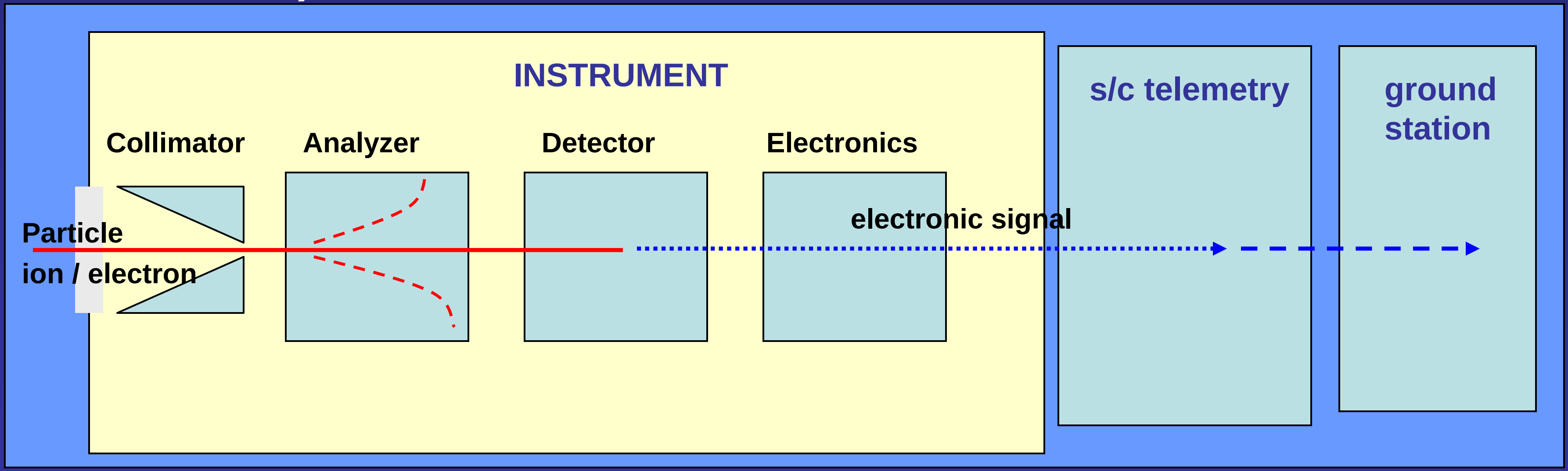
Particle Spectrometers – Parts

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

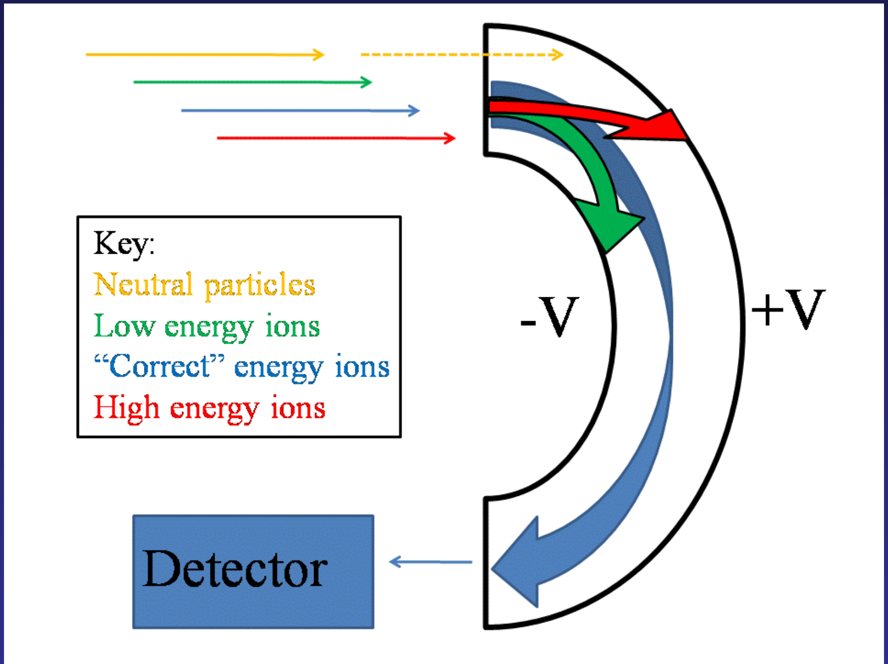
Analyzer: filters particles with pre-selected values of the particle parameters out of the beam for further analysis

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)



Electrostatic Analyzer



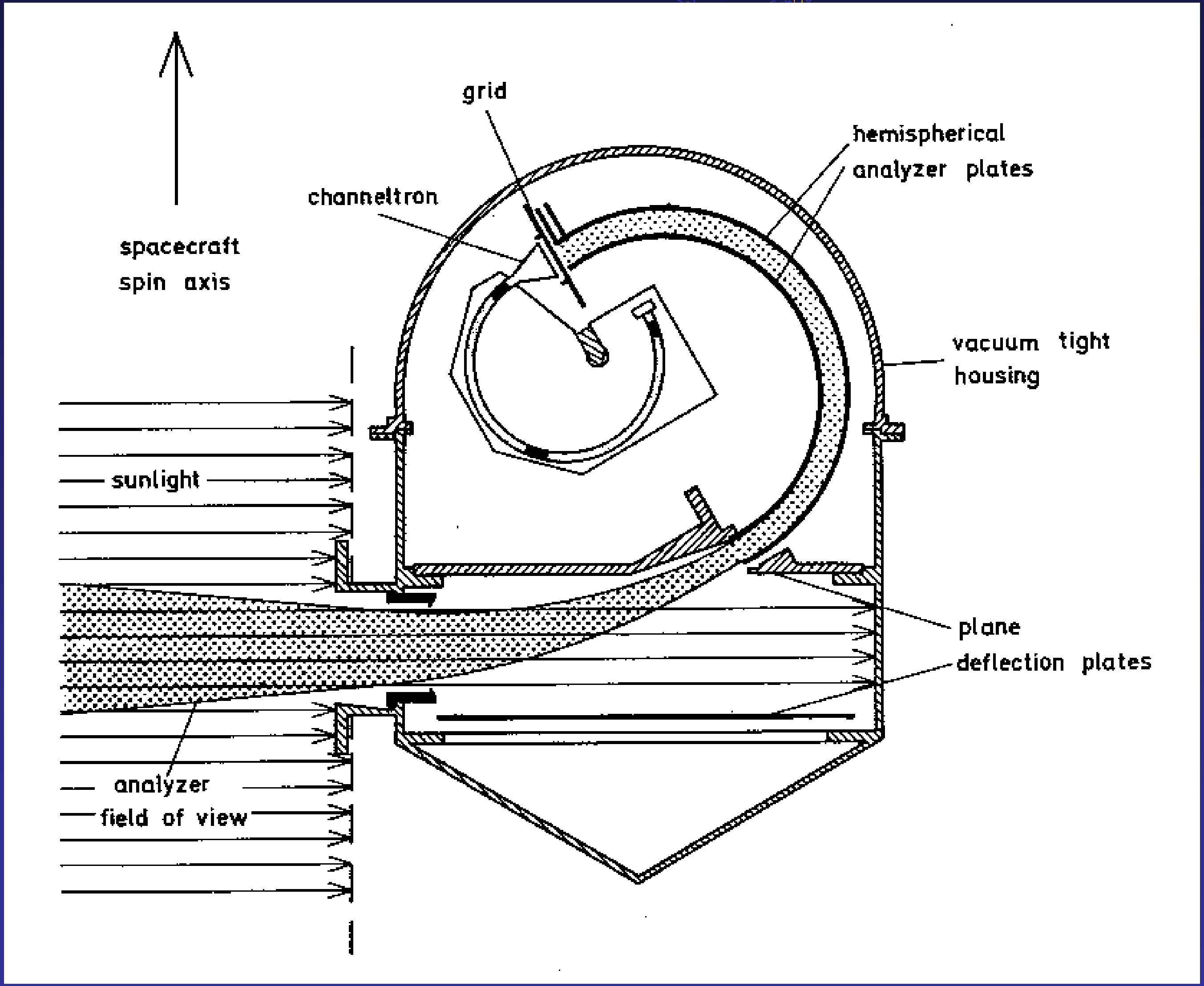
uses an electric field between two curved plates to guide the flight path of a charged particle around a bend to a detector.

