Energetic particles and their detection in situ (particle detectors)
Part I

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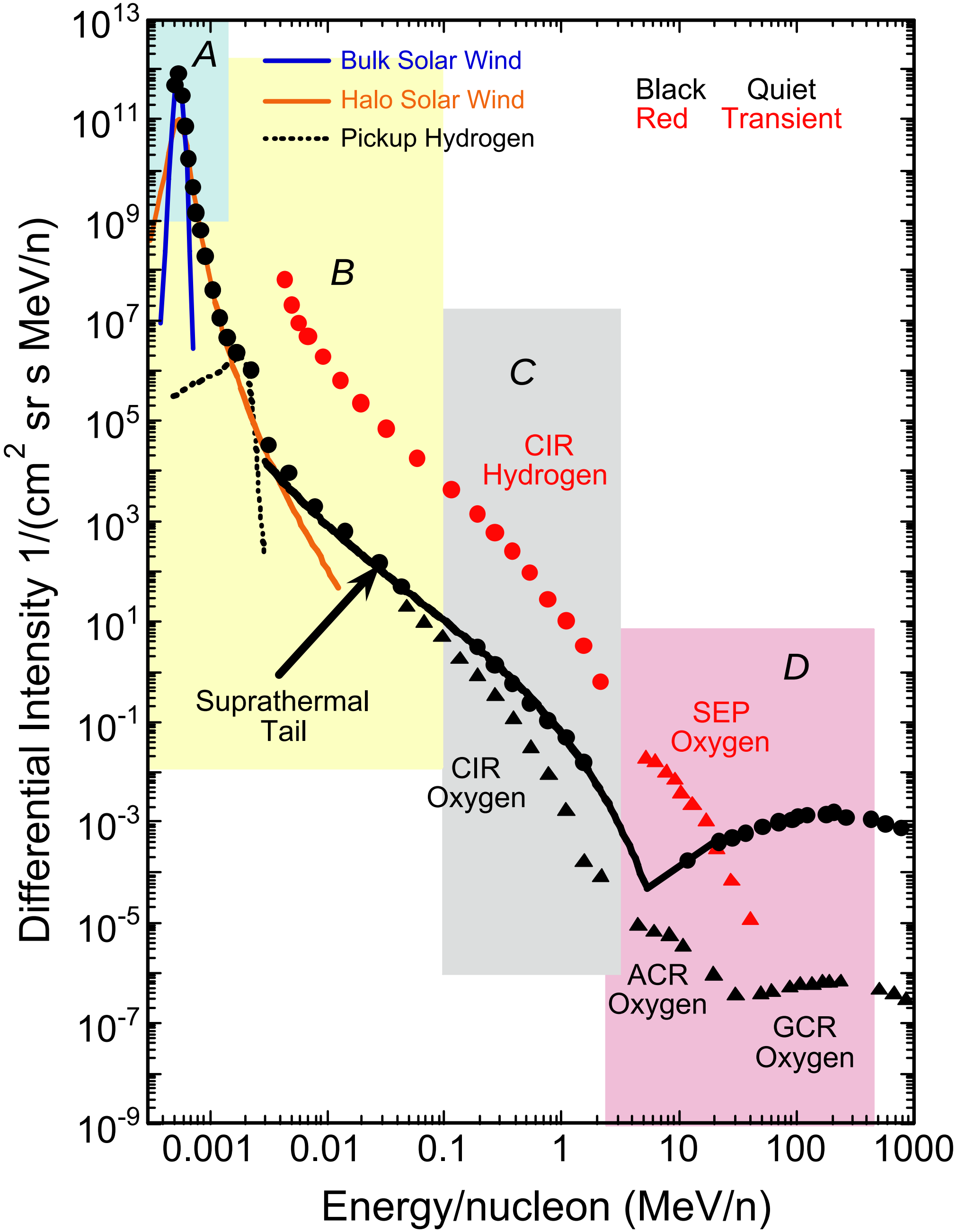
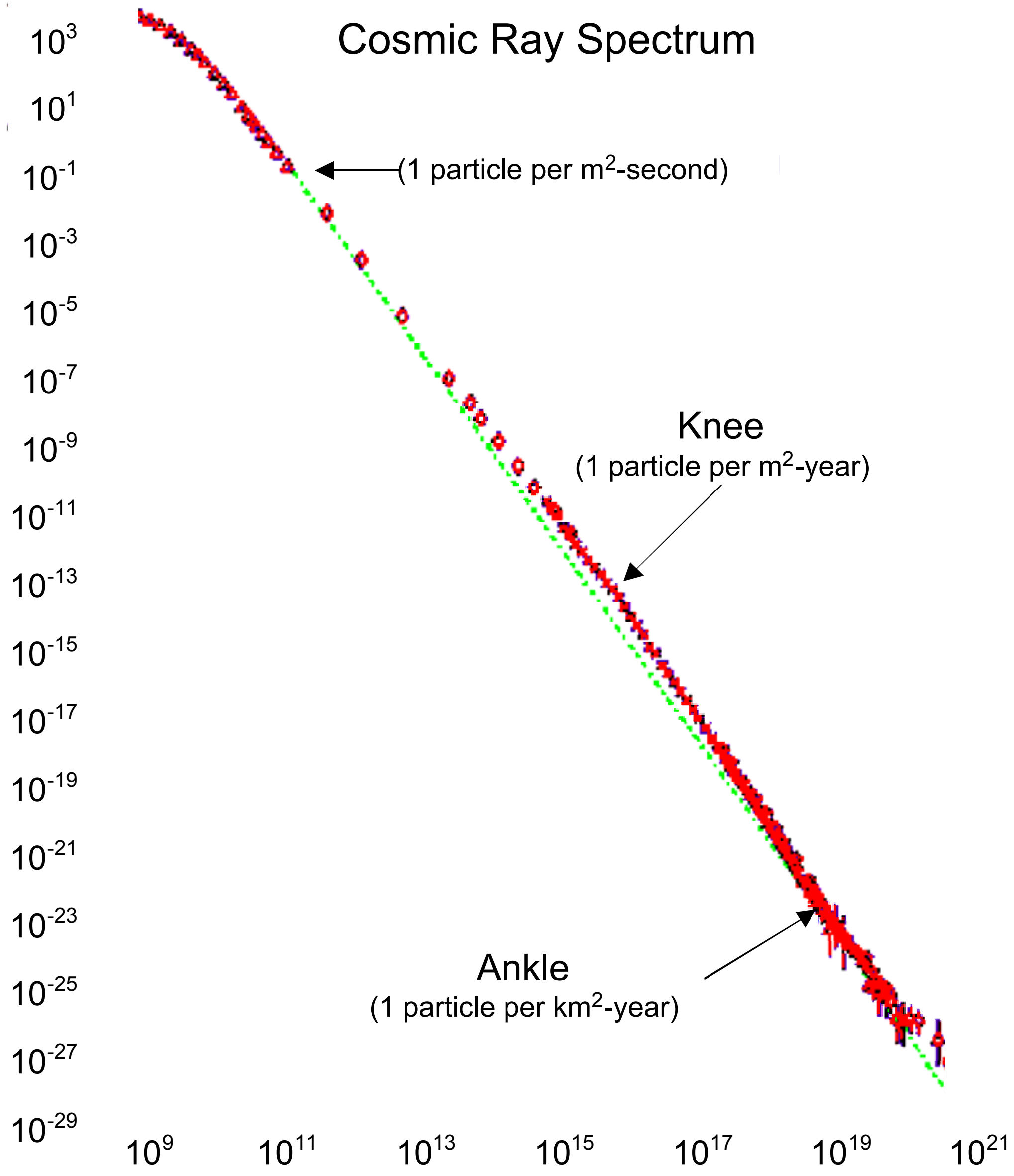
50 Years of Space Physics

