Rocket instrumentation for the mesosphere and lower thermosphere

2009 NSF CEDAR Student Workshop

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Clemson University

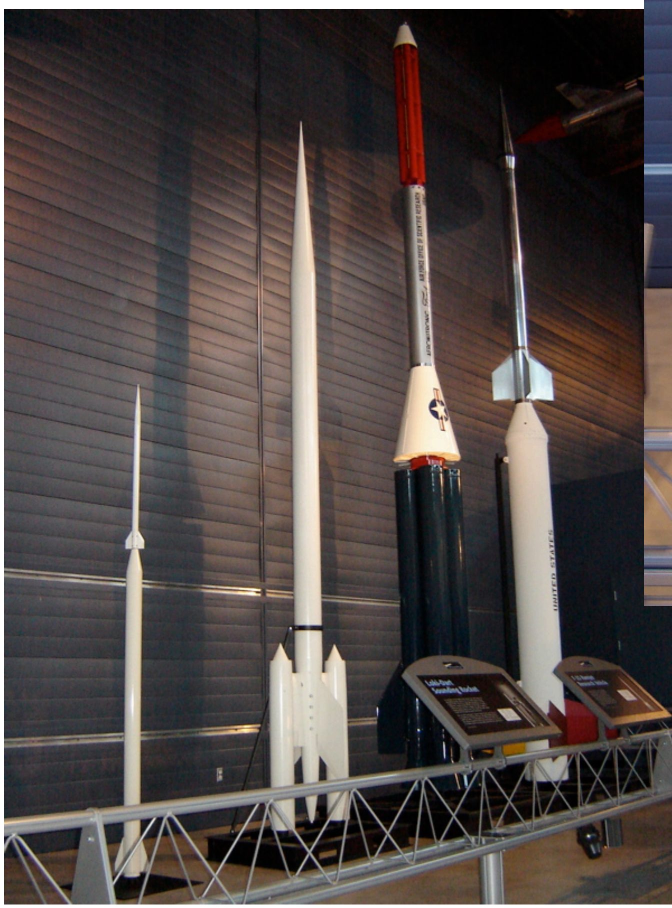
Movie of 2009 Alaska launch

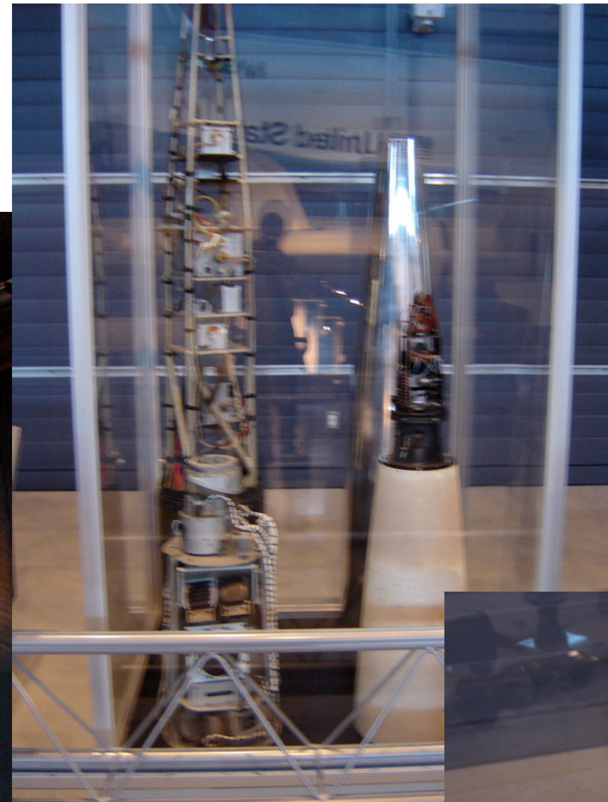
Historical notes 1945-1957

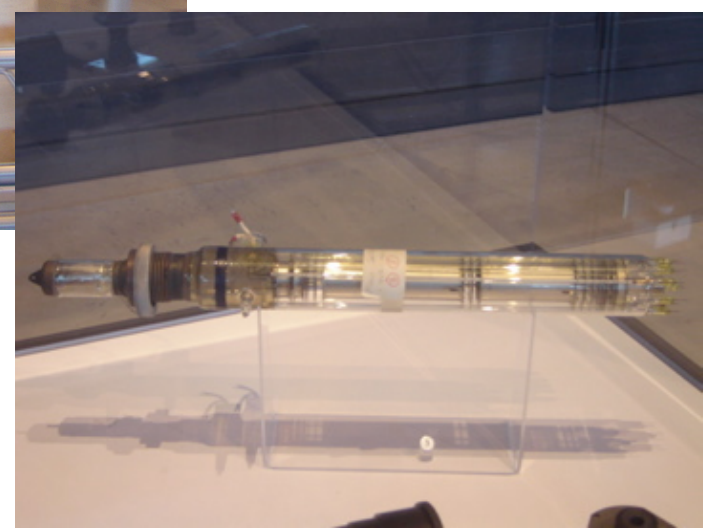
- Rocket science for exploration began in the late 1940s from White Sands, NM
- First direct measurements in the mesosphere
- Always connected to radio science/radar and airglow observations, developed together with scientific ballooning
- “The Rocket Panel” reference atmosphere (Phys. Rev. 88, 1027 – 1032, 1952)
- Reentry region for intercontinental ballistic missiles, satellites, space shuttle
- Highly entangled with defense and security interests (and still is!)


TRAILER
BM-35254
NORTH CAROLINA

From the collections of the
National Air & Space Museum Steven F. Udvar-Hazy Center

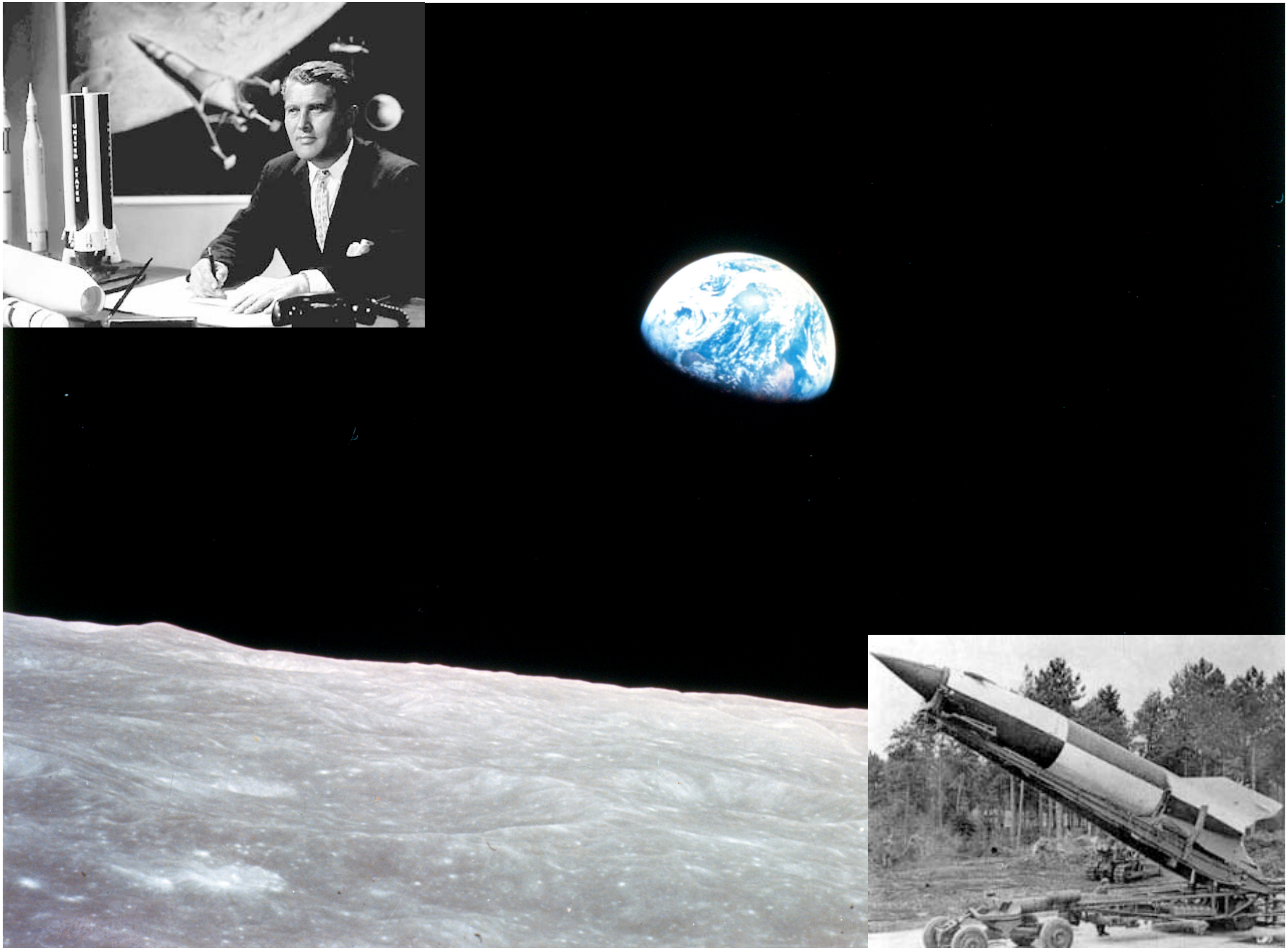






Historical notes 1957-1976

- Civilian programs and international collaboration started with IGY 1957-58: cold summer mesopause, gravity waves
- The Sputnik and Apollo moon program effect
- NASA Sounding Rocket Program
  - "Golden Age" of Rocket Science
  - systematic soundings of the MLT region (~1965-1976), small "meteorological" rockets from up to 30 sites, and also larger rockets (e.g.,Pitot-tube ion gauge payloads)
  - development and refinement of many techniques and dedicated instruments
  - connected to satellite experiments, e.g. mass spectrometry
- European programs
- Soviet Union programs
- Chinese programs
- Small rocket programs also in Japan, France, India, UK
- Many launch sites, including India, Peru, Australia

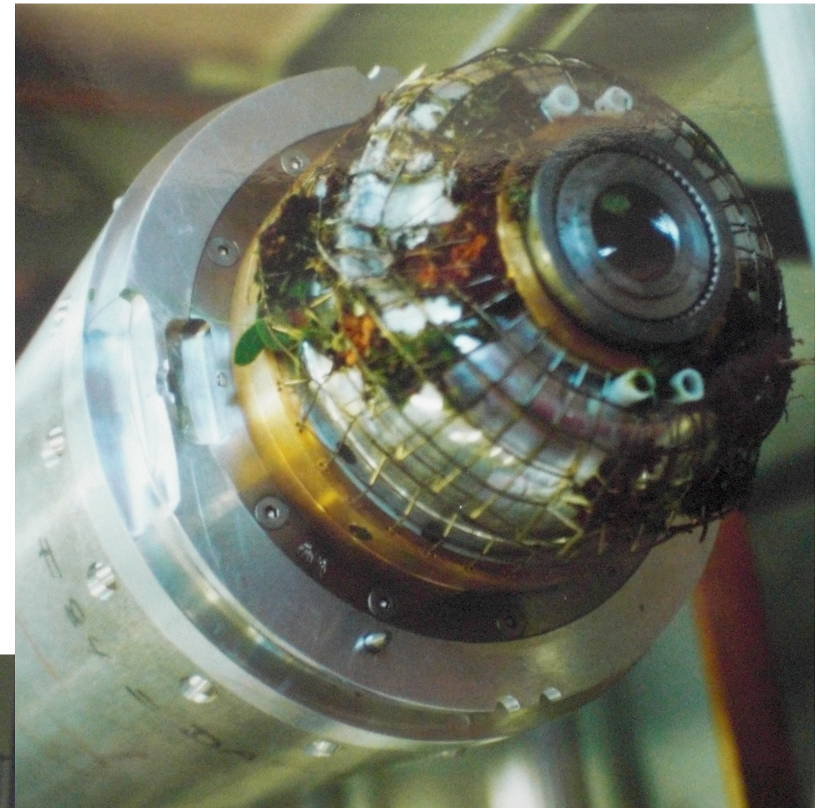


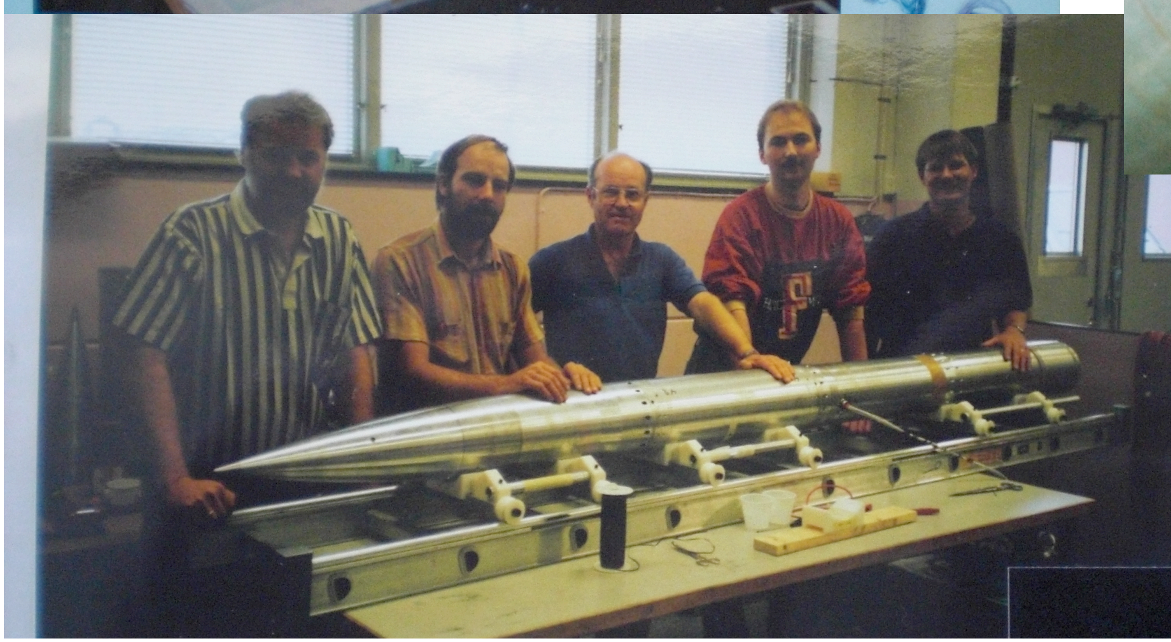
Credit: MBB

Historical notes 1976-1988

- Stronger international collaborations aided by COSPAR, SCOSTEP
- MAP Middle Atmosphere Program
  - Handbook for MAP, Rocket Techniques, ed. Richard A. Goldberg, Vol. 19, 1986
  - MAC/EPSILON 1987 and MAC/SINE 1988 were active when I started in this field at Bonn University
  - new and improved ground based instrumentation: lidars, MST-VHF radar, ISR-UHF radar, airglow imagers
- first global data sets from satellites, Nimbus 7/ LIMS, planning of UARS, MSIS(E) empirical model