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 E 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.

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 in 1974 by H. Rosenbauer (later director at MPS).
The trick: no photo electron could ever make it to the detector!

Evolution of the field-of-fiew

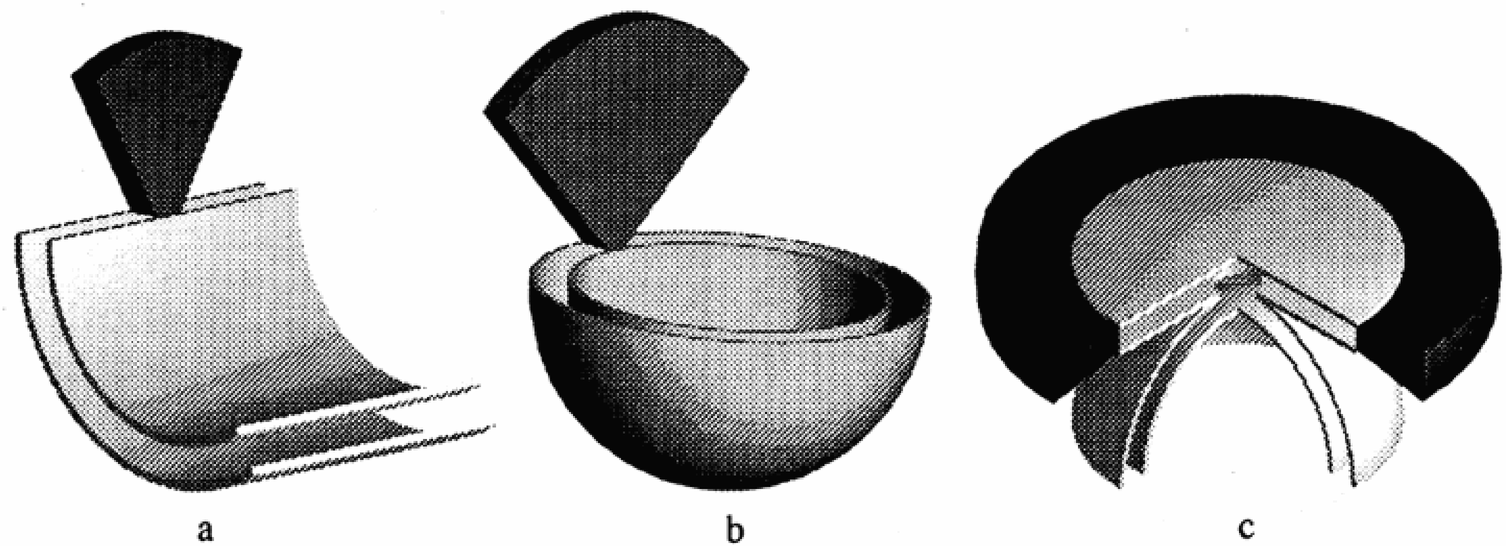
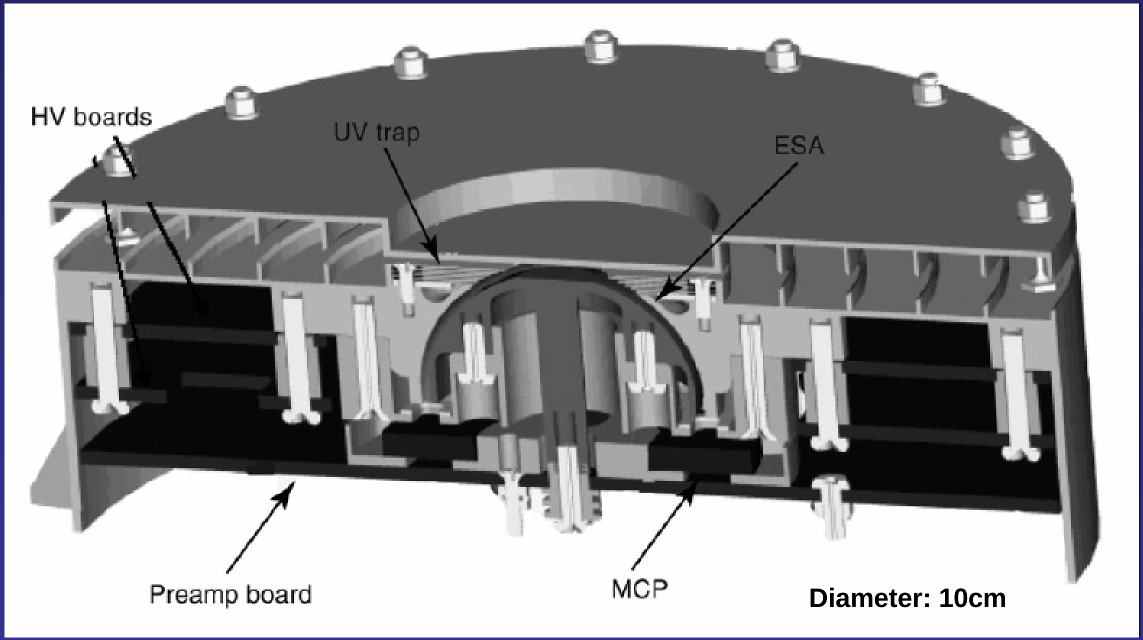


Fig. 1. Evolution of the electrostatic analyzer used in space plasma diagnostics: (a) cylindrical analyzer, (b) spherical analyzer, and (c) top-hat analyzer. The dark regions illustrate the field of view.

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.
The *top hat analyzer* views a full 360 degrees in azimuth with a narrow fan in the orthogonal direction.
On a spinning spacecraft the field of view covers the complete sky.
On non-spinning spacecraft the FOV is extended by scanning platforms or electric deflection at sensor entrance.

The ASPERA Electron Spectrometer ELS (2003)

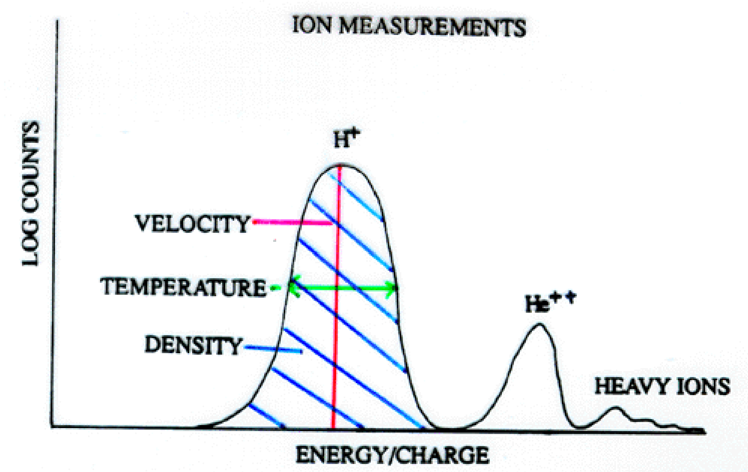
currently flying on the MEX and VEX missions

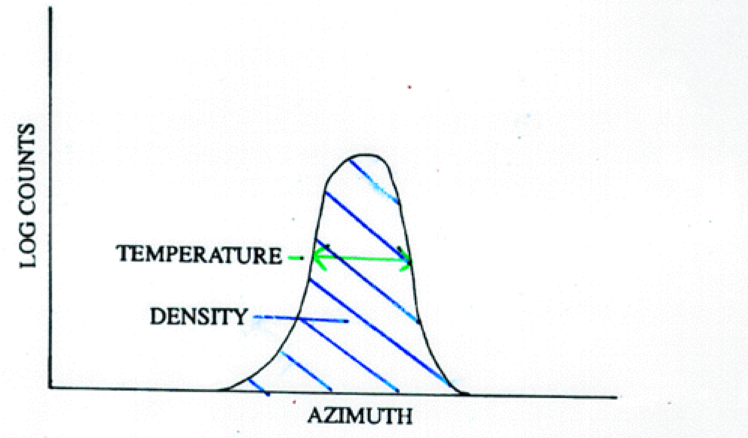


Parameter	*ELS*
Particles to be measured	electrons
Energy range, keV per charge	0.01 - 20
Energy resolution, ΔE/E	0.08
Mass resolution	–
Intrinsic field of view	10 x 360°
Angular resolution (FWHM)	10 x 22.5°
G-factor / pixel, cm² sr	5×10^{-4}
Efficiency, ε, %	8 G
Time resolution (full 3D), s	32
Mass, kg	0.3
Power, W	0.6

The challenge is to build very robust spectrometers with low mass and low power consumption for harsh environments.