- *Space physics* started fifty years ago with the launches on October 4 and November 3, 1957 of Sputnik I and II by the Soviet Union, and Explorer 1 and 3 by the US on January 31, and March 26, 1958
- Explorers 1 and 3 carried James Van Allen's Geiger counters
  - Van Allen wanted to measure the low-energy portion of the differential intensity of cosmic rays (particles of non-terrestrial origin with energies of hundreds of MeV), which could not be observed from the ground or with balloons because of atmospheric absorption
  - He did not find these cosmic rays but instead discovered the Van Allen radiation belts
- Van Allen's discovery of the radiation belts and many of the subsequent discoveries (e.g. Anomalous Cosmic Rays) teach us several important lessons
  - if one explores new territory, be it a new region of space (as was the case with Explorers 1 and 3), a new energy range, new measurement, etc. one is bound to discover the unexpected as has happened over and over again during the last 50 years and is bound to continue
  - new observations and discoveries drive our understanding of the physics of the system by stimulating theories and modeling which then make predictions that can be tested by further observations
  - because all instruments or detection devices have their limitations suspect them first if you get strange or completely unexpected results, and only after you have convinced yourself (and other experts) that it was not some instrumental effect should you believe your observations (which could well be a new discovery)

Differential intensities of protons and oxygen

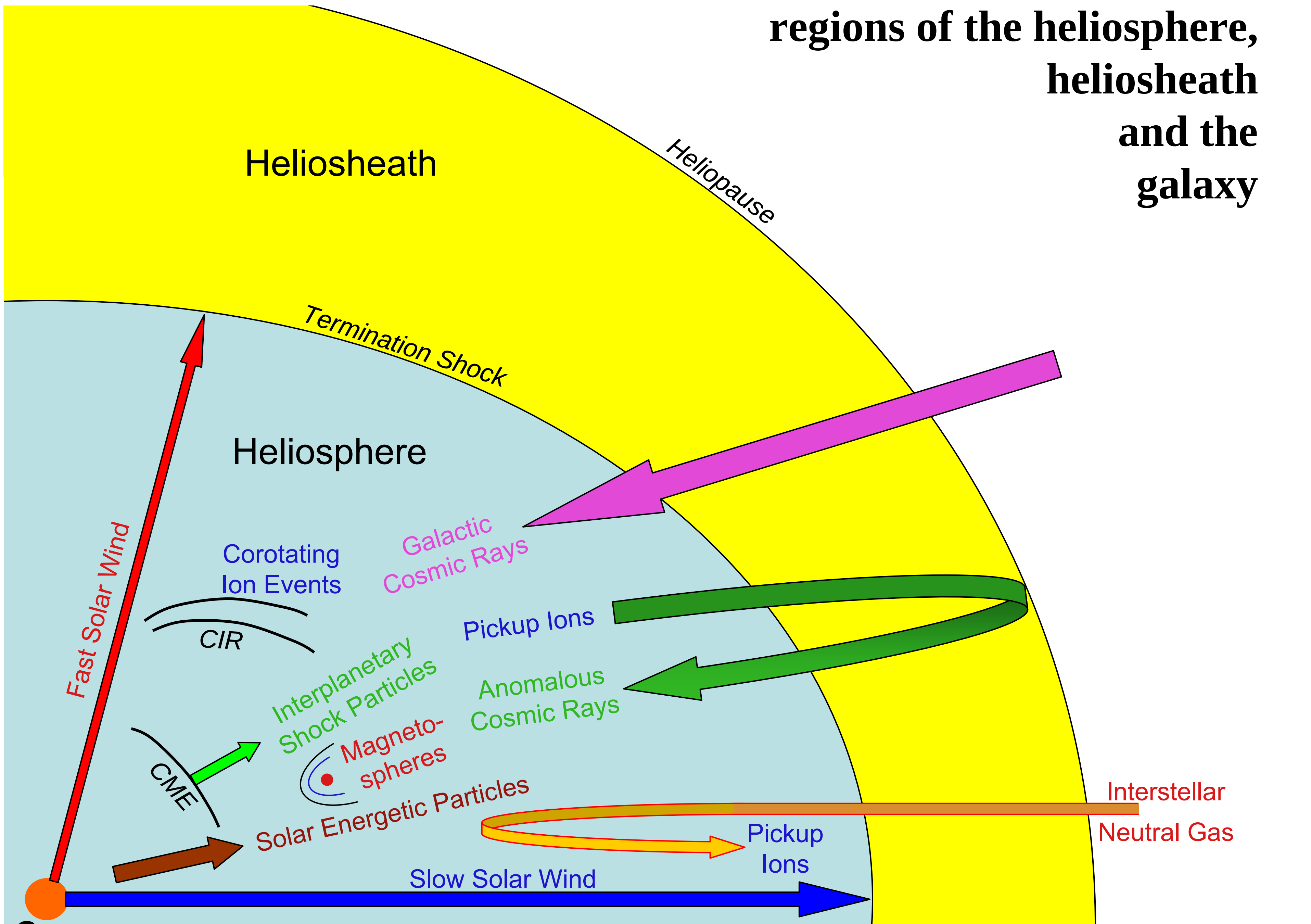


- 50 years ago there were no particle measurements below ~ 300 MeV/nuc
- All of the spectra shown below ~ 300 MeV/nuc were observed using spacecraft instruments
- particles are classified as either
  - quasi-steady or quiet (black)
    Solar Wind ions
    Pickup Ions
    Suprathermal Tails
    Anomalous Cosmic Rays (ACRs)
    Galactic Cosmic Rays (GCRs)
  - transient (red).
    Solar Energetic Particles (SEPs)
    Corotating Particle Events (CIR)
- three to four different techniques are required to obtain measurements from ~100 eV to ~200 MeV/nuc