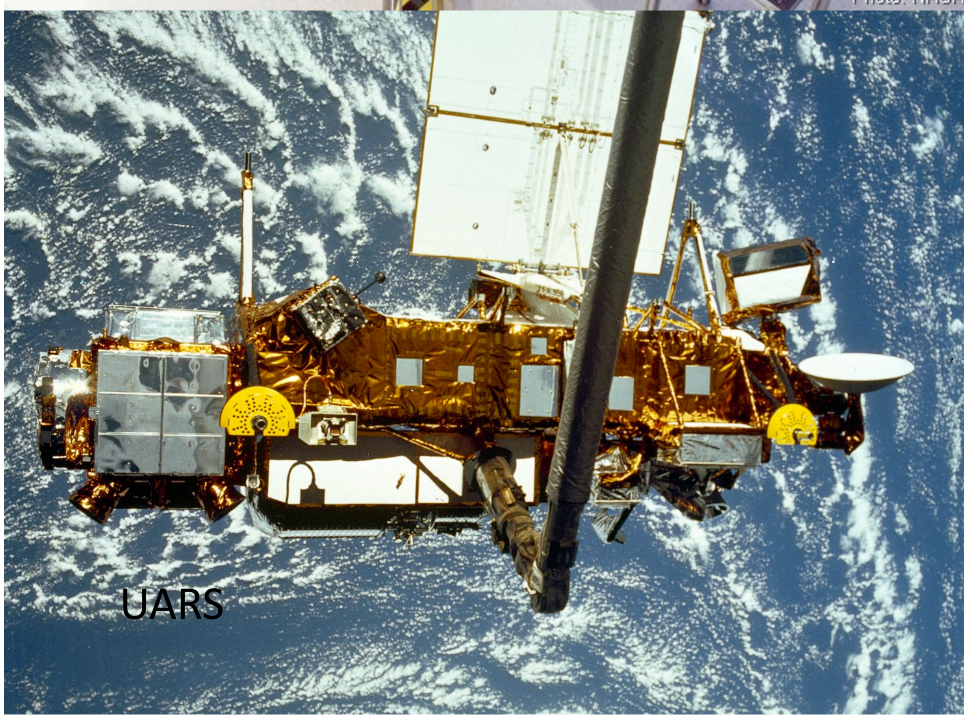

25.1.90
Die erste und geborgene
TURBO-Nutzlast

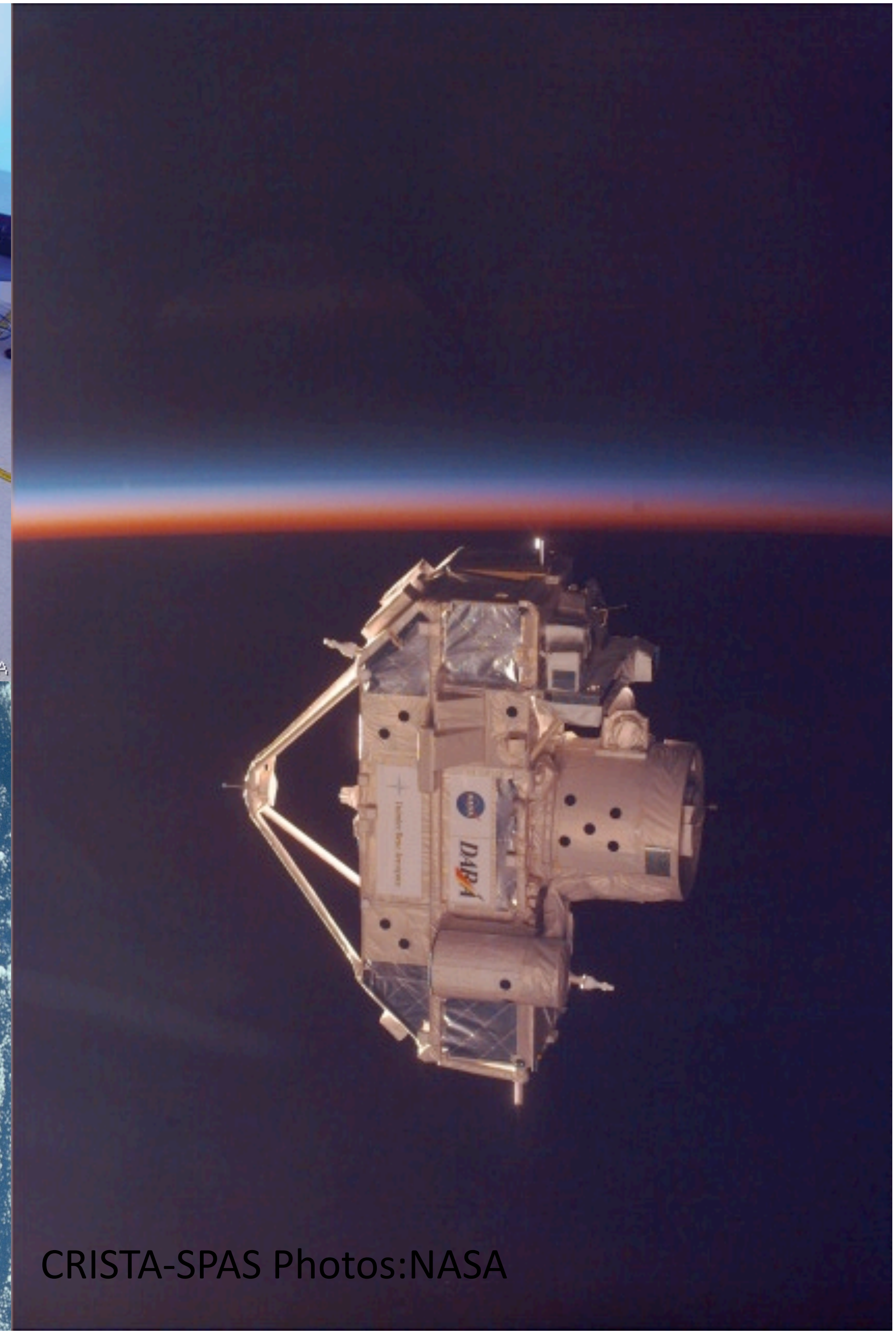




Historical notes 1988-2009

- Increasing efforts on satellite projects (UARS, CRISTA, ENVISAT, TIMED, EOS, ODIN, AIM)
- Stagnation or reduction for traditional sounding rocket science in USA and Europe (cost pressures, end of cold war)
- More sounding rockets developed in Japan, India, China
- Still increasing collaborations, esp. with ground based experiments (CEDAR)
- New national security concerns
- New science triggered by PMSE, NLC, meteor radars: aerosols, dust
- New trends:
  - modularization of payloads, accommodation of student rocket experiments, educational role of sounding rockets
  - new educational opportunities with student satellites (CubeSat)
  - privatization of NASA sounding rocket operations (NSROC)
  - off-the-shelf instruments and components
  - smaller rockets, multiple sub-payloads, miniaturization

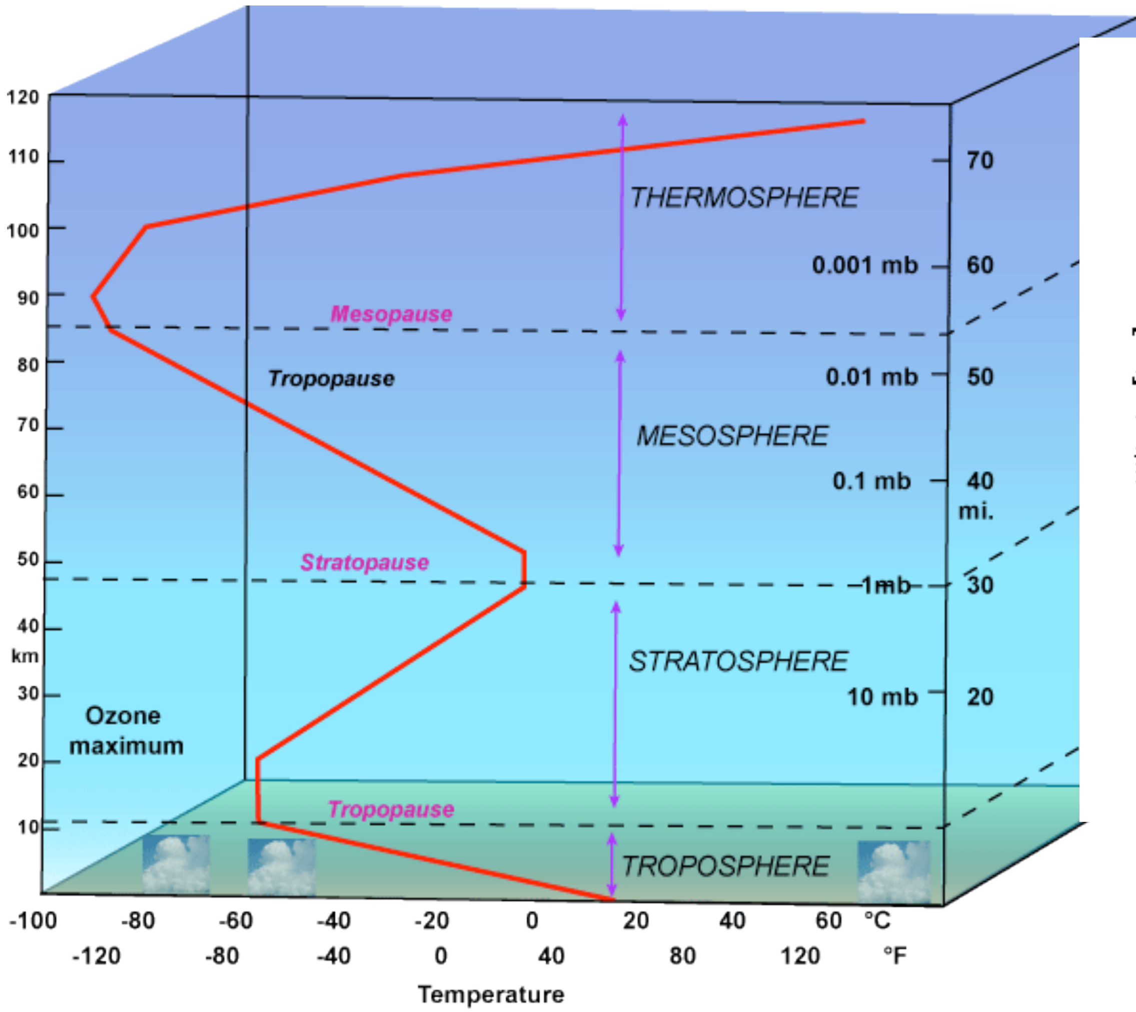

UARS


CRISTA-SPAS Photos:NASA

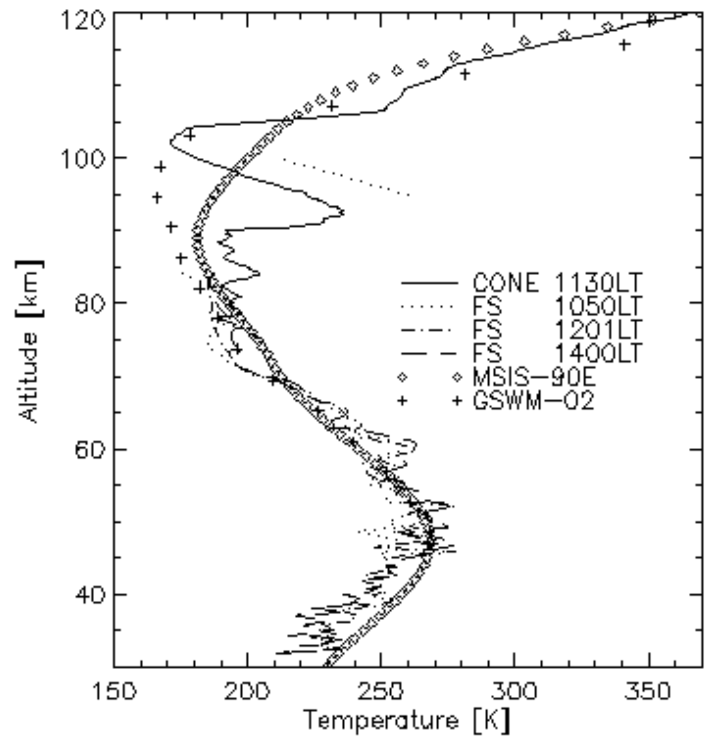
What will we encounter?

- Atmosphere
  - Vacuum, rough to high
  - Gas, mostly N_2, O_2, Ar, CO_2, etc, first mixed by turbulence
  - also a bit O_3, NO, NO_2, H_2O, OH, CO
  - then O, and diffusive mixing and demixing
  - temperature first cold, and sometimes very cold (110 K at 90 km), then rapidly increasing (400 K at 125 km)
- Ionosphere
  - first cold, collisional, then magnetized, electrons and ions can separate, polarization fields, currents
  - light ions, mainly NO^+, O_2^+
  - water cluster ions, fragile, positive and negative
- Meteoric products
  - neutral and ionized metal layers
  - meteoric “smoke”, dust, neutral, positively and negatively charged
  - ice crystals grown on dust, as polar mesospheric clouds
- **All this at supersonic speeds with shock fronts and wakes**

Temperature and density profile



Credit: lsc.vsc.edu



Lehmacher et al, GRL, 2007

Temperature and density profile

- Hydrostatic equilibrium $dp/p=-(mg/kT)dz=-dz/H$
  - $p(z) = p(z_0) \exp(-(z-z_0)/H)$, $\sim 1000^{(z/16\text{ km})}$ mbar
  - scale height $H=H(T,m,g)$, ~ 7 km
  - number density $n \sim 10^{19}\ \text{m}^{-3}$ (at 100 km), 6×10^{20} (at 75 km)
- Knudsen number $Kn=\lambda/L=kT/(2^{½}\ \pi\sigma^2 p)$
  - mean free path $\lambda \sim 0.25$ m (at 100 km), characteristic length L of instrument or payload
- Mach number $M=c_s/U=(\gamma kT/m)^{½}/U$
  - speed of sound c_s, speed of rocket U

How to measure with rockets 1

- Suborbital rocket flights
- Need a motor/vehicle to bring a payload to desired altitude (40 km or higher), upleg
- Happens at supersonic speeds (Mach number M~3+)
- Vehicle is stabilized by roll motion (“spin”) imparted by fins
- Payload may be separated from motor, nosecone deployed above ~60 km, when drag becomes very small
- In mesosphere, attached shock front, with strong heating, ram and wake effects, compression and rarefaction
- In lower thermosphere, Knudsen number, $Kn=\lambda/L>1$, transitional and molecular flow, shock is detached and weaker, nevertheless important

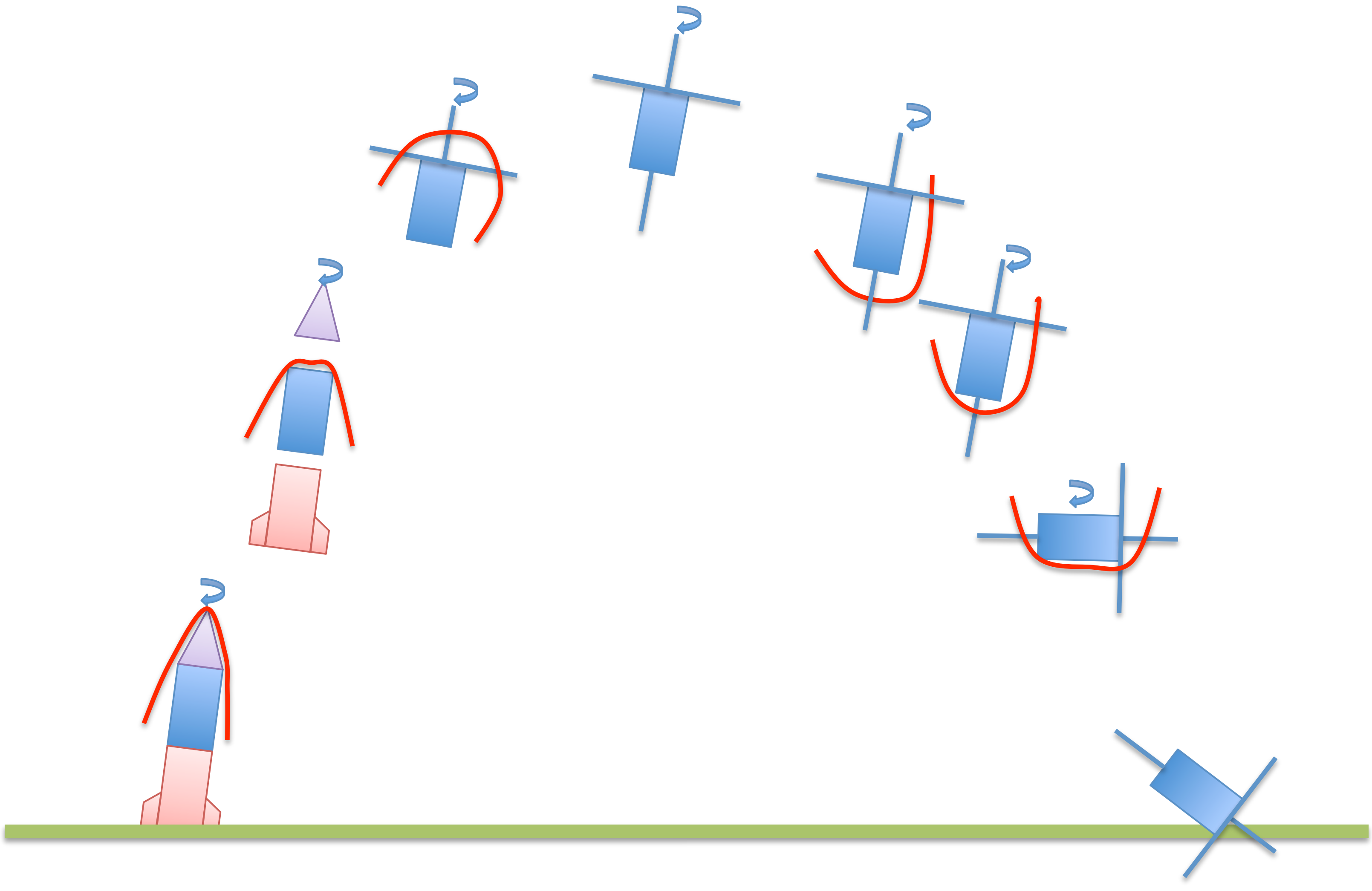
How to measure with rockets 2

- At apogee, motion is horizontal ~200 m/s
- Payload may be unguided, only stabilized by spin, payload axis also precesses (pitch, yaw axis, ”coning”)
- Payload may be despun
- Payload may be guided by attitude control system (ACS) and oriented along certain axis
- Smaller payloads may be decelerated by parachutes, below 70-80 km, subsonic in lower mesosphere

How to measure with rockets 3

- To circumvent complicated flow and shock environments
  - measure in ram (e.g. nosetip probe on upleg)
  - carefully shape instruments and orifices
  - mount instruments on deployable booms to extend beyond the payload shock and be in the "undisturbed" atmosphere and plasma
  - seal instruments, use clean, homogeneous surfaces, keep payload clean and dry, avoid outgassing
  - cryogenic instruments, "freeze out" the shock
  - subsonic descent
- Typical payloads reenter the atmosphere at 80-70 km, unguided payloads tip over and keep rotating about yaw axis, "flat spin"
- Payloads considerably deviate from ballistic trajectory below 20-30 km
- Parachute recovery possible, land and sea recovery
- Total time above 60 km: 4 minutes, very high measurement rates, (several kHz), high sensitivity (pA, particle counting)

Phases of an unguided sounding rocket flight



Why still measure with rockets?