What electrostatic analyzers can measure





If ions move at the same velocity (as for example in the solar wind) an electrostatic analyzer is sufficient to:

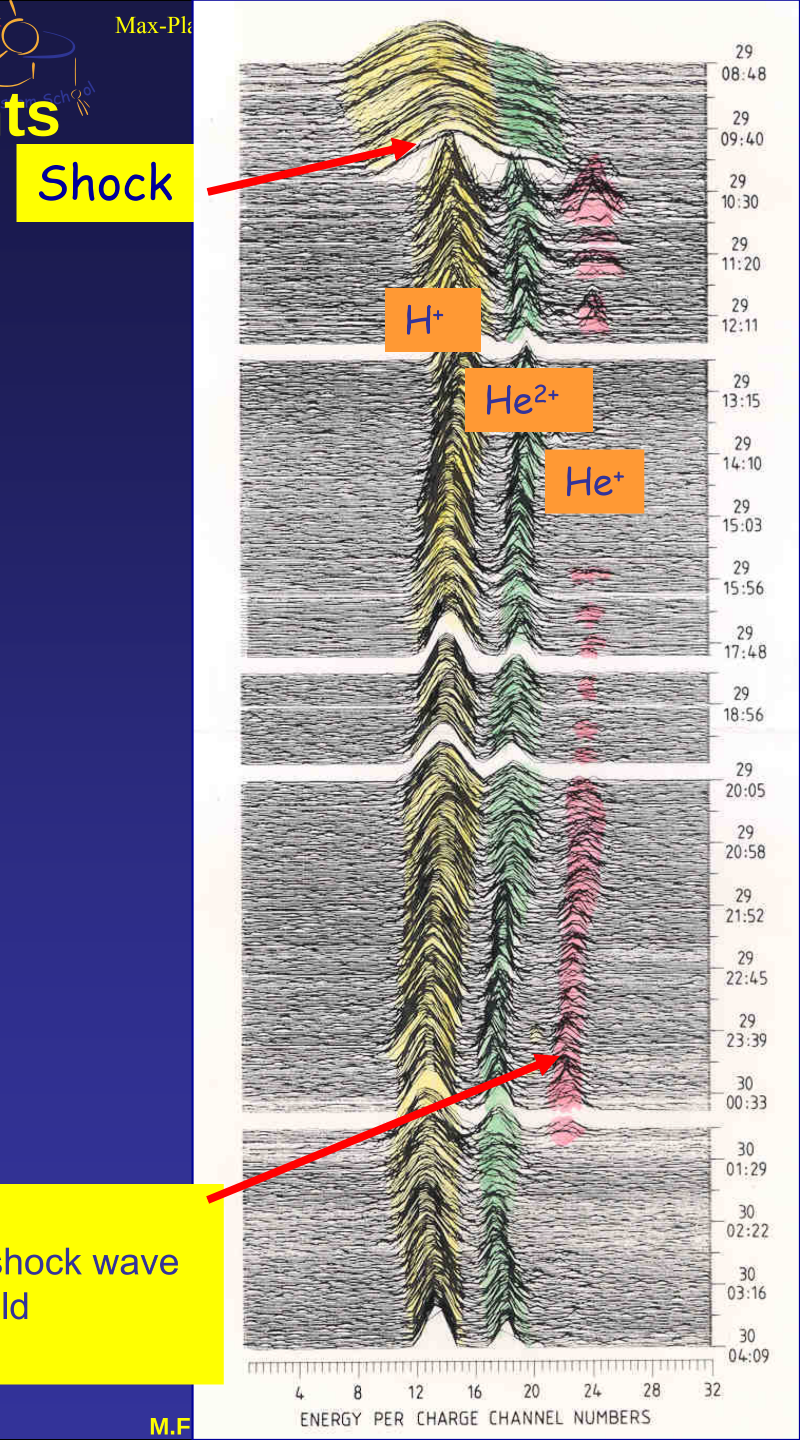
1. separate ion species
2. determine density, velocity and temperature of the distribution.

The maximum energy resolution achieved so far in space is 0.14% (Cassini CAPS IBS) sufficient to do isotopic analysis.

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.



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.

How can you measure the mass of ions when you know the energy?

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

using Gyroradius r=mv/QB in a static or variable field B

provide good mass resolution, but complex, slow, massive, limited field-of-view.

Stray magnetic fields that may affect other measurements.

time of flight instruments

using velocity in a electrostatic potential

good sensitivity, all species simultaneously measured, broad field of view.

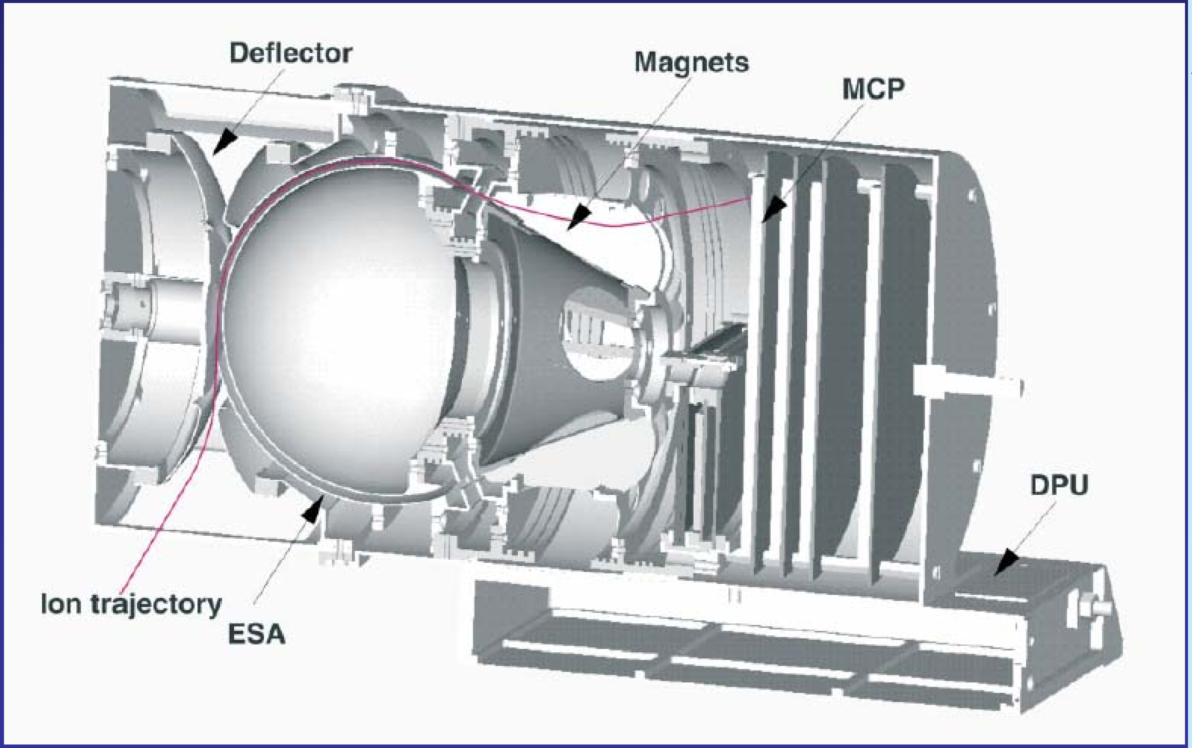
Only modest M/Q resolution ($M/\Delta M < 10$).

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.