Differential intensities of protons as a function of energy

Particles are accelerated invarious regions of the heliosphere, heliosheath and the galaxy

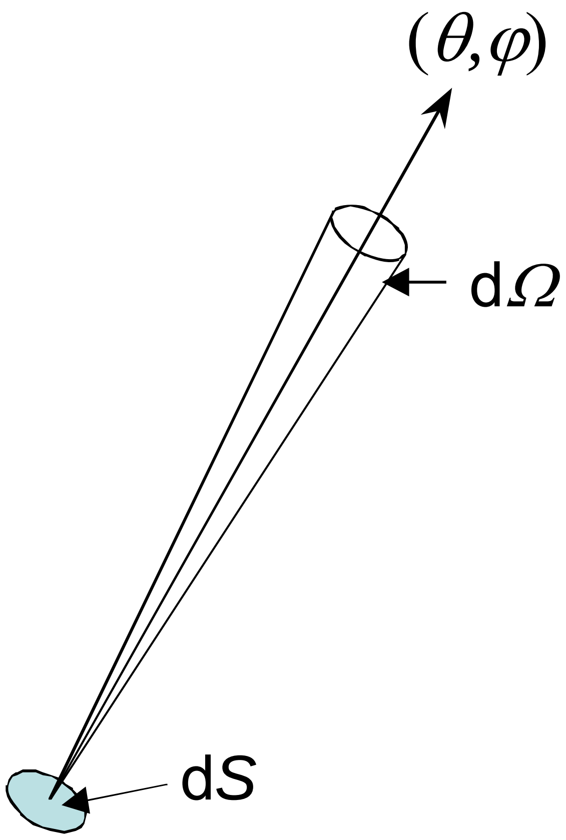


What needs to be measured?

Distribution function or *phase space density (f)*

$f(\mathbf{v},q,m) = f(v,\theta,\varphi,q,m) = \mathrm{d}n(\mathbf{v},q,m)/\mathrm{d}^3\boldsymbol{x}\,\mathrm{d}^3\boldsymbol{v}$

phase space density units: (s^3/km^6)



Differential intensity (dj/dE)

$dj/dE = [\mathrm{d}n(E,q,m)/\mathrm{d}t]/[\mathrm{d}S\mathrm{d}\Omega\,\mathrm{d}E]$

differential intensity units: (cm^2 s sr MeV)

$f(v,\theta,\varphi,q,m) = [\mathrm{d}n(v,q,m)/\mathrm{d}t]/[\mathrm{d}S\mathrm{d}\Omega\, v^3\mathrm{d}v] =$

$[m^2/2][\mathrm{d}n(E,q,m)/\mathrm{d}t]/[\mathrm{d}S\mathrm{d}\Omega\, E\mathrm{d}E] =$

$A^2(m_pc^2)^2[dj/dE(E,\theta,\varphi,q,m)]/[2c^4E]$

I used $\mathrm{d}n(v,q,m)/(\mathrm{d}S\mathrm{d}r) = [\mathrm{d}n(v,q,m)/\mathrm{d}t]/[\mathrm{d}S\bullet(\mathrm{d}r/dt)] =$
$[\mathrm{d}n(v,q,m)/\mathrm{d}t]/[\mathrm{d}S\bullet v]$