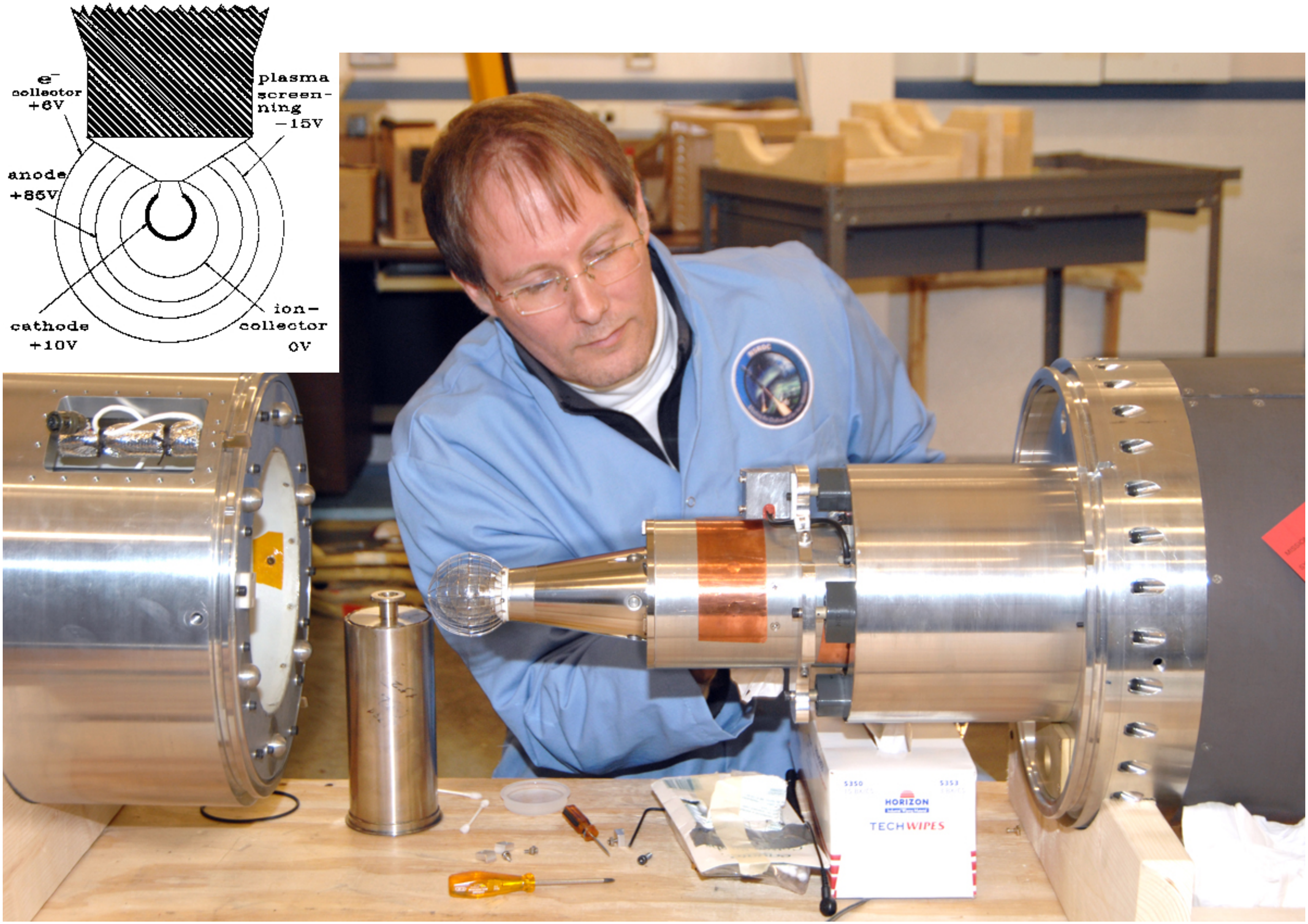
- Go where no other vehicle can measure (40-200 km)
- Achieve high spatial (vertical) resolution
- Measure several parameters at the same time and the same volume
- Compare and validate ground-based and satellite measurements
- Relatively portable technique
- Respond to specific geophysical conditions
- Understand the measurement environment (plasma, supersonic rarefied flow)

Challenges: Why not measure with rockets?

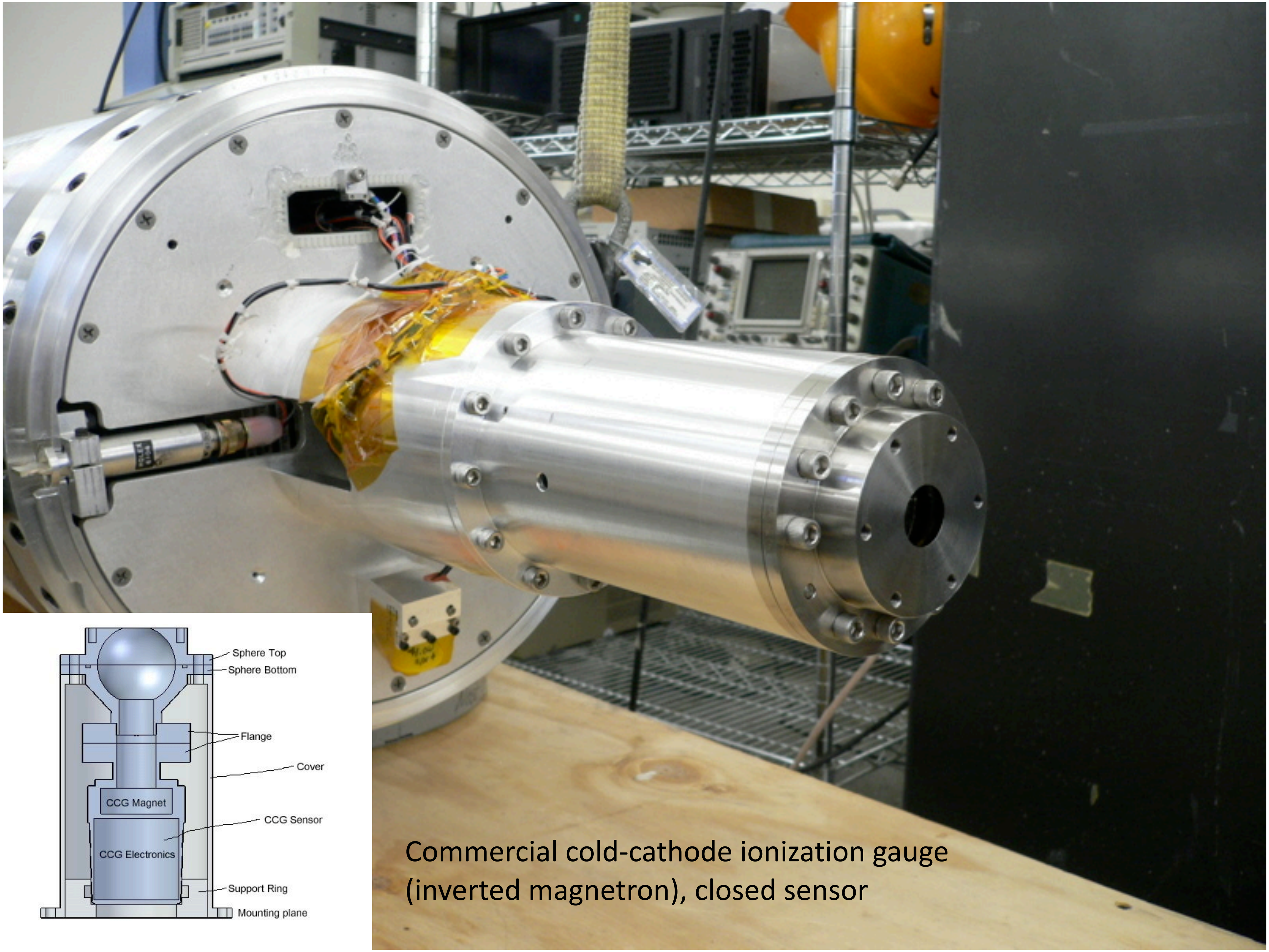
- High-risk experiments
- Experiments, payload and motor infrastructure require very careful preparation and testing, large collective experience
- Single snapshots of the atmosphere
- Electrodynamic and flow environment complicates the interpretation of data
- High costs, experiments cannot be easily repeated, results reproduced
- Limited number of launch sites, availability of ground-based facilities

Measurements of the neutral atmosphere 1

- Density, pressure (~5 to 10^{-6} mbar, 40-150 km)
  - drag measurement, inflatable spheres (tracked by radar, or GPS position), accelerometer spheres, $F=\frac{1}{2}\rho v^2 C_D A = m a_D$
  - vacuum pressure gauges: capacitance manometers, thermal conductivity (Pirani), viscosity (vibrating crystal), ionization gauges, cold-cathode (Penning, inverted magnetron), hot-cathode (triode, Bayard-Alpert)
- Constituents, partial pressures, mixing ratio x~0.8…10^{-6} (N_2,O_2,Ar,He,Ne,Kr,CO_2,O,H_2O,NO,O_3,…)
  - gas analyzers, mass spectrometers (magnetic focusing), mass filters (quadrupole)
  - also require first ionization, problematic with reactive species, cryogenic instruments
- Optical methods for reactive species O_3, NO, NO_2, H_2O, OH,O
  - UV absorption, chemiluminescence, airglow, silver film sensor, infrared absorption, emission spectrometers, also cryogenic



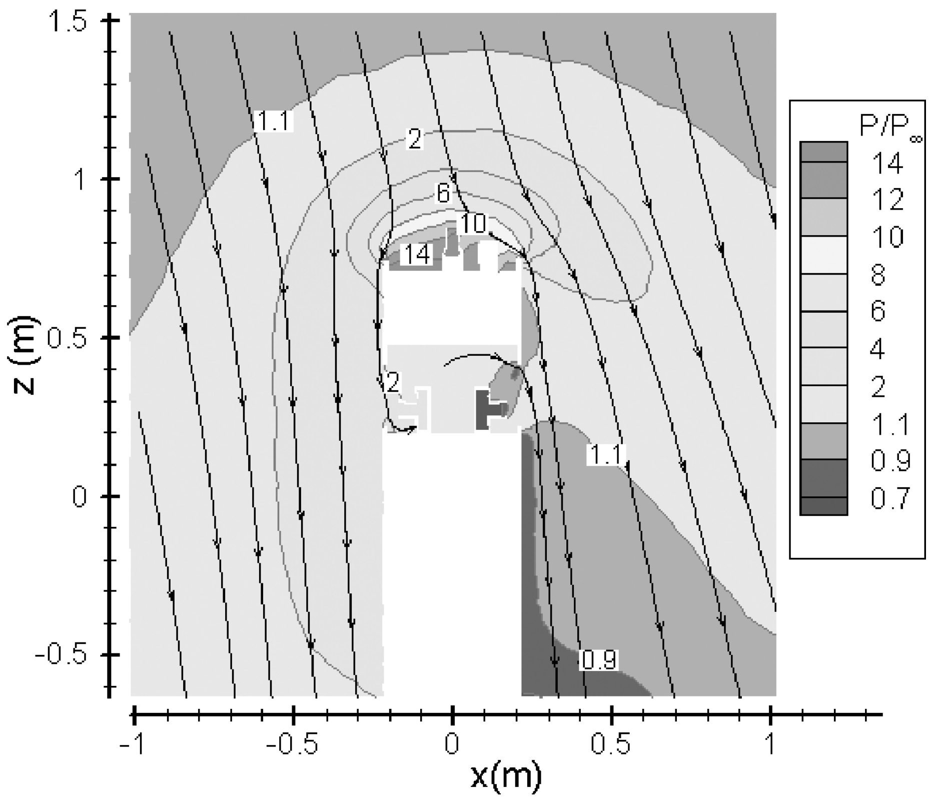
CONE ionization gauge and DC electron probe, open sensor

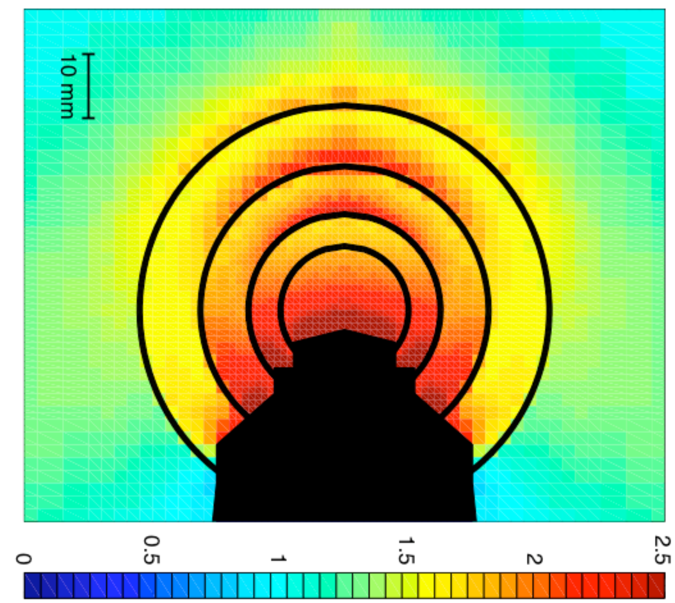


Commercial cold-cathode ionization gauge (inverted magnetron), closed sensor

a) 90 km

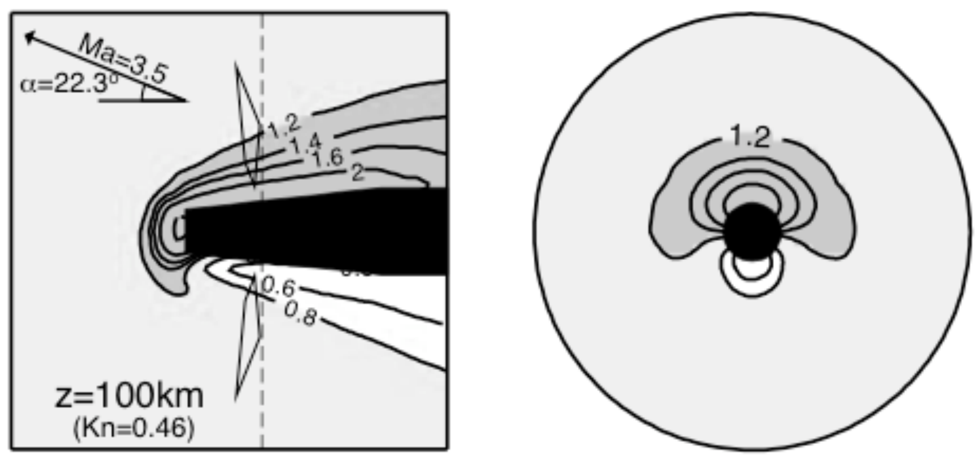
DSMC Simulations, preferably in 3-D





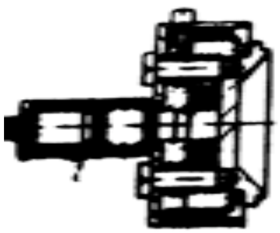
Rapp et al., Ann. Geophys., 2001

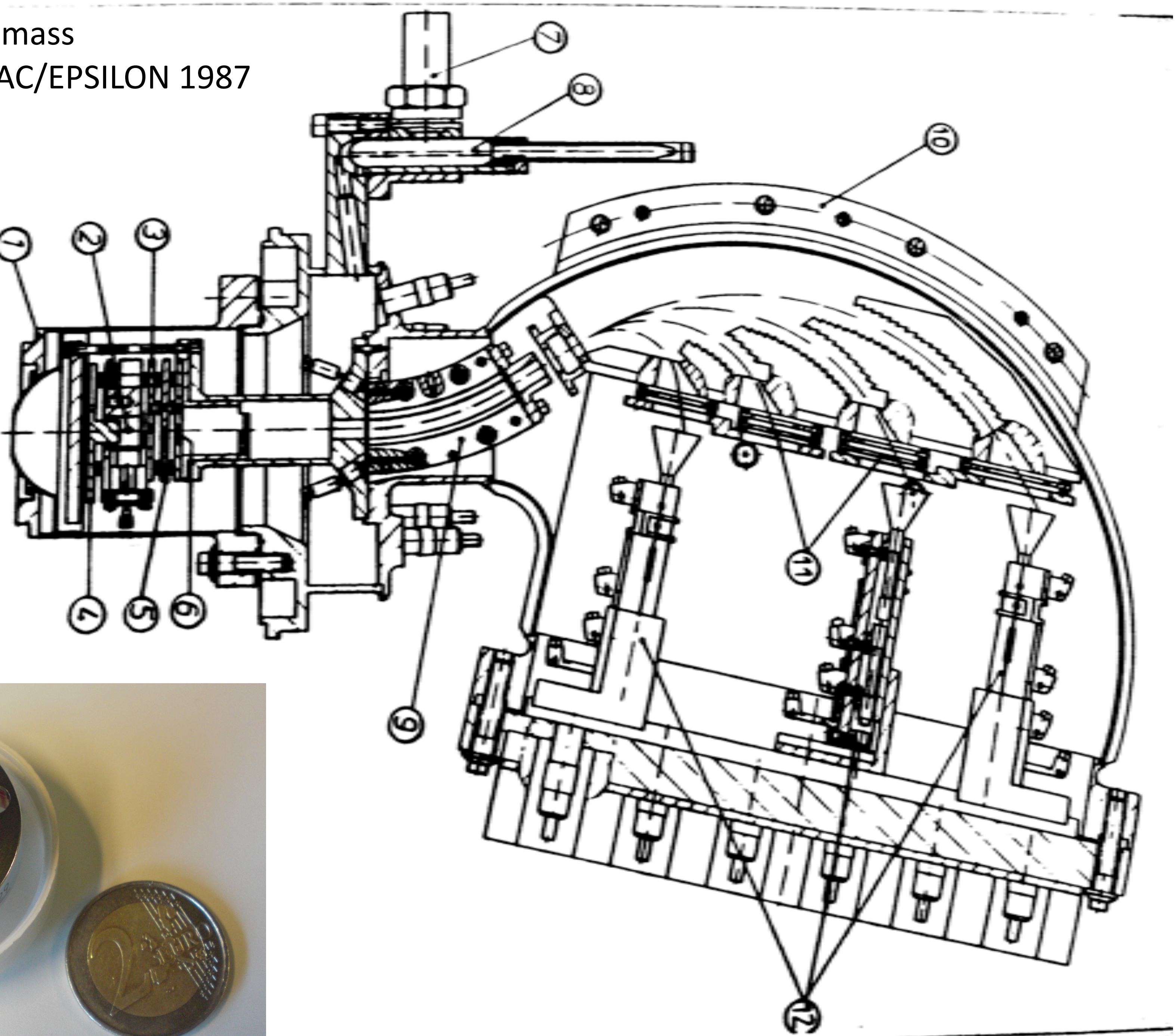
Sun et al., J. Spacecraft Rockets, 2006



Kurihara et al., Ann. Geo., 2006

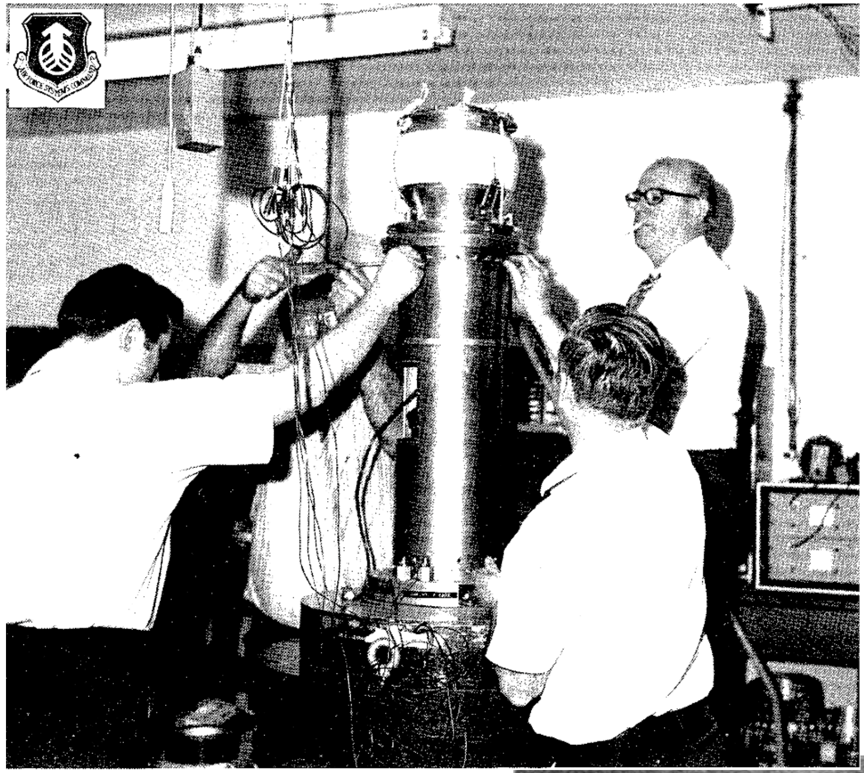
BUGATTI neutral mass spectrometer, MAC/EPSILON 1987