The ASPERA Ion Spectrometer IMA (2003)

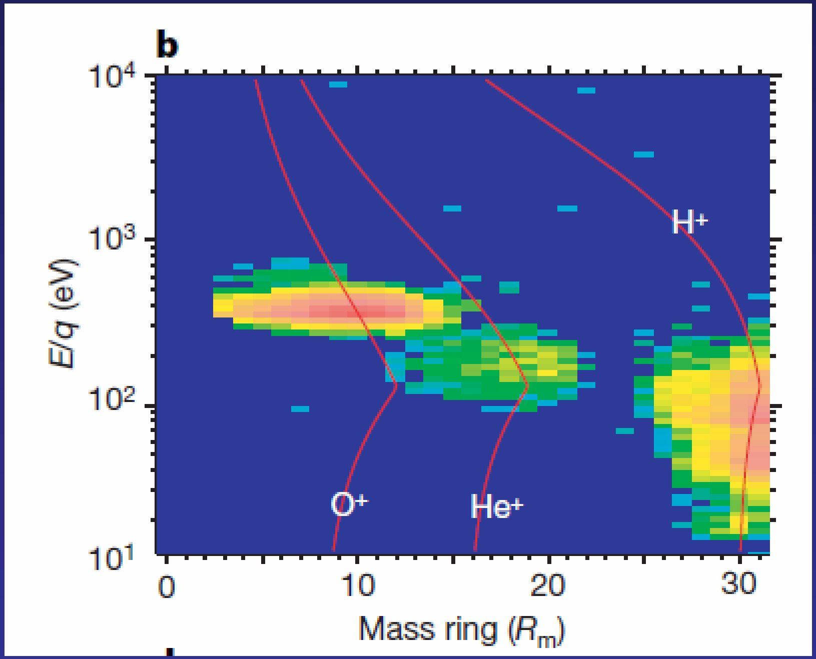
currently flying on the MEX and VEX missions



Parameter	*IMA*
Particles to be measured	ions
Energy range, keV per charge	0.01 - 30
Energy resolution, $\Delta E/E$	0.07
Mass resolution	m/q = 1, 2, 4, 8, 16, >20
Intrinsic field of view	90 x 360°
Angular resolution (FWHM)	4.5 x 22.5°
G-factor / pixel, cm^2 sr	3.5×10^{-4}
Efficiency, ε, %	inc. in G
Time resolution (full 3D), s	32
Mass, kg	2.2
Power, W	3.5

Measurements by a compact magnetic mass spectrometer

Ion escape from Venus (VEX-Aspera,Barabash 2007)

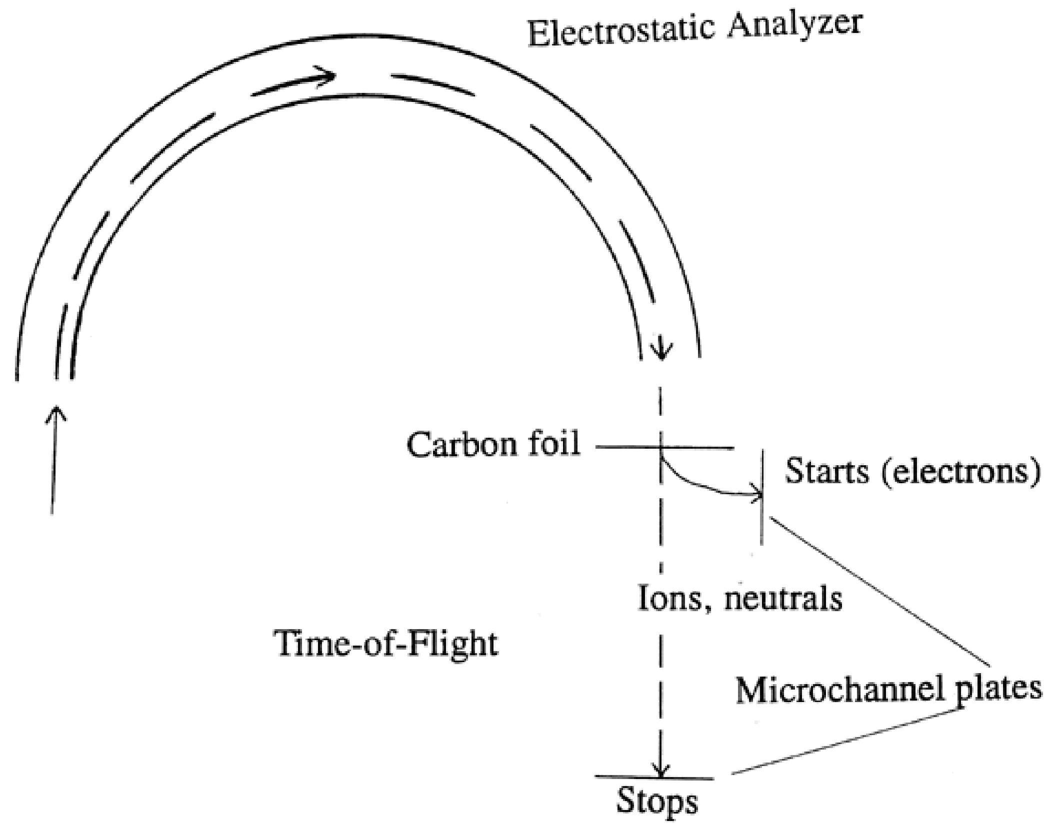


Advantage: high efficiency of measurement

Disadvantage: low mass resolution, limited mass range

A simple time of flight analyzer

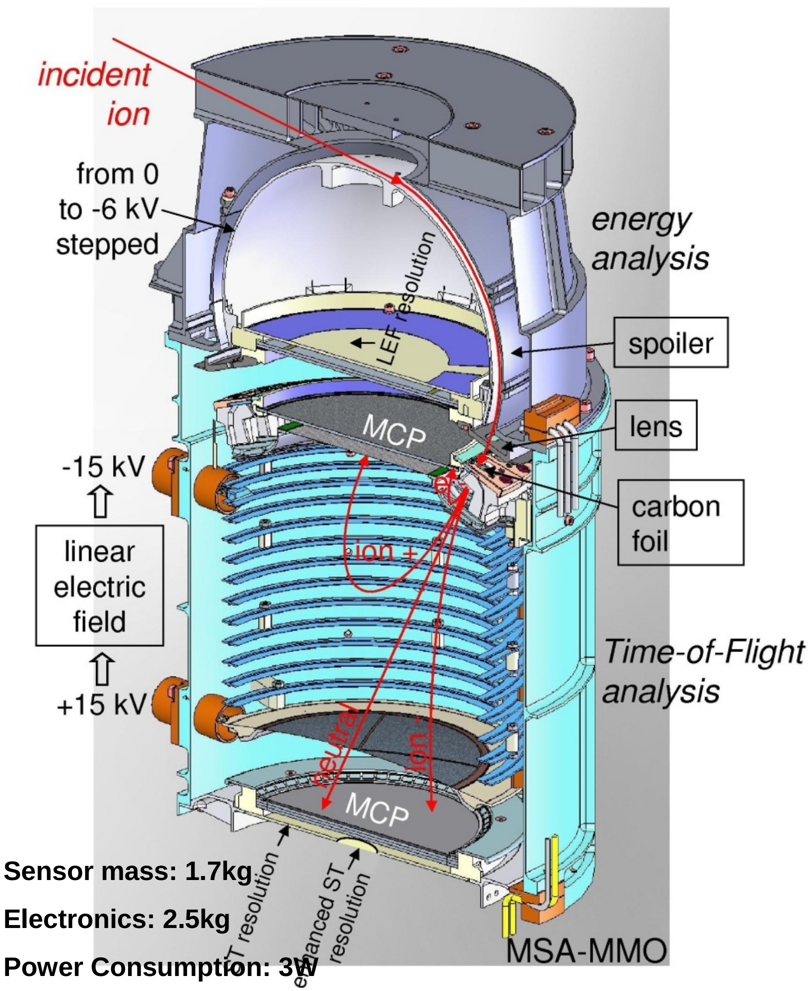
When the ion leaves the analyzer section it passes through a very thin carbon film. This passage knocks out an electron that is captured by a positively charged plate and triggers a start pulse. When the ion reaches a stop plate another pulse is generated and the time between the pulses is the time of flight. The energy loss and angular spreading caused by the passage through the foil degrades the M/Q resolution here.