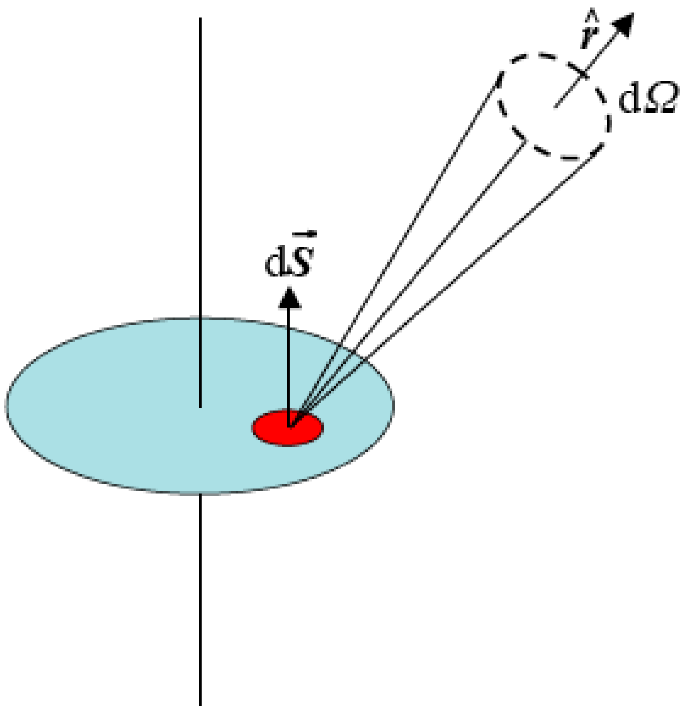
$$\boxed{\begin{array}{c} f(v,\theta,\varphi,q,m) = 0.545A^2\bullet[dj/dE]/E = 0.545[dj/dT]/T \\ v = 438\sqrt{T} \text{ and } T = E/A \text{ is the } \textit{energy/nucleon} \text{ in keV/n; } v \text{ is } \textit{particle speed in} \text{ km/s} \end{array}}$$

What is measured?

- *Counting rate* of particles above or between some energy limits and arriving within the detector's field-of-view (FOV)
- *Energy* or *speed* of particles
- *Precise arrival directions* of particle
- Particle *mass*, ion *charge*, or *mass/charge*
- To compute the differential intensities or phase space densities from measured quantities requires knowledge of the instrument characteristics such as its *geometrical factor* and detection *efficiencies*

Geometrical Factor

- Computation of the differential intensity, $dj/dE = [\mathrm{d}n(E,q,m)/\mathrm{d}t]/[\mathrm{d}S\mathrm{d}\Omega\,\mathrm{d}E]$ requires knowledge of the *geometrical factor* (GF) which is the integral over the FOV of the detector of the quantity $\mathrm{d}S\mathrm{d}\Omega$
- Common units for the GF are cm^2-steradian (cm^2-sr)



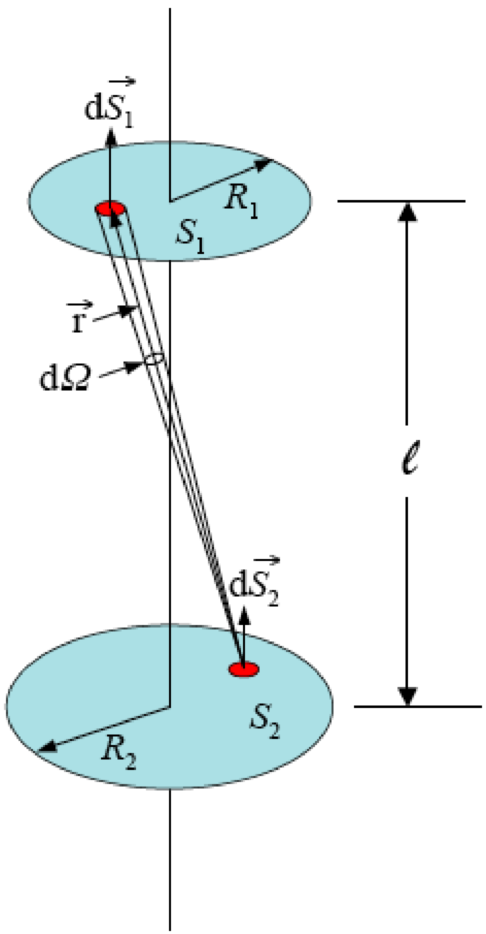
Calculation of the *geometric factor* of a simple detector system

$$GF = \int_S \int_\Omega (\hat{r} \cdot d\vec{S})\, d\Omega = \pi S[1 - \cos^2(\Theta)]$$

$$= \pi S \text{ (for } \Theta = 90°)$$

Calculation of the *geometric factor* of a particle telescope consists of two planar detectors of areas S_1 and S_2, separated by ℓ

$$\mathrm{GF}_2 = \int_{S2}\int_{\Omega} (\hat{\mathrm{r}}\cdot d\vec{S}_2)\,d\Omega$$