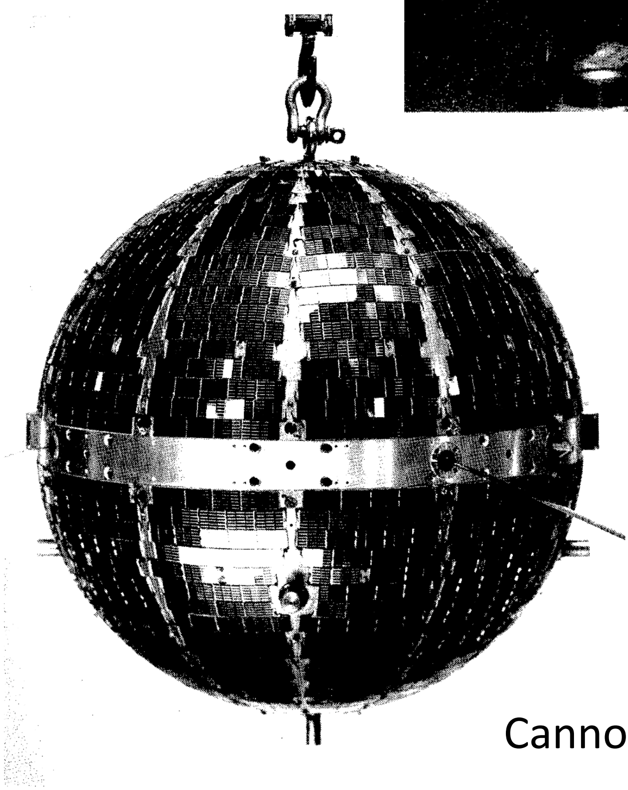




Ferran Micropole Analyzer

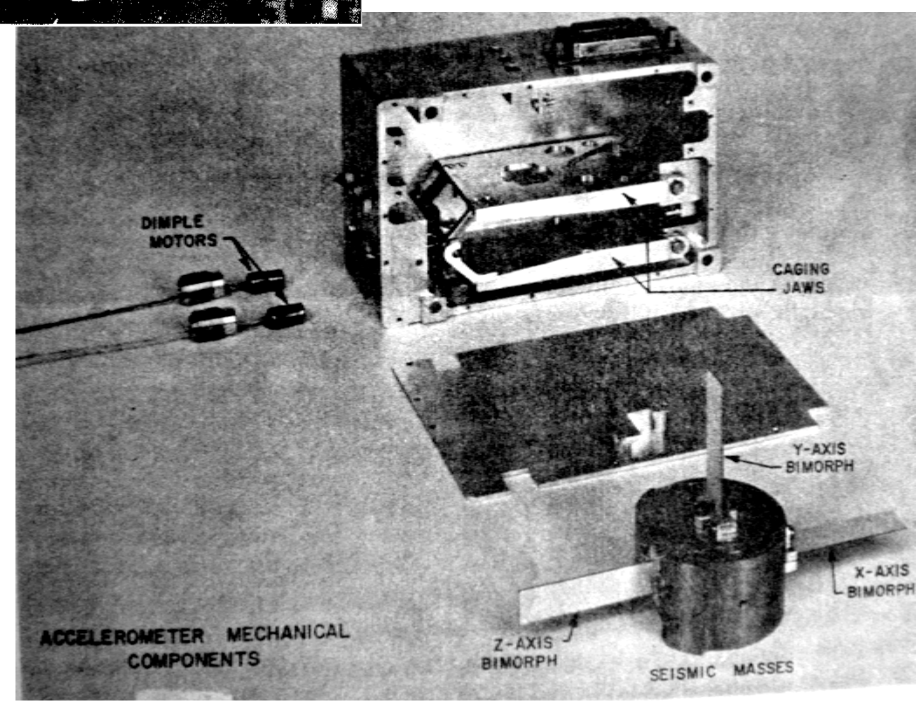
Accelerometer Spheres, Champion, PL-TR,1995





CannonBall-2

Philbrick et al., AFGL-TR, 1978

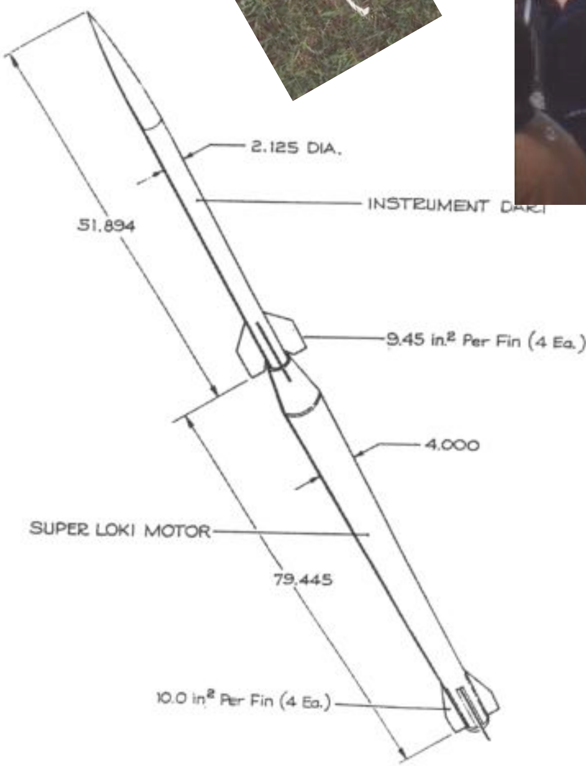


Measurements of the neutral atmosphere 2

- Temperature (1 to 10^{-6} mbar, 40-150 km)
  - thermistor (rocket datasonde on parachute, works up to 65 km)
  - speed of sound (rocket grenades)
  - rotational and vibrational spectrum of N_2 (Delta/NTV)
  - Langmuir probe for electron temperature (D region)
  - mostly from density integration, assuming hydrostatic equilibrium

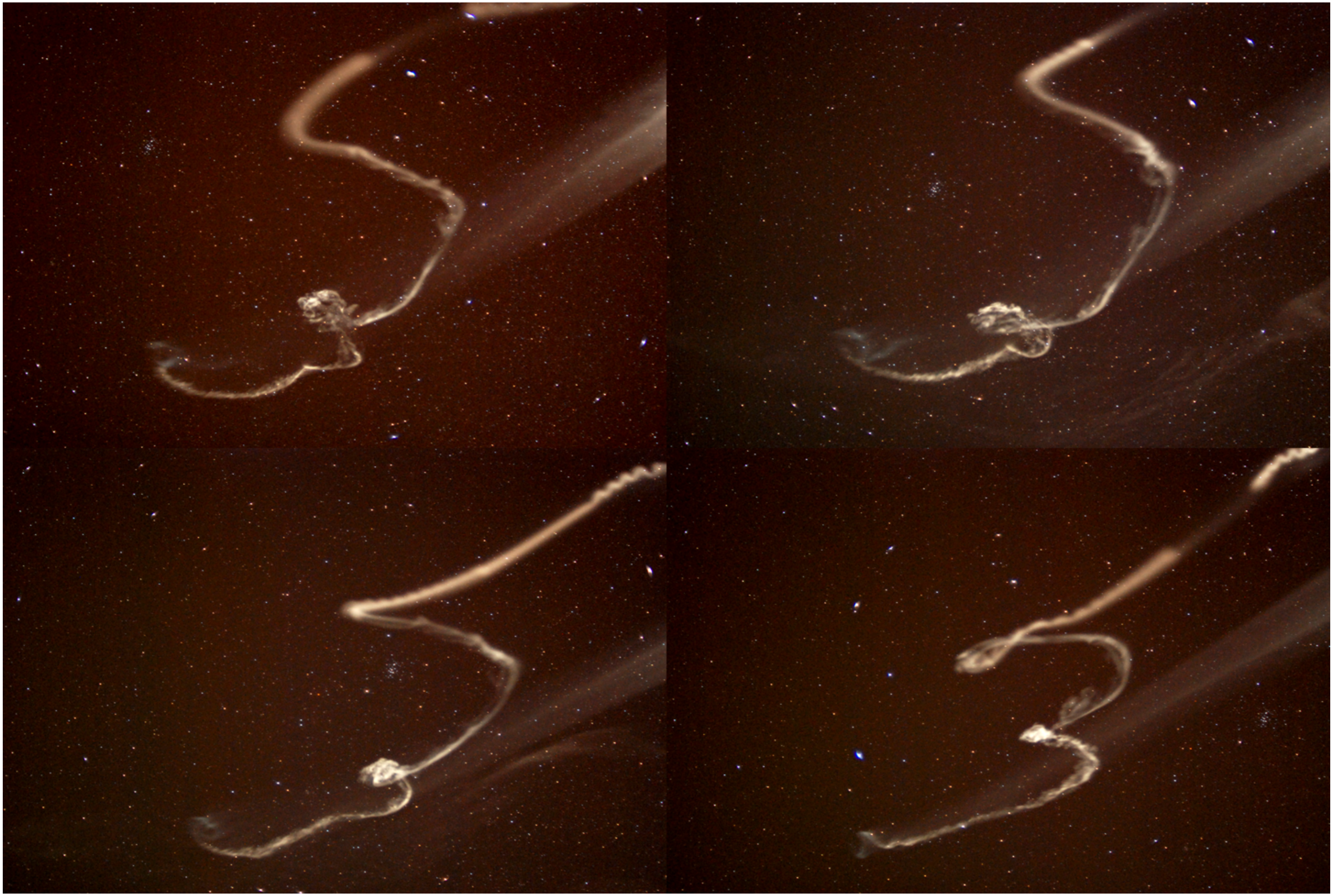
- Wind
  - datasonde (radar track of parachute)
  - inflatable falling sphere (radar track, GPS)
  - chaff (radar track)
  - chemical release (trimethyl aluminum, sodium, lithium, barium), requires dark sky and ground observations of trail
  - accelerometer sphere (rigid, inflatable)
  - differential pressure measurements

Credit: mtu.edu

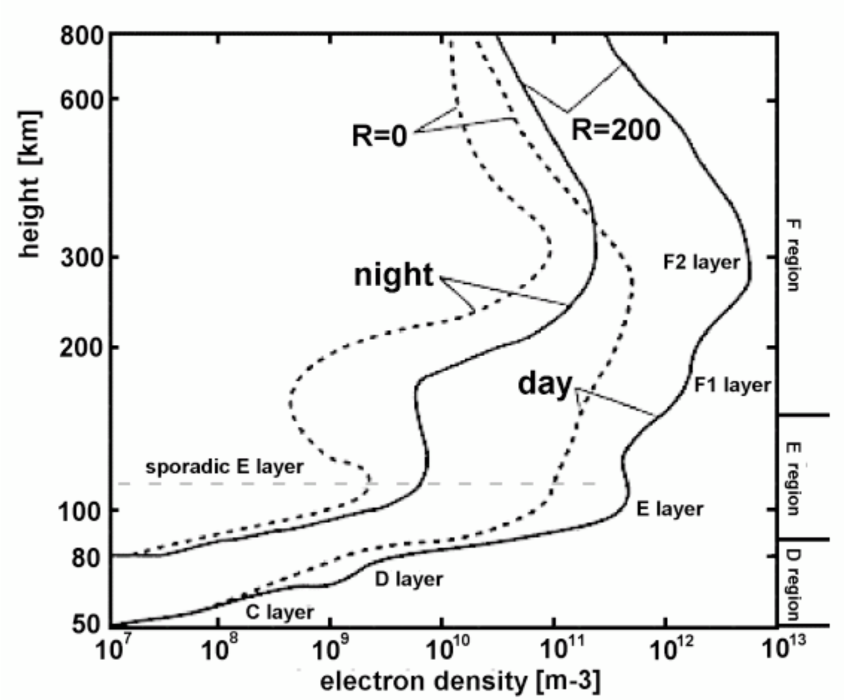


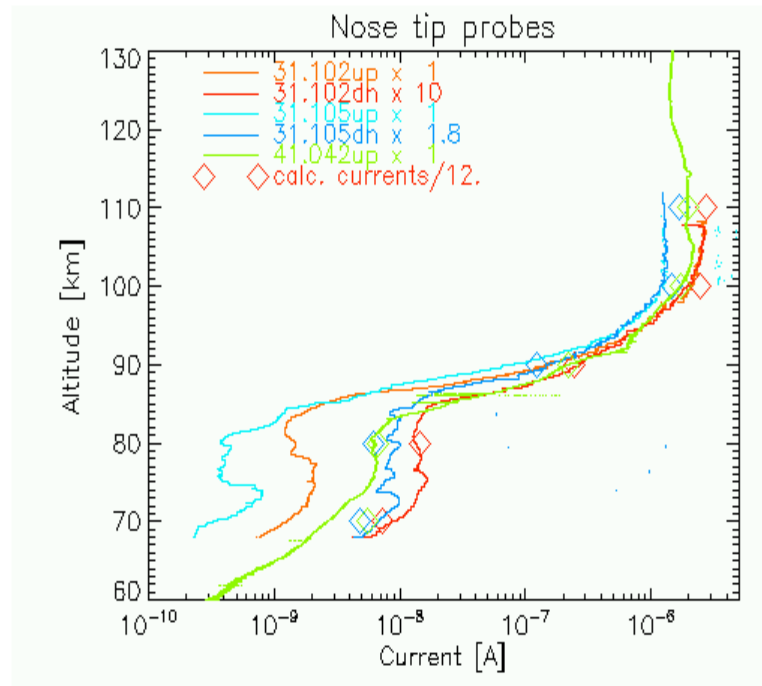
Credit: uwo.ca

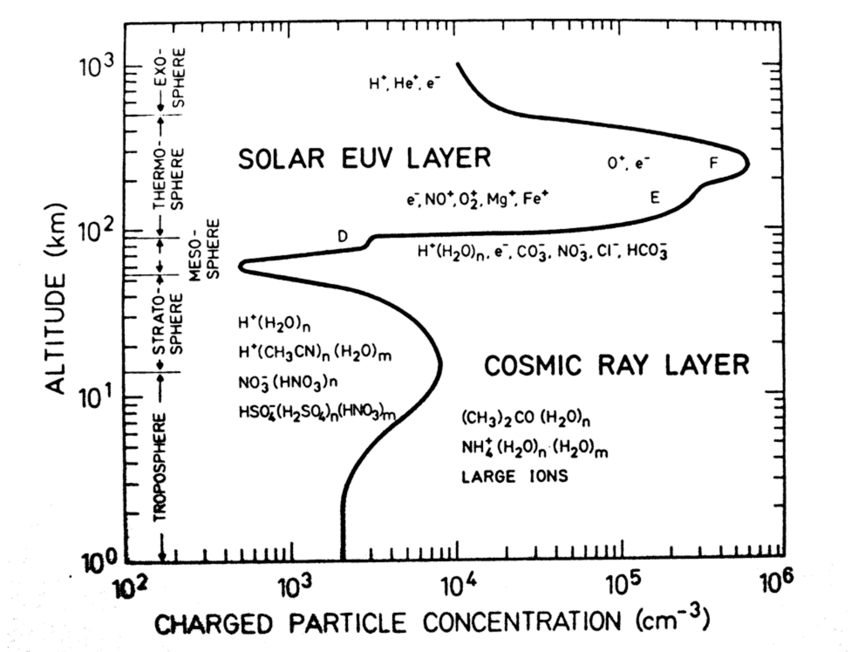
TMA releases upleg, Poker Flat, February 2009