Major factor limiting M/Q resolution in traditional Time-of-Flight Plasma Instrument: Energy and angle straggling in carbon foils.

The time-of-flight ion sensor MSA (2010)

Current design for the BepiColombo mission



Sensor mass: 1.7kg

Electronics: 2.5kg

Power Consumption: 3W

- FOV : 8° x 260° (after closing due to mast)
- angular resolution (max) : 8° x 11.25°
- energy range : 5 eV/q – 40 keV/q
- energy steps : 32 or 64 steps (nominal step duration : 3.9 ms)
- energy resolution : 10 %
- analyzer constant : 7.1
- inner deflector radius : 57.9 mm
- outer deflector radius : 61.9 mm
- deflection angle : 110°
- mass range : 1-60 amu
- mass resolution : m/Δm = 40 for energies < 15 keV/q (nominal)
  m/Δm = 10 for energies > 15 keV/q
- time resolution : 3D distribution in 4 s (32 energies)
  3D distributions in 8 s (64 energies)
- G-factor : 1.9 x 10^{-3} cm2 sr keV/keV (nominal)
  1.9 x 10^{-7} cm2 sr keV/keV (for solar wind ions)

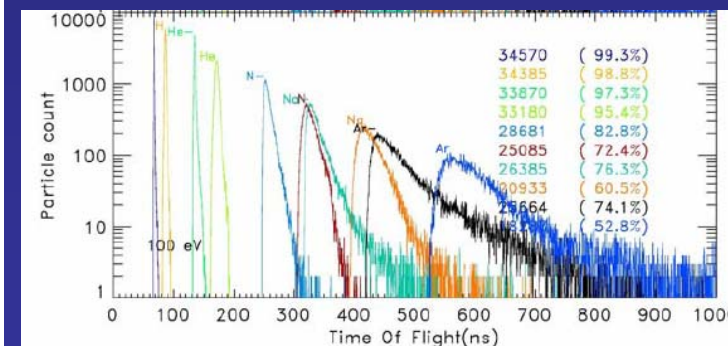
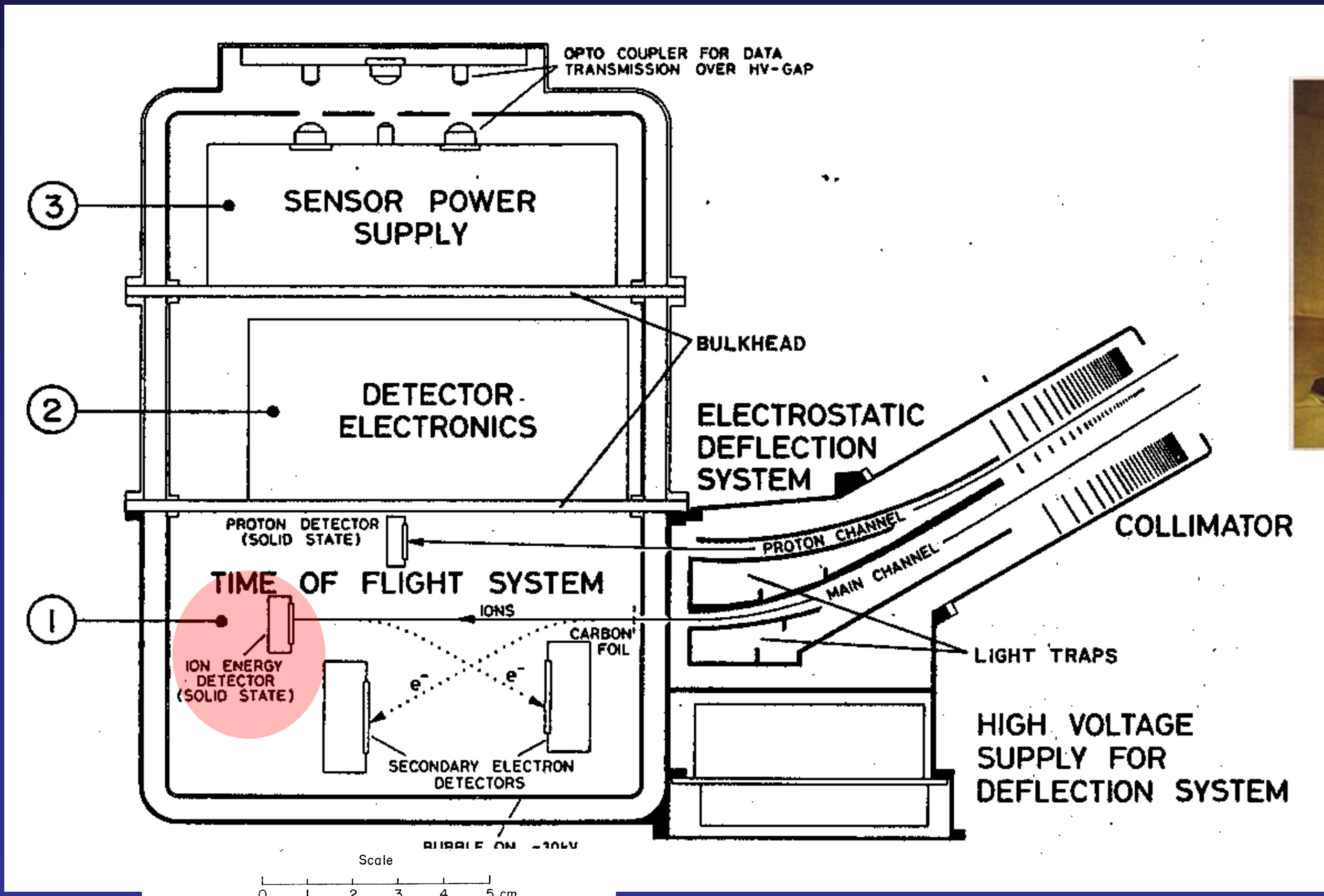


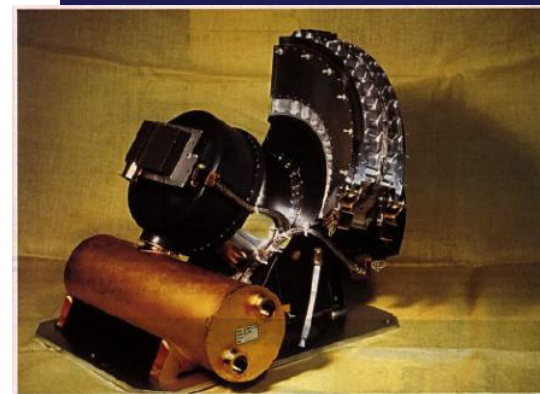
Figure 2.3-7 Model TOF spectra for various species on the ST detector.

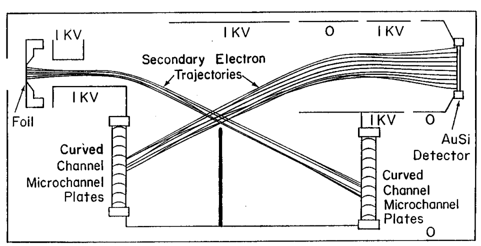
Expected performance

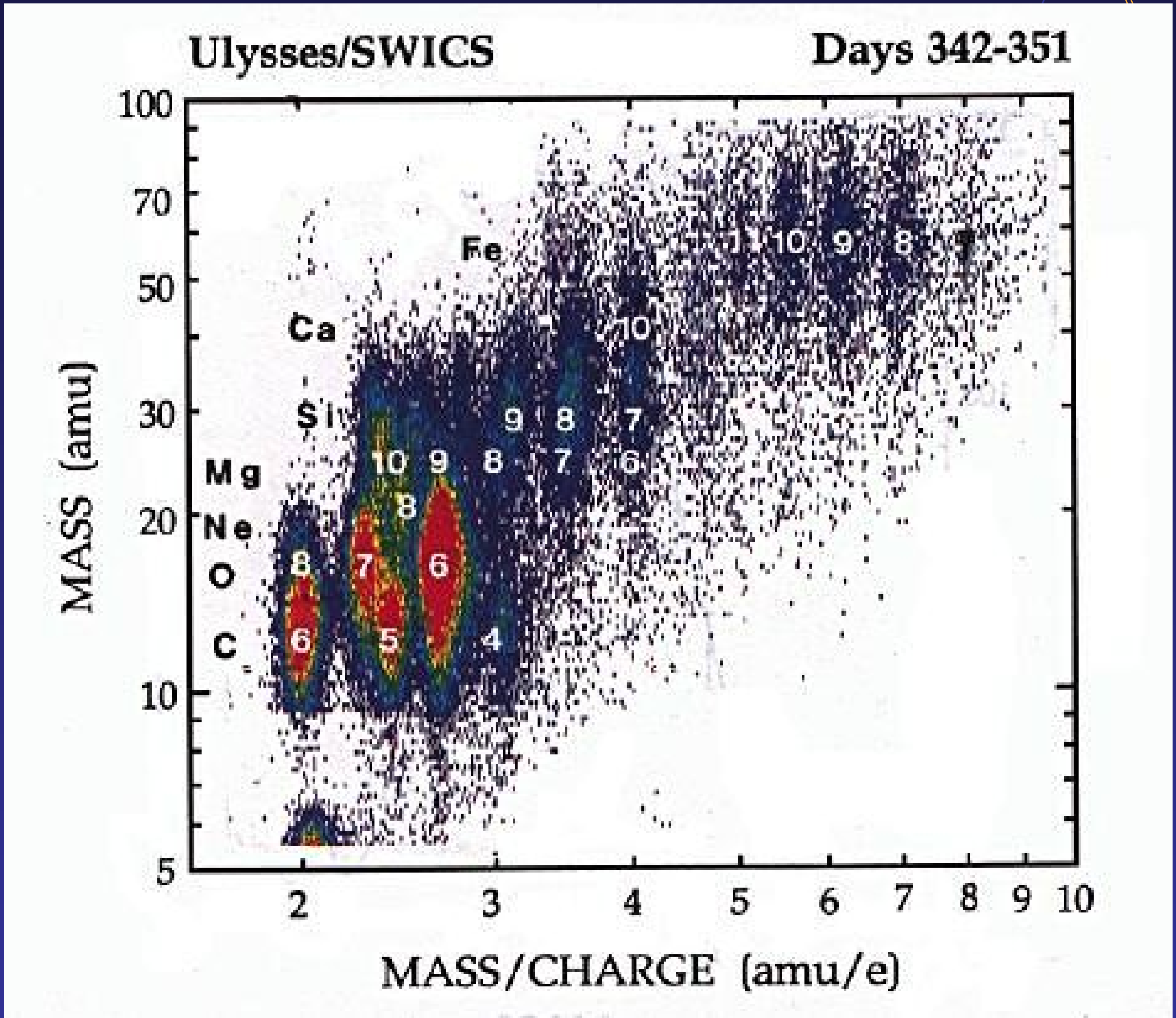
Other Designs with Special Capabilities

Concept of the SWICS/Ulysses TOF Spectrometer



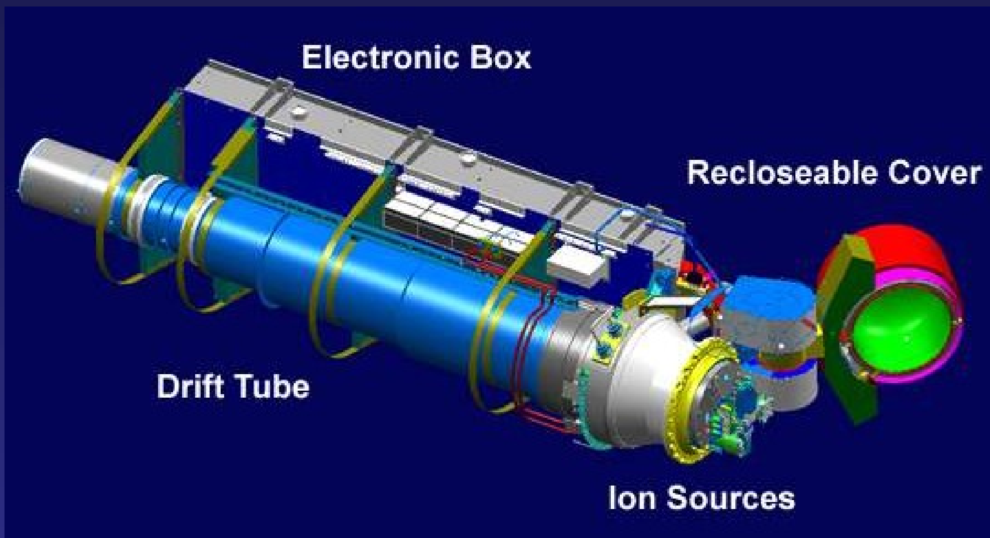






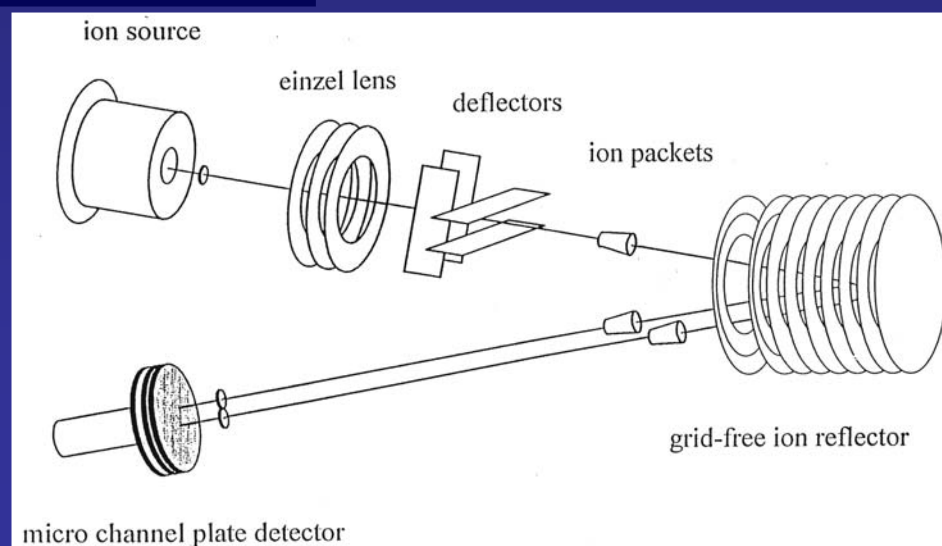
charge and mass spectrum of the solar wind