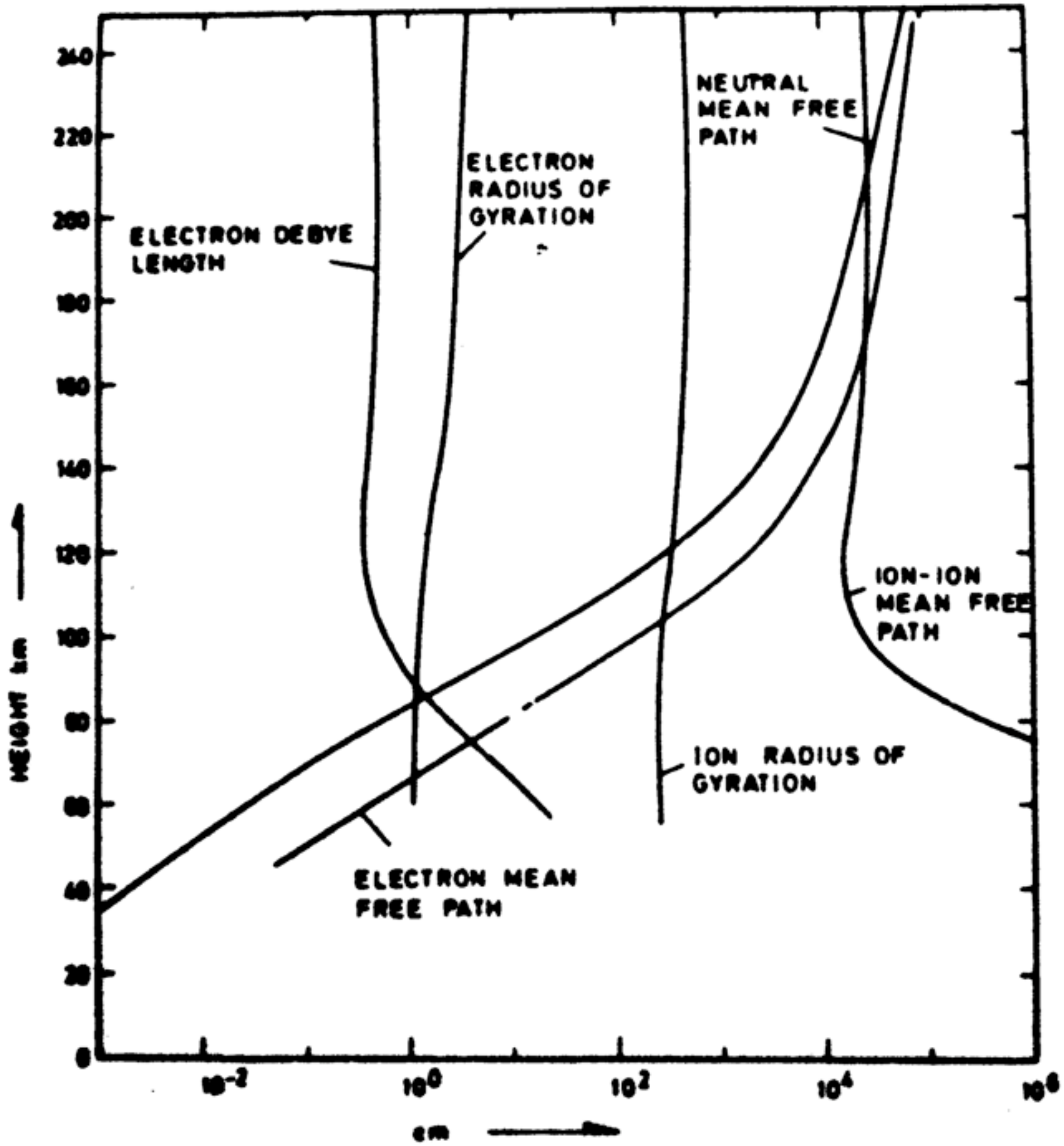
Ionosphere


height [km]
electron density [m-3]
R=0
R=200
night
day
F2 layer
F1 layer
E layer
D layer
C layer
sporadic E layer
F region
E region
D region


Nose tip probes
31.102up x 1
31.102dn x 10
31.105up x 1
31.105dn x 1.8
41.042up x 1
calc. currents/12.
Altitude [km]
Current [A]


SOLAR EUV LAYER
COSMIC RAY LAYER
ALTITUDE (km)
CHARGED PARTICLE CONCENTRATION (cm-3)
EXO-SPHERE
THERMO-SPHERE
MESO-SPHERE
STRATO-SPHERE
TROPOSPHERE
LARGE IONS

Length scales in ionosphere



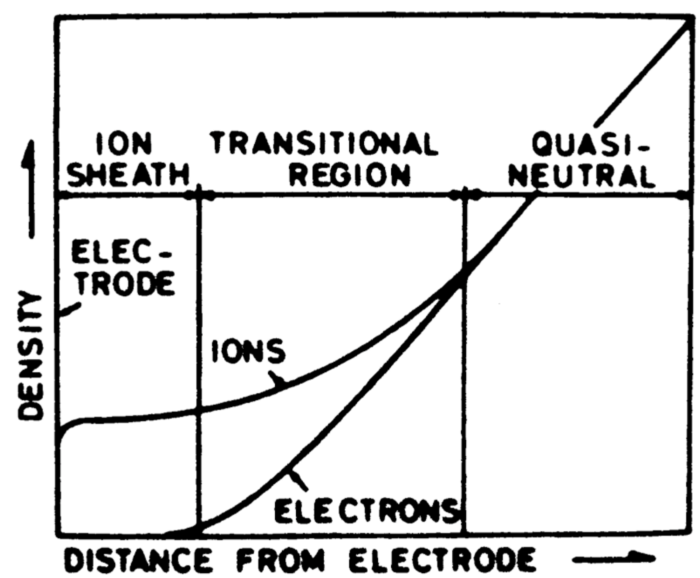
gyro frequency $f_{ce}=(1/2\pi)(eB/m_e)$

Thrane, MAP 19, 1986

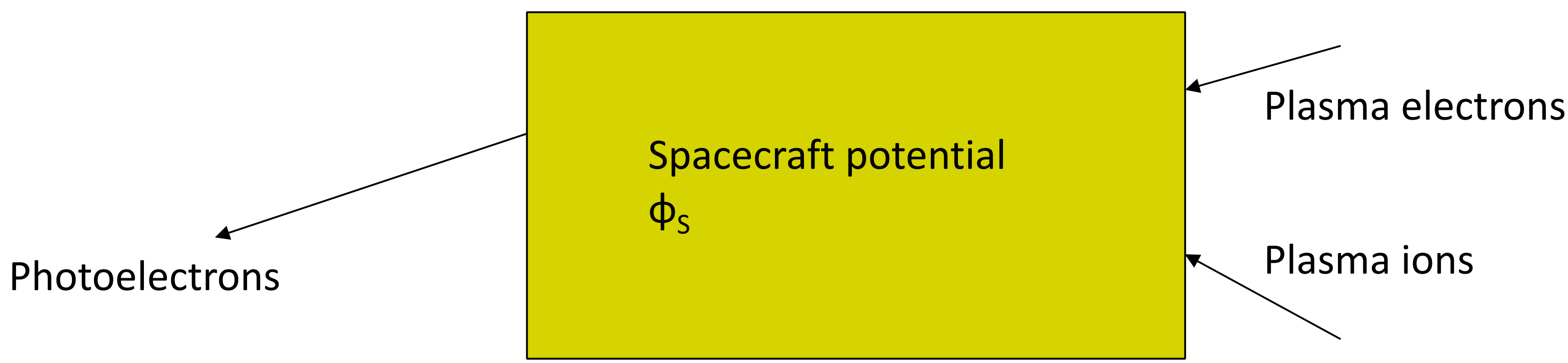
Instruments in a plasma 1

- Charged particles easy to attract, electrons even in wake
- Quasi-neutrality of plasma is disturbed by payload and applied potentials
- Debye length, $\lambda_D=(\varepsilon_0 kT/q^2N_0)^{1/2}$
  - screening length, ion or electron sheath around conductor
  - λ_D=3 mm (at 100 km), λ_D=100 mm (at 75 km)

for a negative probe bias;
Thrane, MAP 19, 1986

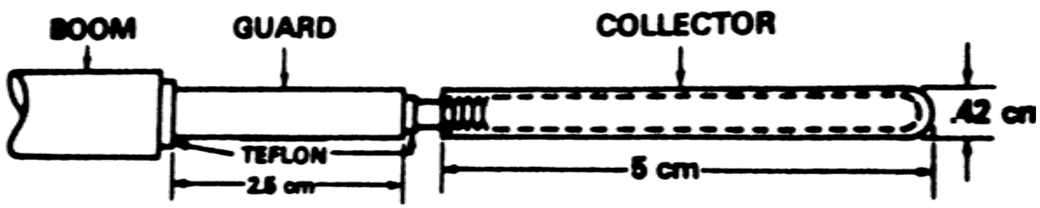


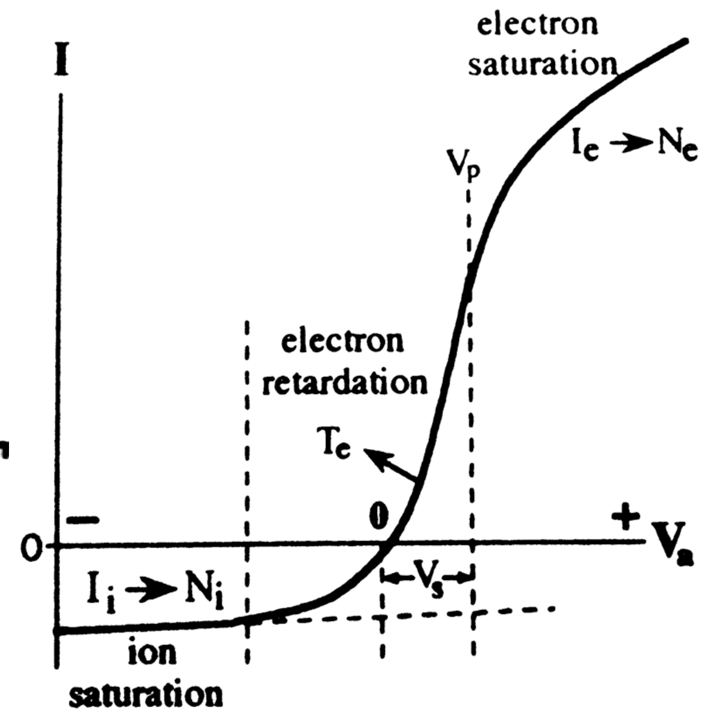
Instruments in a plasma 2



- effective probe potential $\phi_P = \phi_S + \phi_{bias}$
- large differences for day and night
- frictional charging possible in lower atmosphere
- collected current must return to ionosphere; small probes, homogeneous, conducting surfaces

Langmuir probe 1

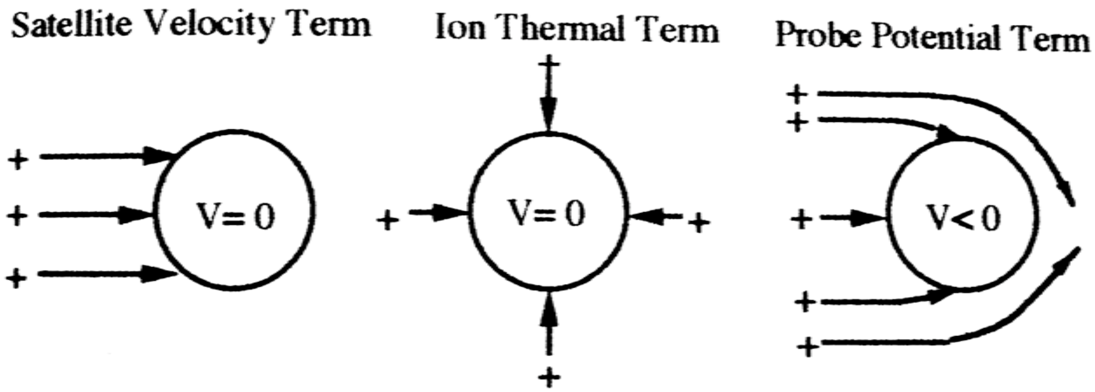


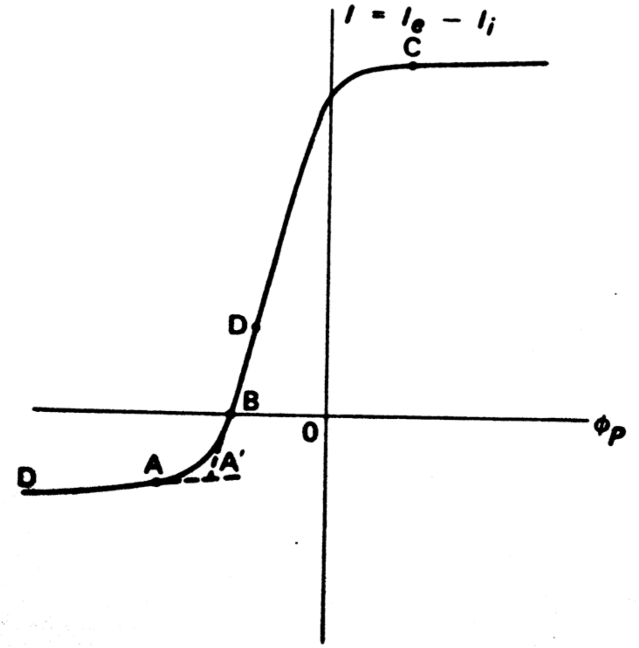


Brace, AGU, 1998

- sweep voltage between ion and electron saturation values, a few volt, DC probes operate at fixed bias in saturation, faster
- $I_e = N_e A e 2\pi^{½} (kT_e/2\pi m_e)^{½}(1+eV/kT_e)^{½}$ (long cylinder)
  - for $eV >> kT_e$ (D region): $I_e = N_e A e 2\pi^{½} (eV/2\pi m_e)^{½}$
- spherical probe depends on temperature
  - $I_e = N_e R^2 e (2\pi e V^2/m_e kT)^{½}$
- electron temperature from retardation region
  - $I_e = N_e A e (kT_e/2\pi m_e)^{½} \exp(eV/kT_e)$

Langmuir probe 2



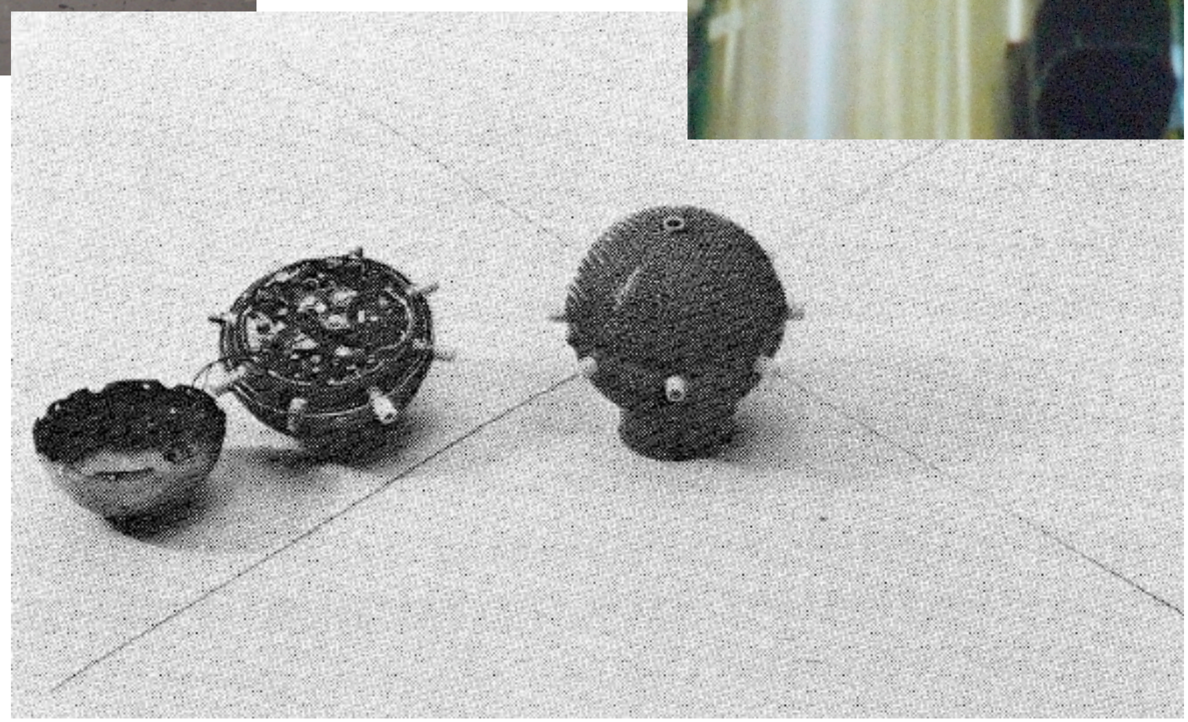


Brace, 1990; Thrane, 1986

- ion saturation current
  - $I_i=N_iAq_iv_i\pi^{-1}(1+kT_i/m_iv_i^2+2eV/m_iv_i)^{1/2}$
  - for fast rocket in cold plasma $I_i=N_iq_iv_i\pi R^2$, independent from ion mass and temperature