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

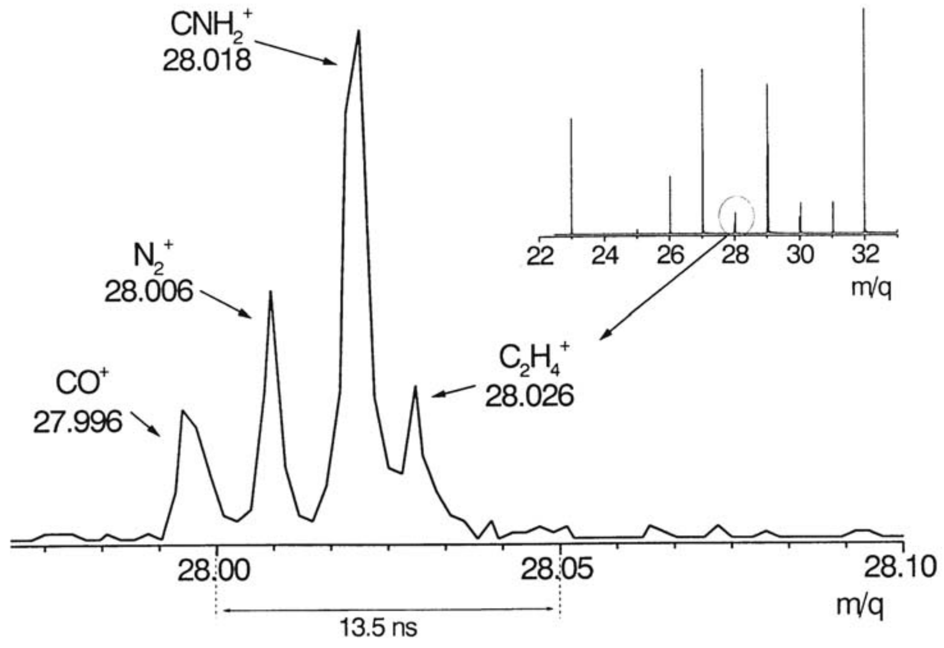


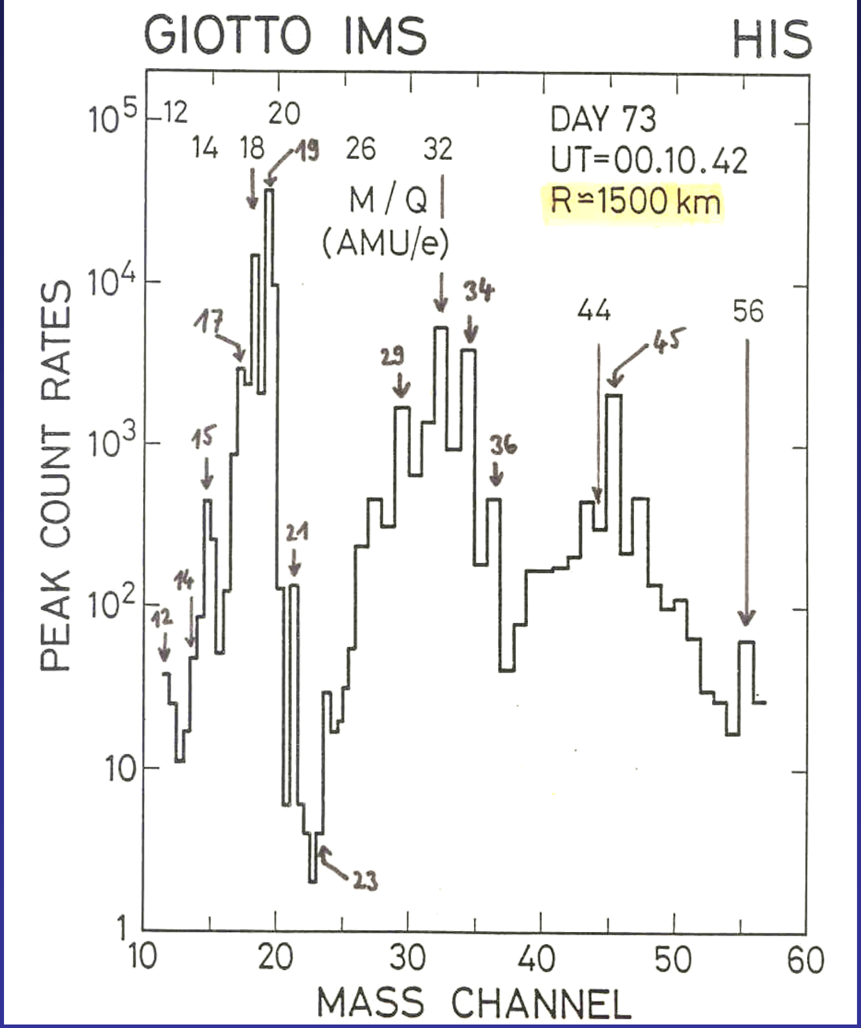
Instrument parameters

- Mass range: 1-1000 amu
- Mass resolution M/ΔM=500 (1% Level) by long drift path at low energy
- High time resolution by simultaneous mesurement of different masses
- Typical entrance energy < 10eV



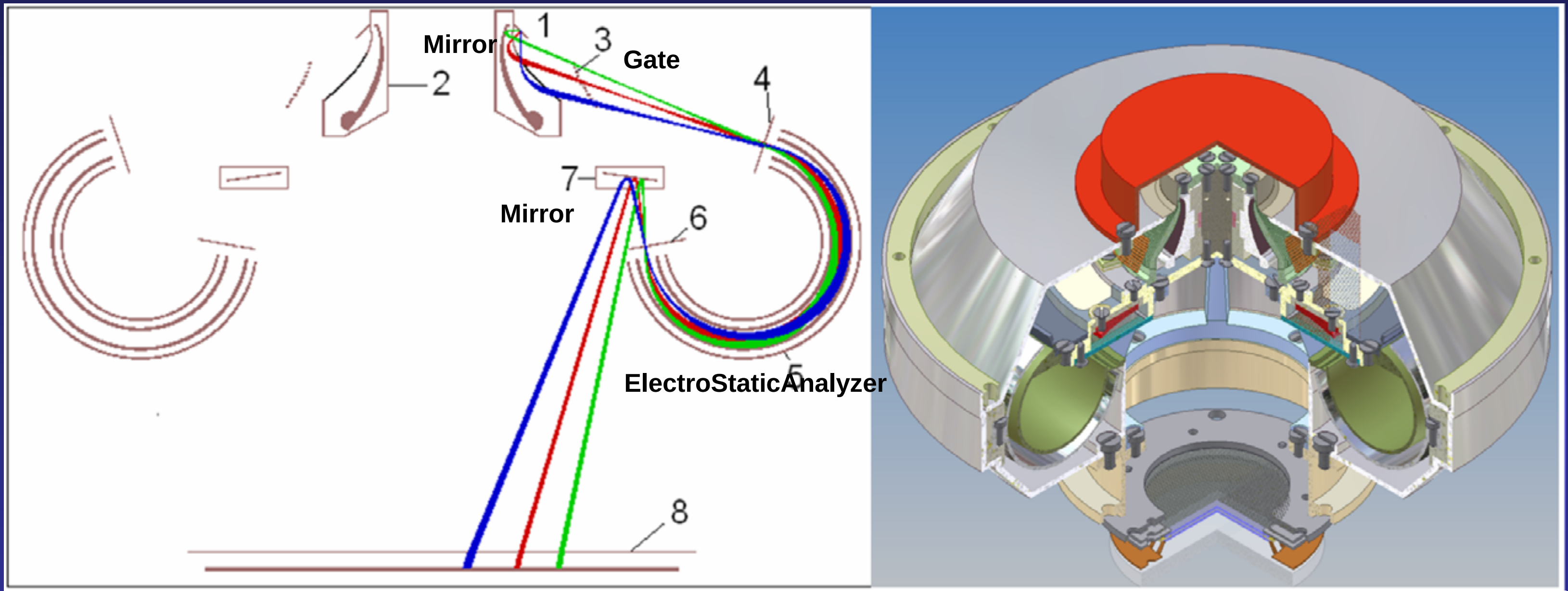
ROSINA/RTOF on ROSETTA
Reflektron-Time-of-Flight-Spektrometer





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

BepiColombo PICAM Ion Camera (2010)



MCP

Ions are reflected by electrostatic mirrors such that an image of the particle distribution is projected onto the MCP.

In addition TOF can be measured by switching flow On and Off using an electric gate.

How do we measure energetic neutral atoms?

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

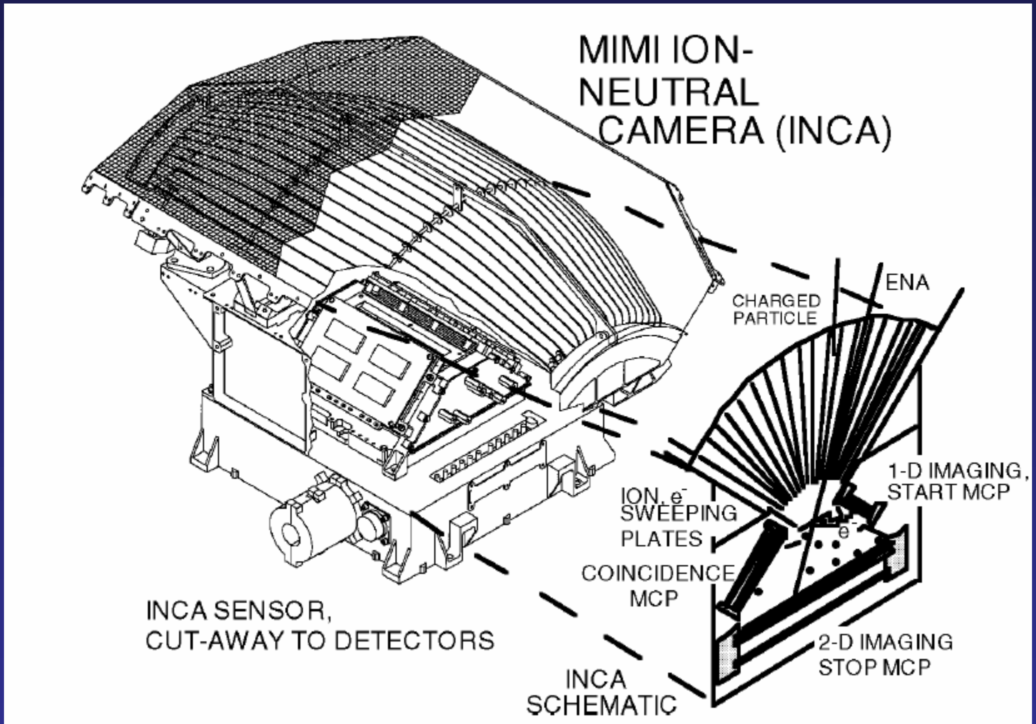
→ E + B fields, TOF system, E-PHA

step 5: perform imaging

→ direction-sensitive detection (MCP, SSD)