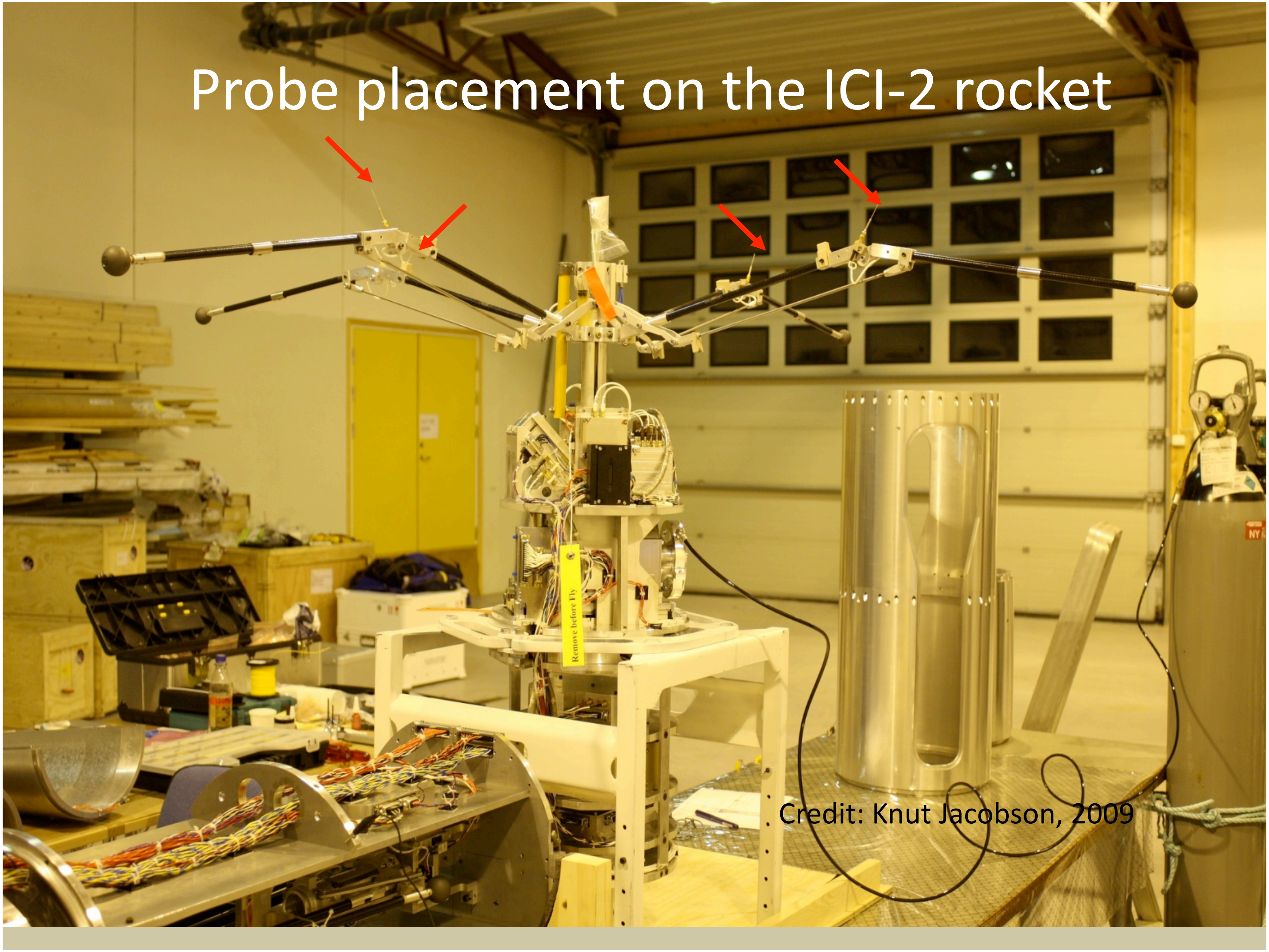
Penn State Nosetip probe

large ion probe, NLC91/ DECIMALS



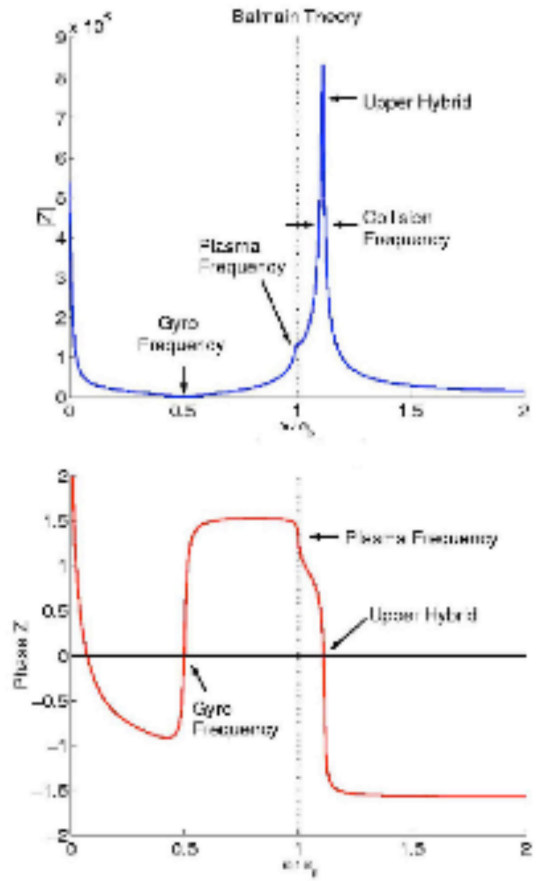
Ion probe free-flyer, Blix et al., JGR, 1990

Probe placement on the ICI-2 rocket



Credit: Knut Jacobson, 2009

Impedance Probe



Impedance of a dipole antenna in a magnetoplasma (Ward & Swenson, USU).

Plasma frequency = resonance frequency of unmagnetized, cold plasma

$f_{pe} = (1/2\pi)(N_e e^2/\varepsilon_0 m_e)^{1/2}$

electron plasma frequency:

$$f_pe/\mathrm{kHz} \approx \sqrt{80.6 \cdot N_e/\mathrm{cm}^{-3}}$$

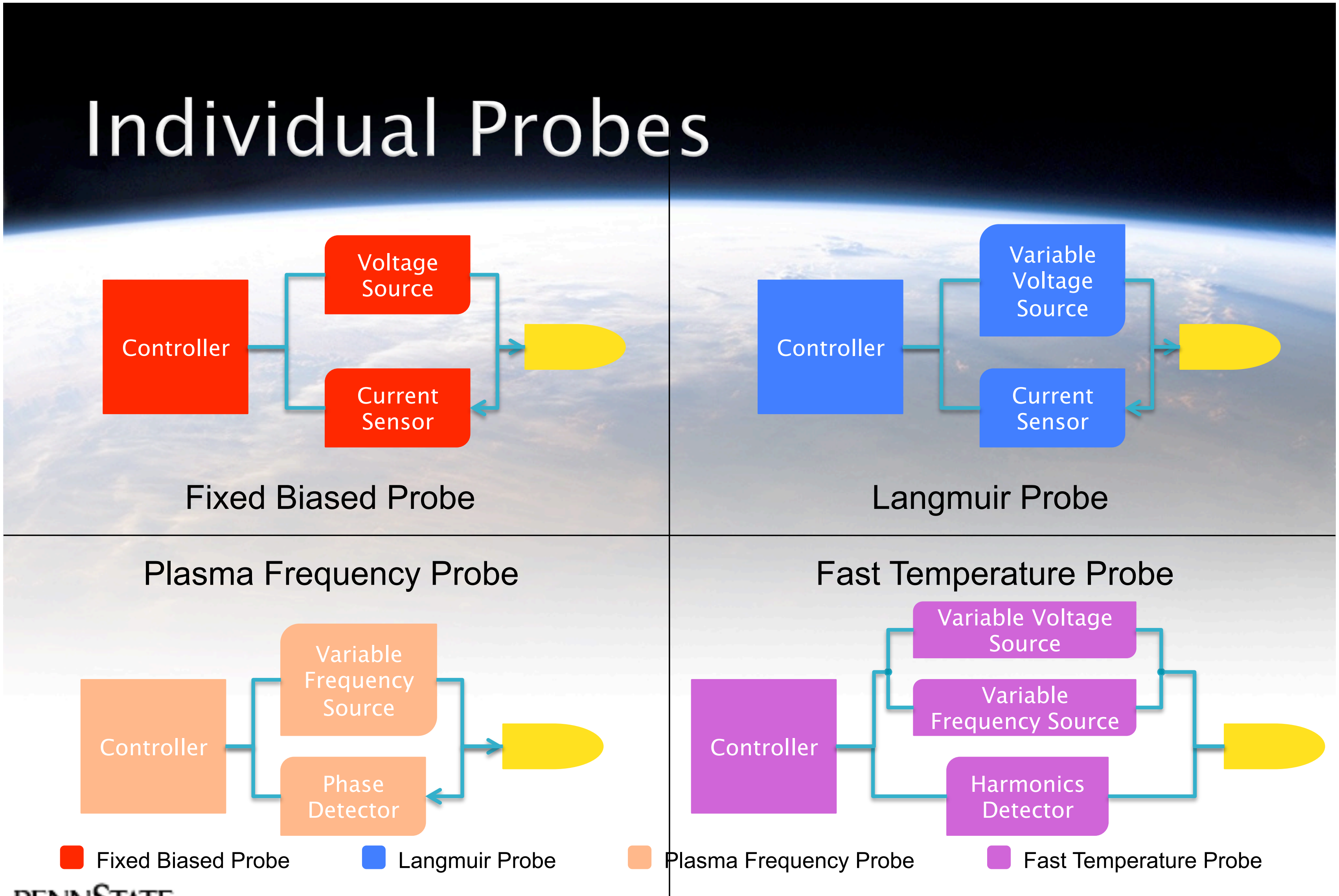
electron cyclotron frequency:

$$f_ce/\mathrm{kHz} \approx 0.28 \cdot B/\mathrm{nT}$$

upper hybrid frequency:

$$f_{uh} = \sqrt{f_{pe}^2 + f_{ce}^2}$$

Credit: C. Steigies, 2009

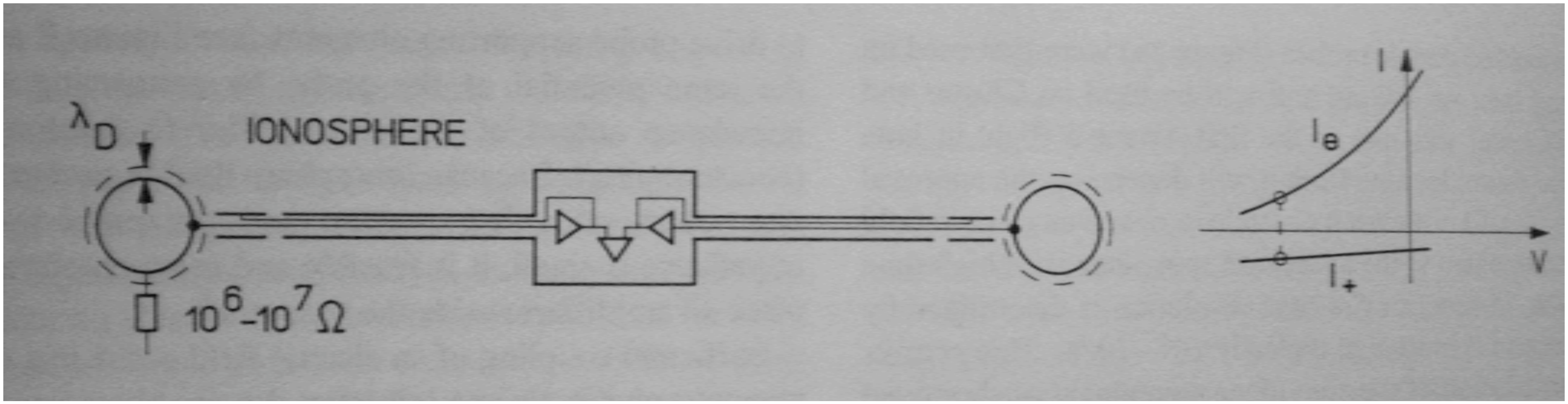


proposed Hybrid Plasma Probe
Credit: A. Kummer, 2009

Radio wave propagation

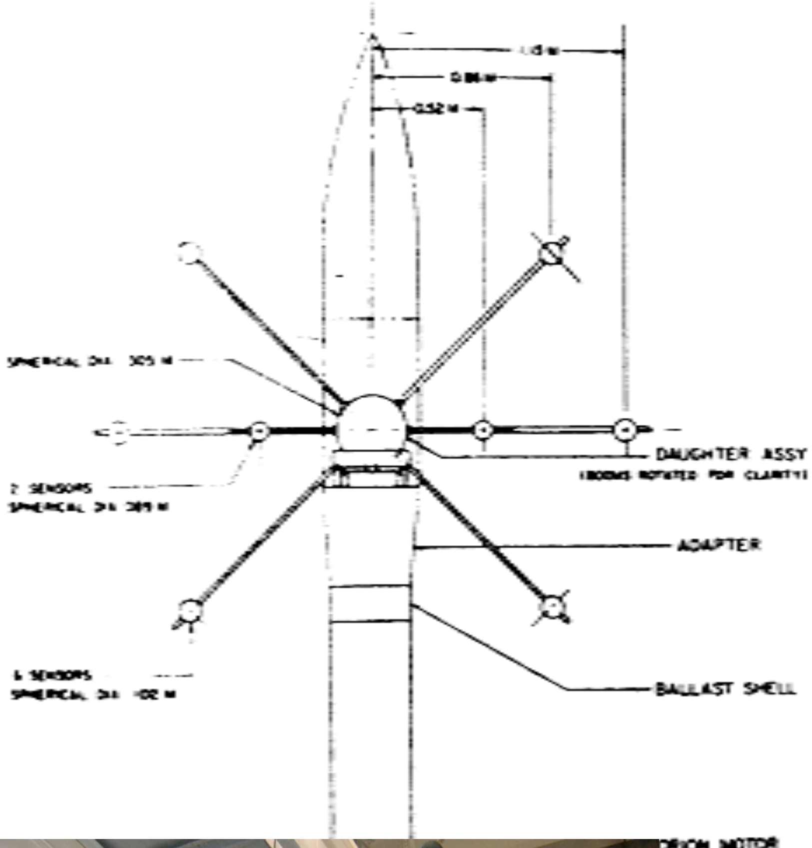
- ground based transmission, in situ reception
  - Faraday rotation in magnetized plasma, and differential absorption
  - Provide absolute electron density measurements in D region and lower E region
  - Smith et al., MAP 19, 1986; Friedrich et al. since
- in situ transmission, ground based reception
  - “beacon” experiments
  - high power requirement onboard

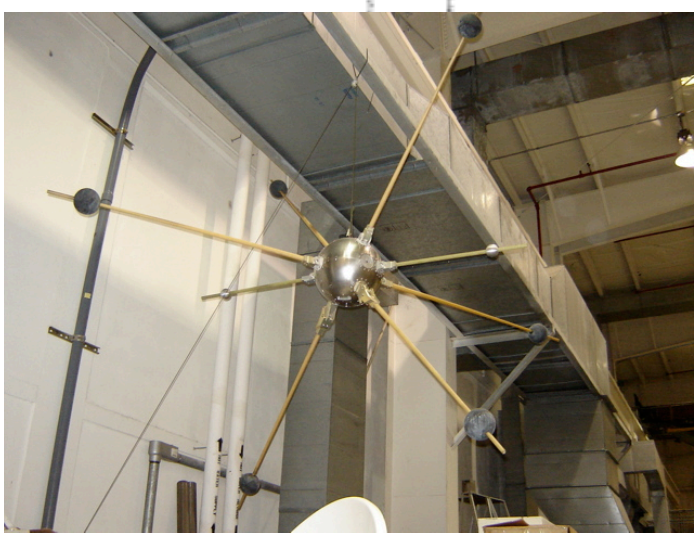
Electric fields

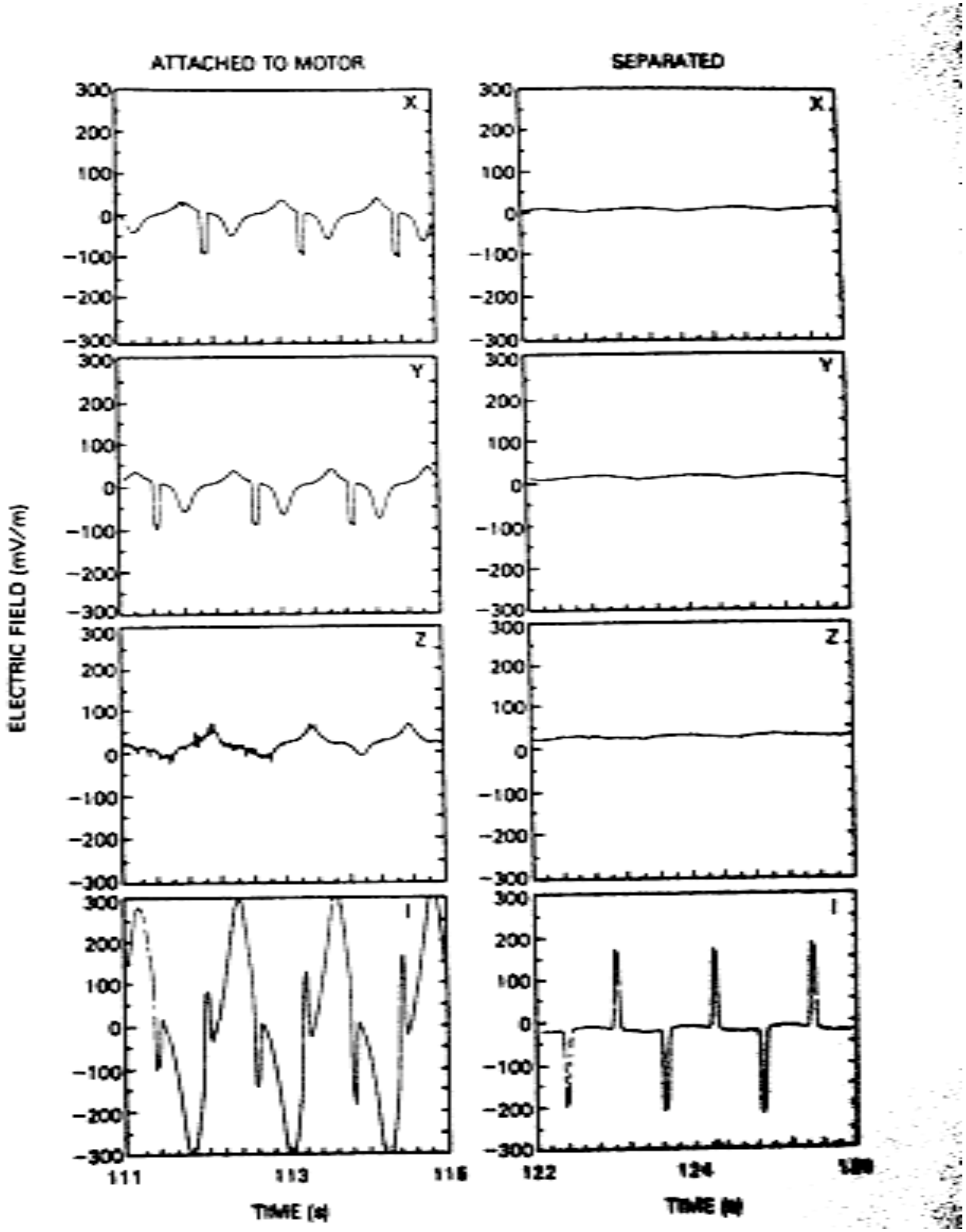


Pedersen, AGU, 1998

- passive double probes
- $(\phi_1-\phi_2)/|d| = (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \bullet \mathbf{d}$



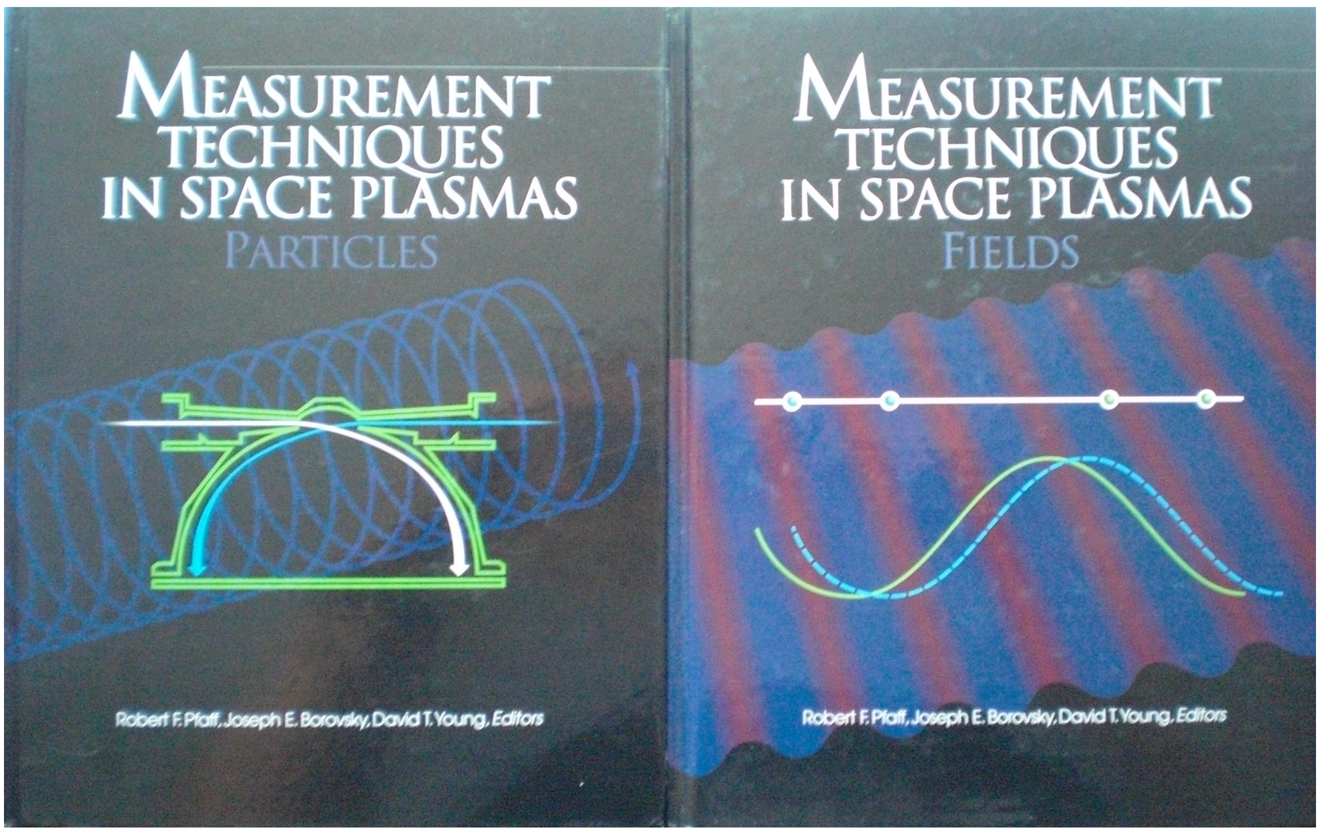




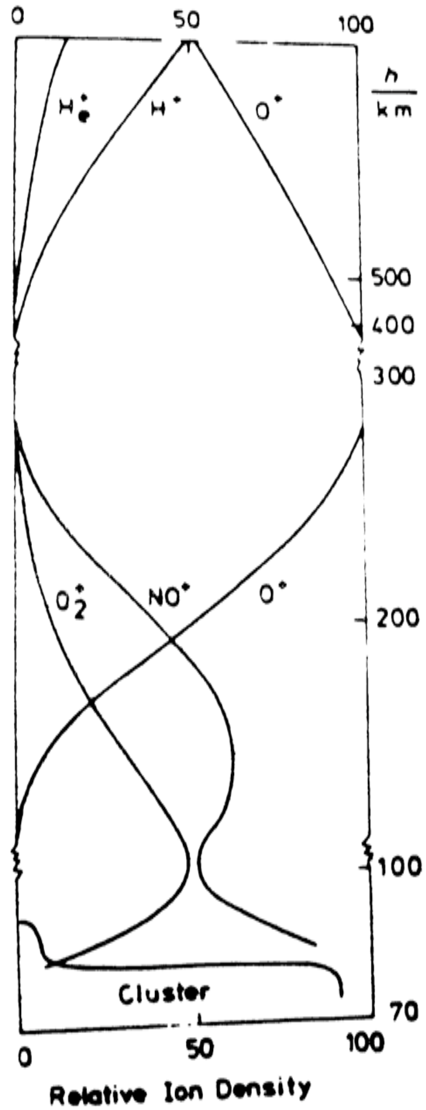
Maynard, AGU, 1998

Many more instruments…

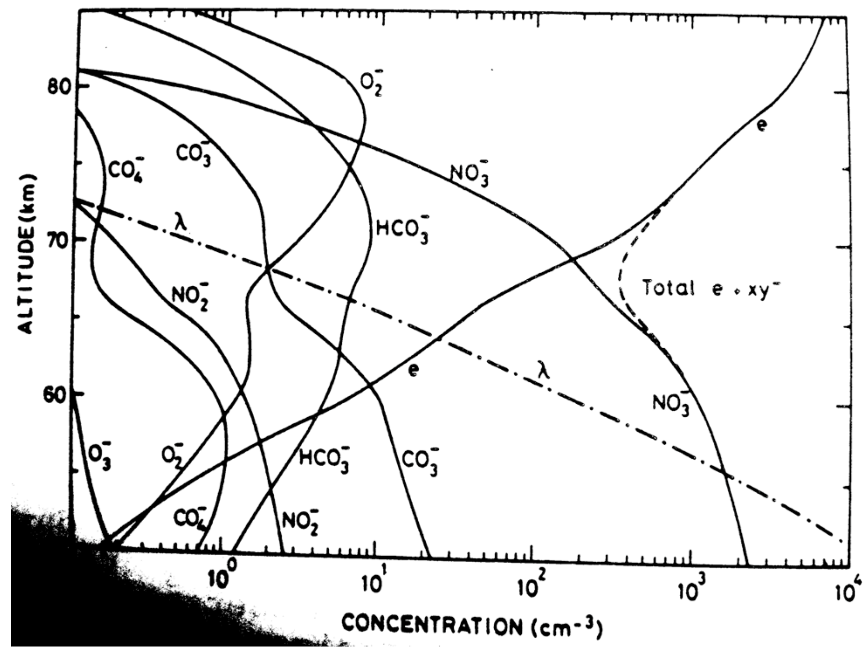
- retarding potential analyzer, “top hat” electrostatic analyzer, other particle energy spectrometers, imaging analyzers
- detectors for X rays, energetic particles, UV, energy deposition



Ion composition

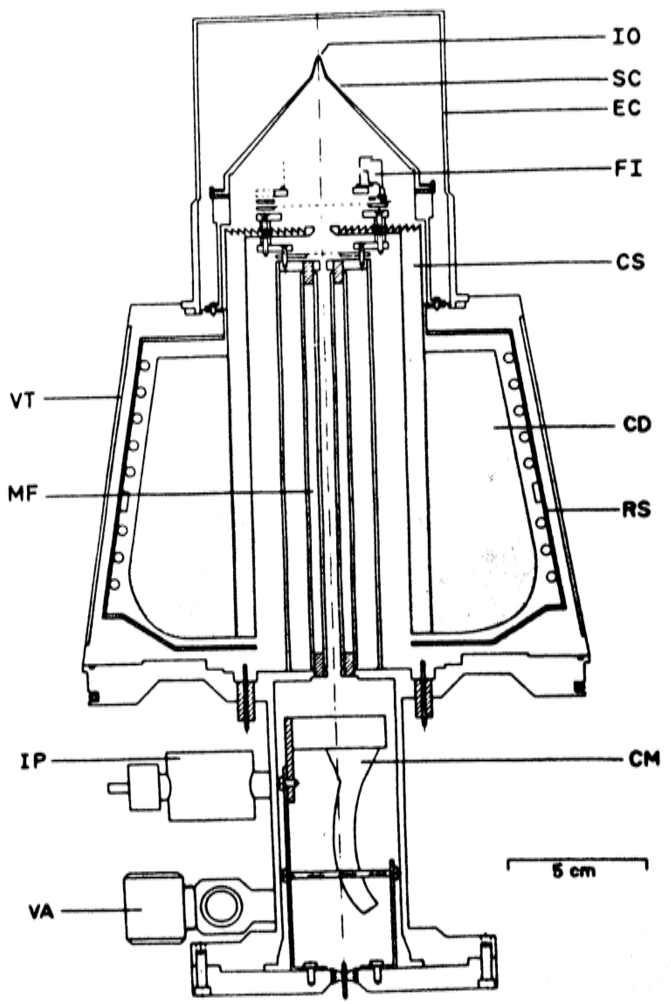


positive ions, IRI

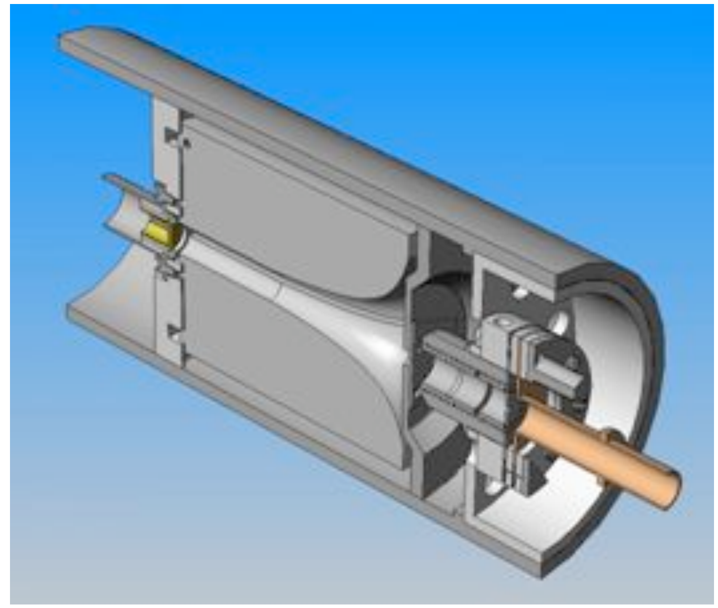


negative ion model, Wisemberg and Kockarts, JGR, 1980

Ion mass spectrometers 1

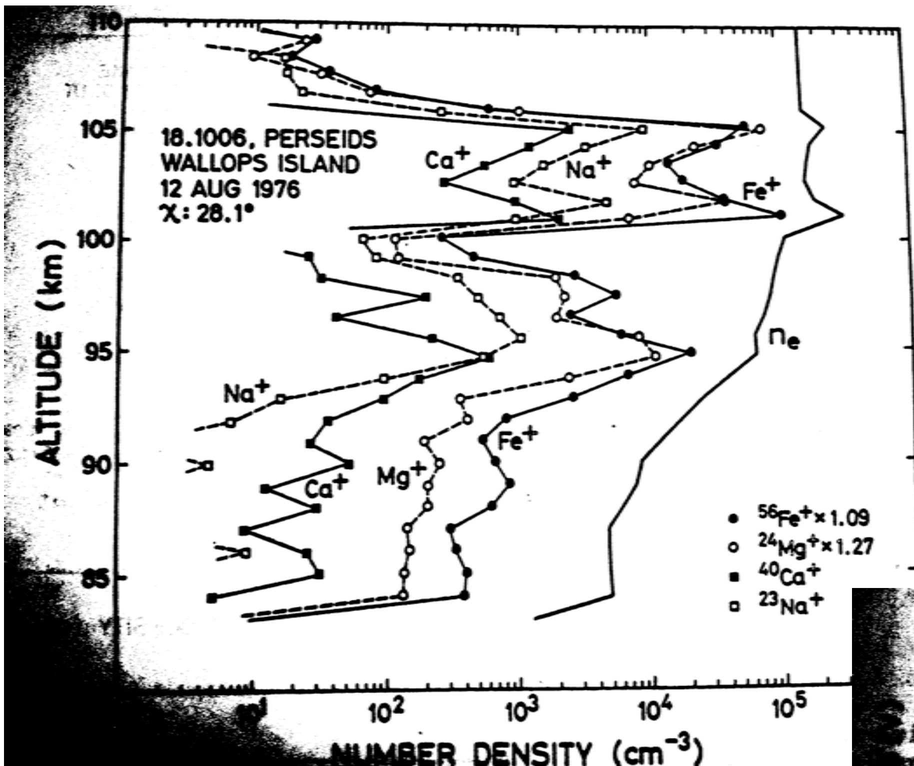


cryogenic, quadrupole, parachute
Arnold et al., 1977



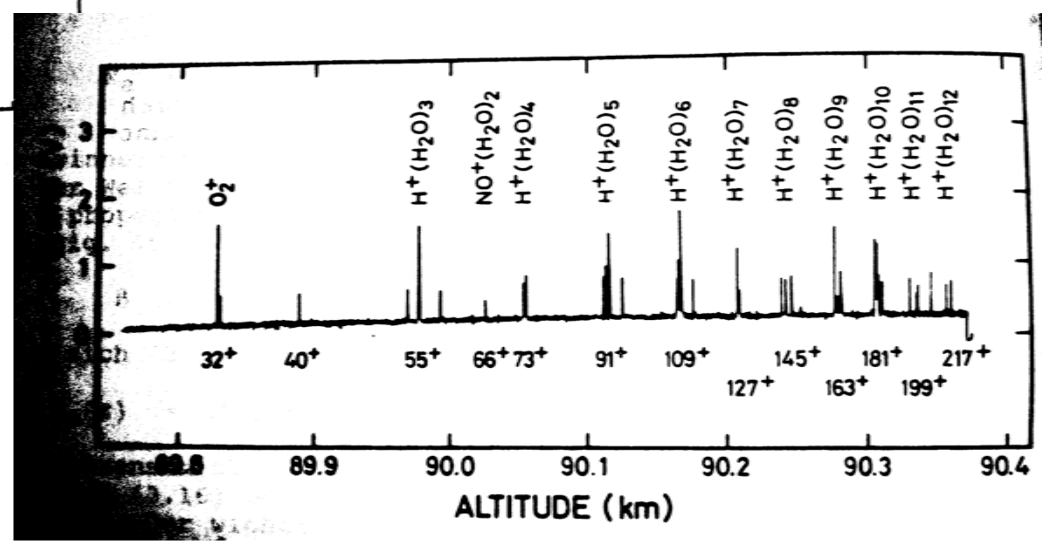
Rotating electric field ion mass spectrograph (REFIMS); J. Clemmons; Credit: pacetechhawaii.com

Ion mass spectrometers 2



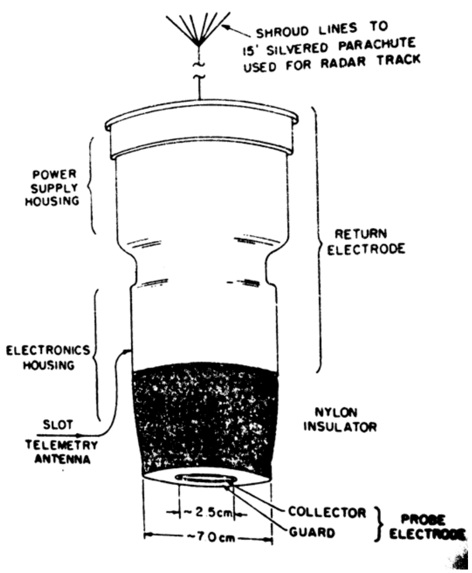
Metallic ions during meteor shower; Kopp and Ramseyer, 1987

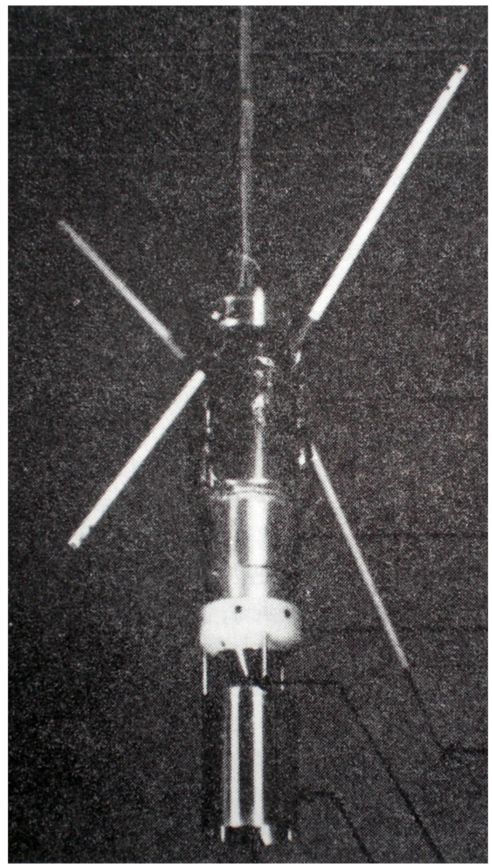
Water cluster ions in NLC region; Kopp et al., 1980