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

Cassini INCA Neutral Camera (2000)



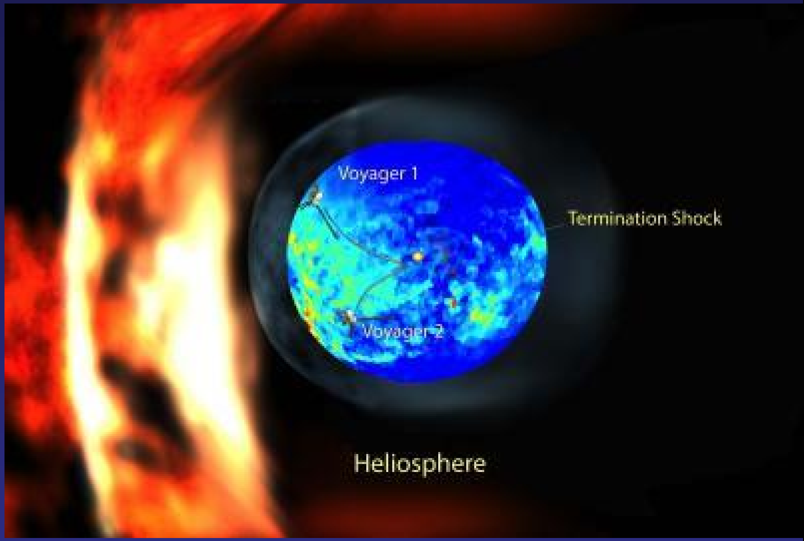
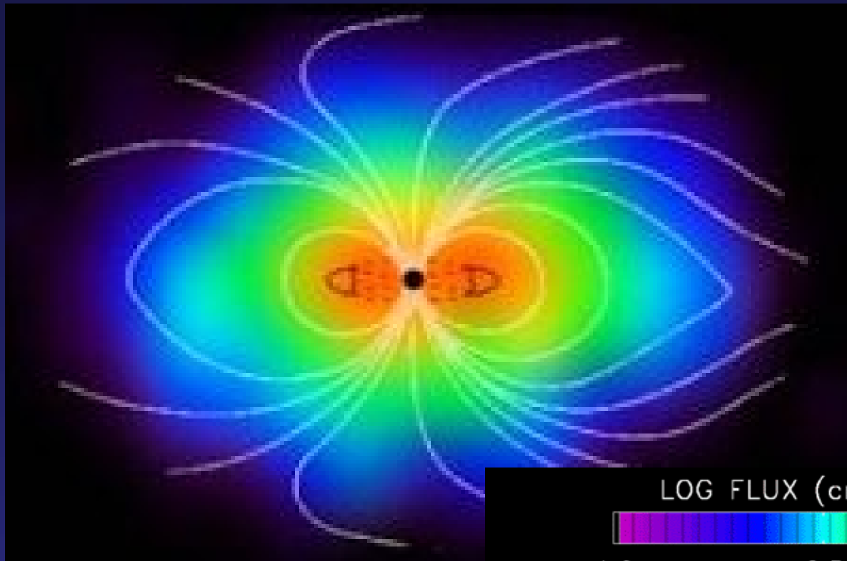
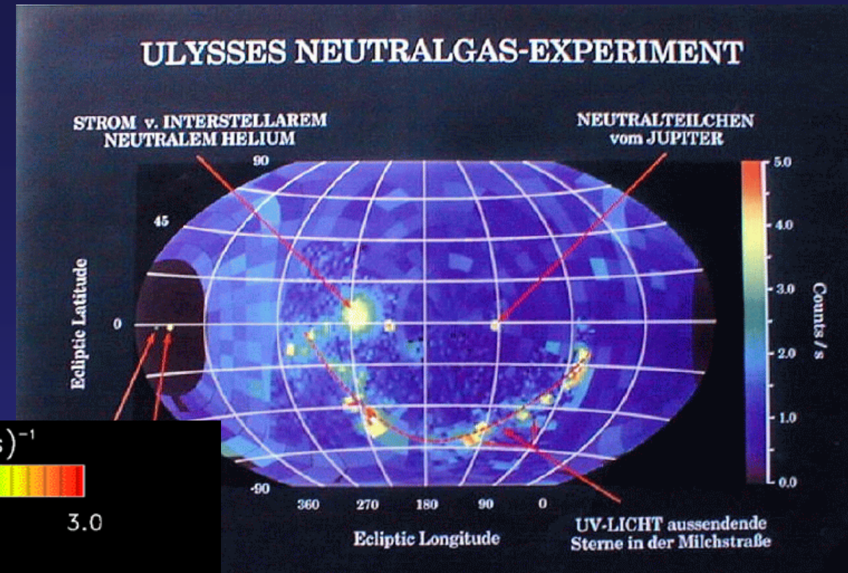


Image of the heliospheric termination shock taken by INCA

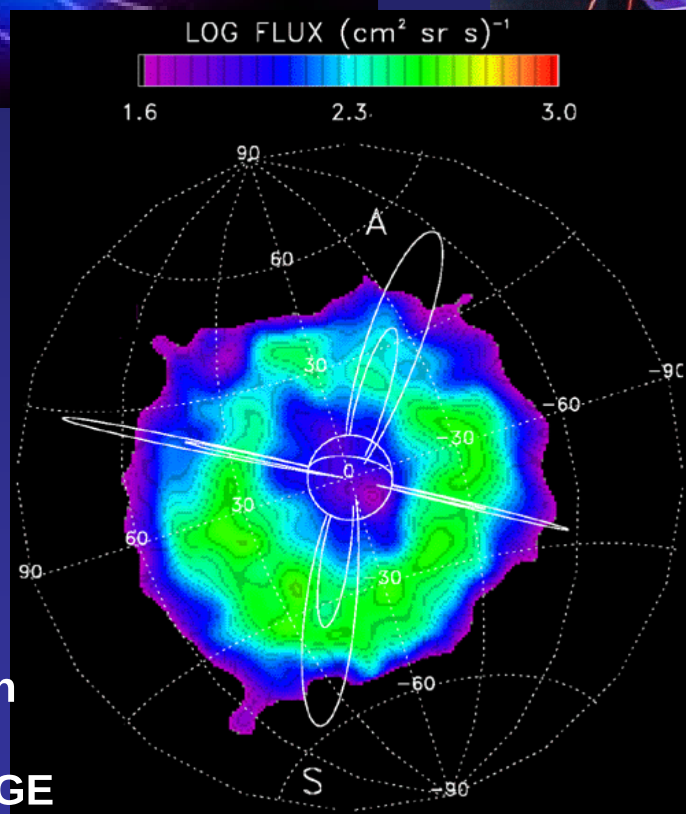
Mass: ca. 20kg



Io torus viewed by INCA on Cassini



Interstellar neutral gas detected by GAS on Ulysses



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

Particle Imaging Science

is just starting

When Theodor Wulf climbed up the Eiffel tower in 1910 with his electrometer he could not have imagined what followed.

Thank you!