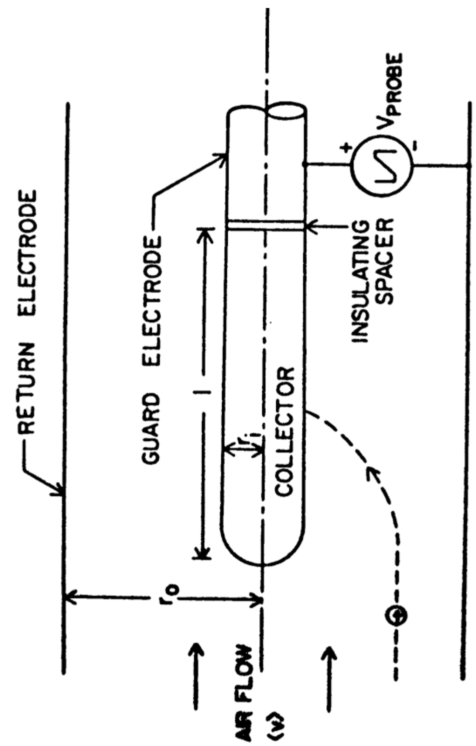


Conductivity probes

- Blunt probes $I_{\pm} = (2r^2/R)\sigma_{\pm}V$
- Gerdien condensors $I_{\pm} = (2\pi L/\ln(R/r))\sigma_{\pm}V$
- parachute descent



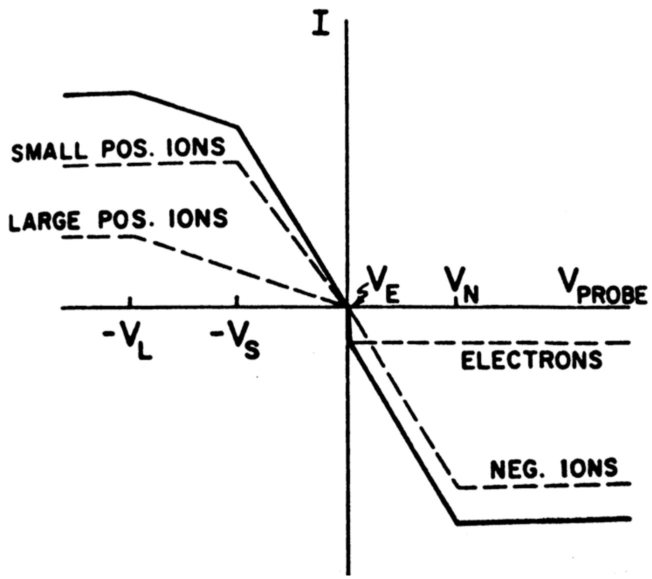


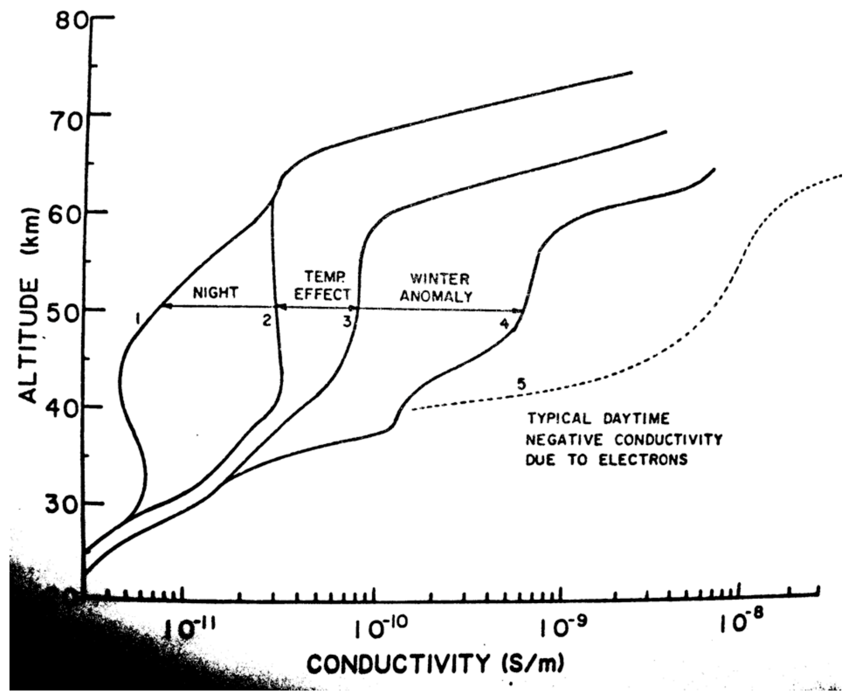


Hale, Croskey; Mitchell, MAP 19, 1986

Conductivity and mobility

- ion mobility, swept Gerdien, -26 V …+19 V
  - $k_{\pm} = v\,(R^2-r^2)\,\ln(R/r)/(2LV_{break})$



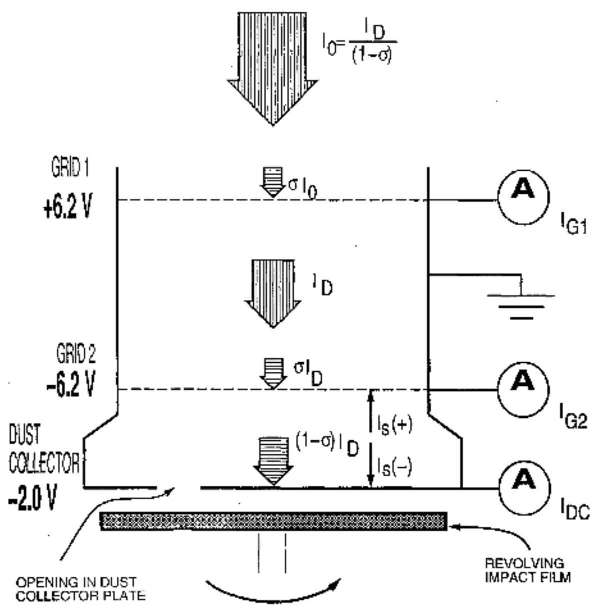


Mitchell, MAP 19, 1986

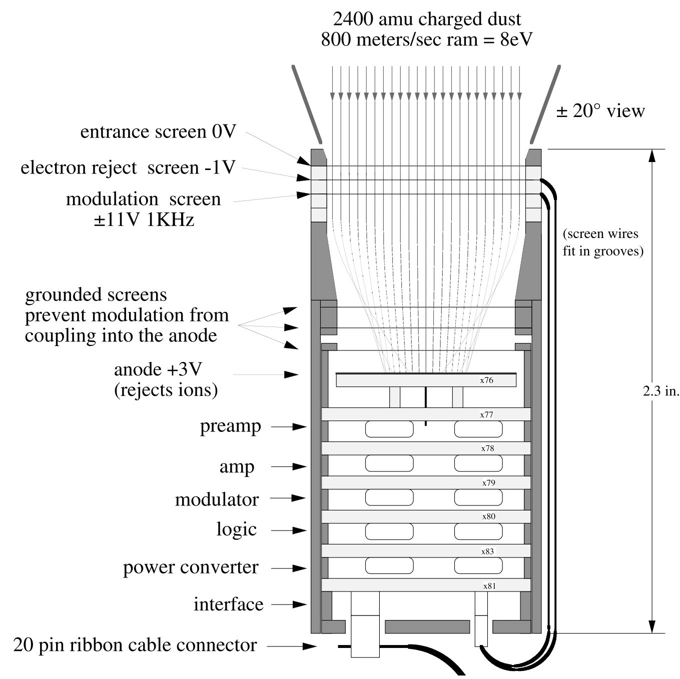
Neutral and charged dust in the mesosphere

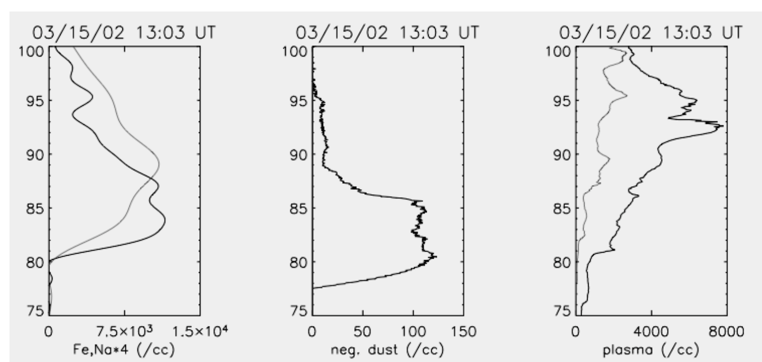
- Indirect evidence and case for dust: NLC, low conductivity, Hunten "smoke", occasionally large electric fields
- Polar Mesospheric Summer Echoes (PMSE), high turbulent Schmidt numbers due to reduced electron diffusion, electron biteouts and enhancements; ionospheric heating experiments
- Interest in dusty plasmas
- Supersonic rocket probes have difficulty to detect dust due to aerodynamics

Detectors for charged dust 1



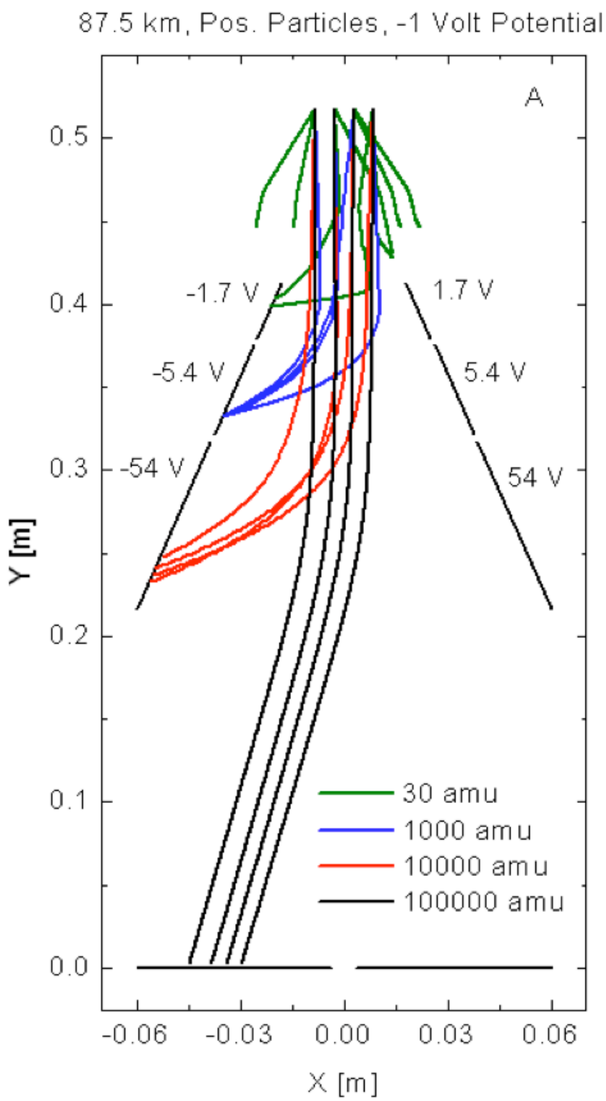
Havnes et al., JGR, 1996; during NLC/PMSE conditions

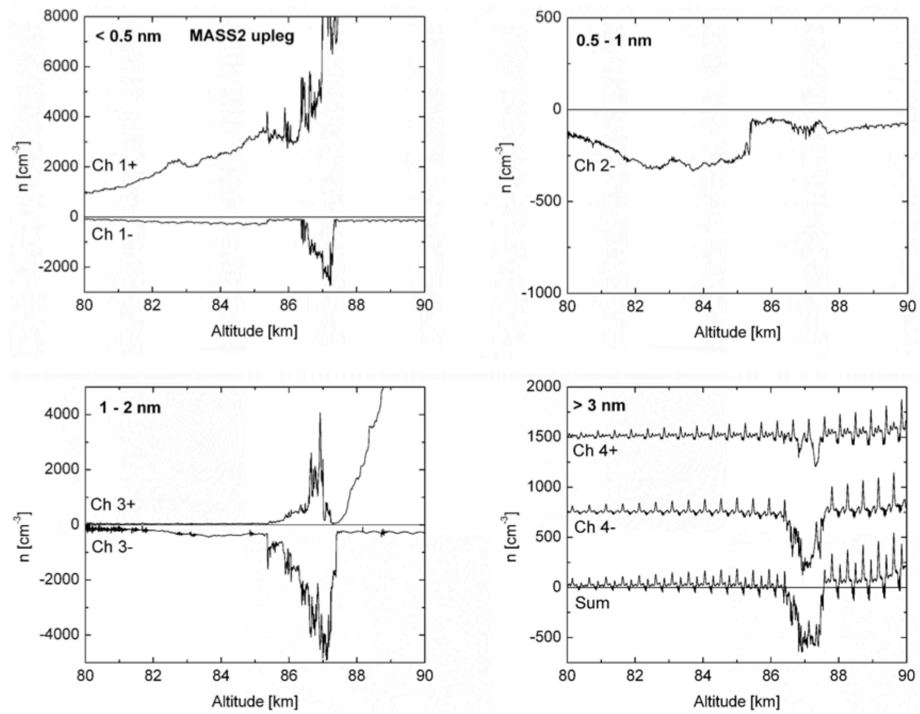




Lynch et al.,2005; Gelinas et al., 2005; winter daytime

Detectors for charged dust 2

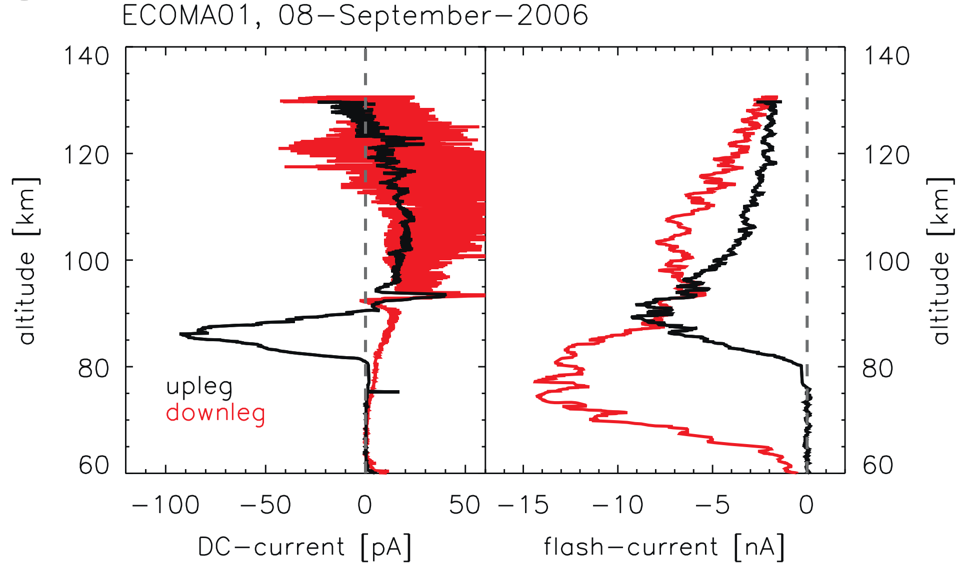




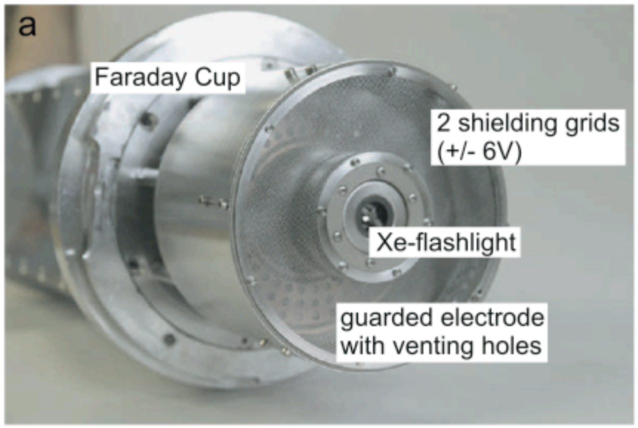
Robertson et al., Ann. Geo., 2009; NLC and PMSE

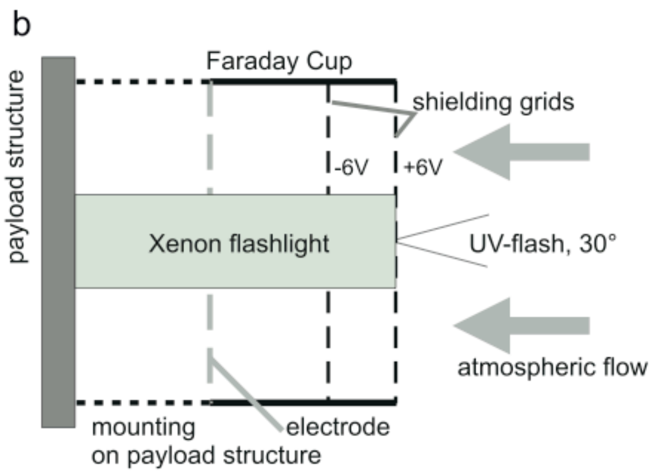
Detectors for charged and neutral dust

Strelnikova et al., JASTP 2008



Rapp et al., JASTP 2008





Croskey, JASR 2006;Gerdiens with flash lamps ->

Conclusions

- Sounding rockets have been at the forefront in discovery and exploration of the MLT region.
- They still are the only means for in situ measurements between ~40 km and ~200 km.
- Besides new research, they have proven to provide a testbed for ned satellite technology.
- They continue to serve an important role in K12, undergraduate, and graduate education to advance atmospheric and space physics and engineering, and to interest students and the public in this field.

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