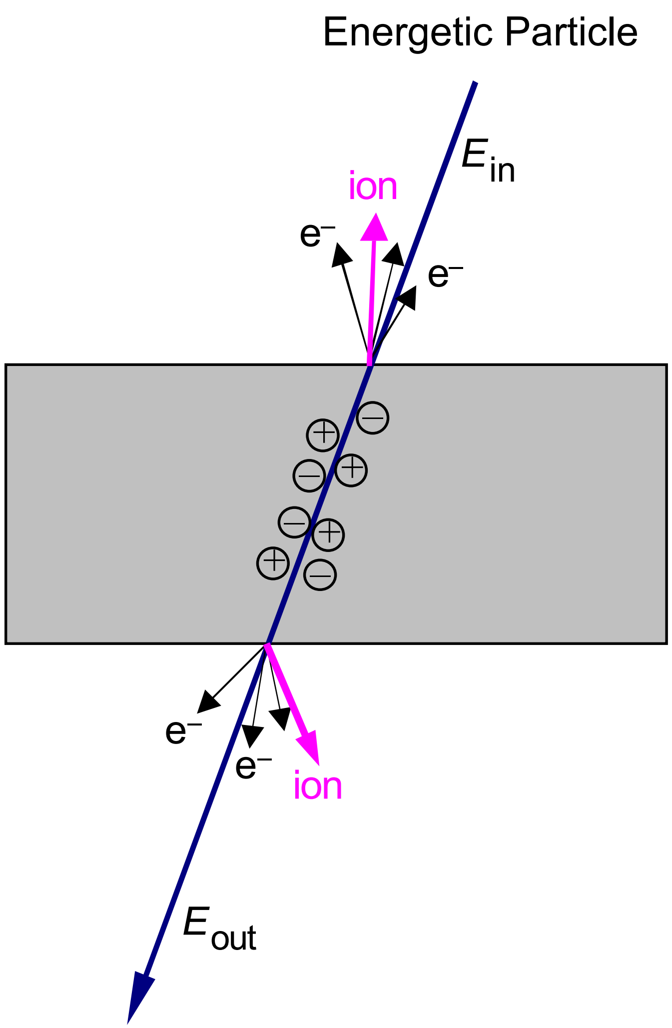


$$\mathrm{GF}_2 = (\pi^2/2)[R_1^2 + R_2^2 + \ell^2 - \sqrt{(R_1^2 + R_2^2 + \ell^2)^2 - 4R_1^2R_2^2}]$$

$$\boxed{\approx \pi^2 R_1^2 R_2^2/\ell^2 = S_1S_2/\ell^2} \text{ for } R_1 \ll \ell \text{ and } R_2 \ll \ell$$

- To compute the geometrical factor of more complex geometries one makes use of
  - Monte Carlo techniques
  - Forward models that are especially useful when coordinate frame transformations (e.g. from the solar wind to the spacecraft frame) are required.

Interactions of energetic particles with matter



- An energetic particle (or photon) passing through a slab of material gives up some of its energy to eject electrons and ions from the surfaces of the slab
- Furthermore they ionize or excite some of the atoms or molecules of the material, or create charge carriers
- In this process they lose some or all (if they stop in the slab) of their energy
- This loss of energy is called *energy loss by ionization*

Stopping Power

- Heavy particles of mass *A* (atomic mass units) and nuclear charge *Z* (electron charge units) interact with the material they are traversing by distant collisions with electrons in the material
- In each interaction the heavy particle loses a small amount of its energy, but deviates little (small scattering) from its original straight path
- Energetic electrons lose a much larger fraction of their energy in each collision and scatter much more, even reversing their direction in direct collisions with nuclei of the material.
- The energy loss d*E* in traversing a thickness d*x* of the material, or the *stopping power* is given by

$$-dE/dx = (4Z^2 m_e c^2/\beta^2)\bullet C\bullet\rho\bullet[\ln\{2m_e c^2\beta^2/(\bar{I}(1-\beta^2))\} - \beta^2] \quad (1)$$

where $m_e c^2$ is the electron rest energy, c is the speed of light, β is v/c, v is the particle speed, $C = \pi N_o e^4(z/m)/(m_e{}^2 c^4)$, z, m and ρ are the average nuclear charge, nuclear mass and mass density, respectively of the material, and $\bar{I}$ (~13.5z eV) is the average ionization potential of electrons in the material.

Stopping Power (continued)

- Dividing both sides of equation (11) by ρ, and substituting the numerical values for C = 0.150(z/m) cm^2 and $m_e c^2$ = 0.511 MeV, gives for the energy loss by ionization expressed in MeV per g/cm^2 units

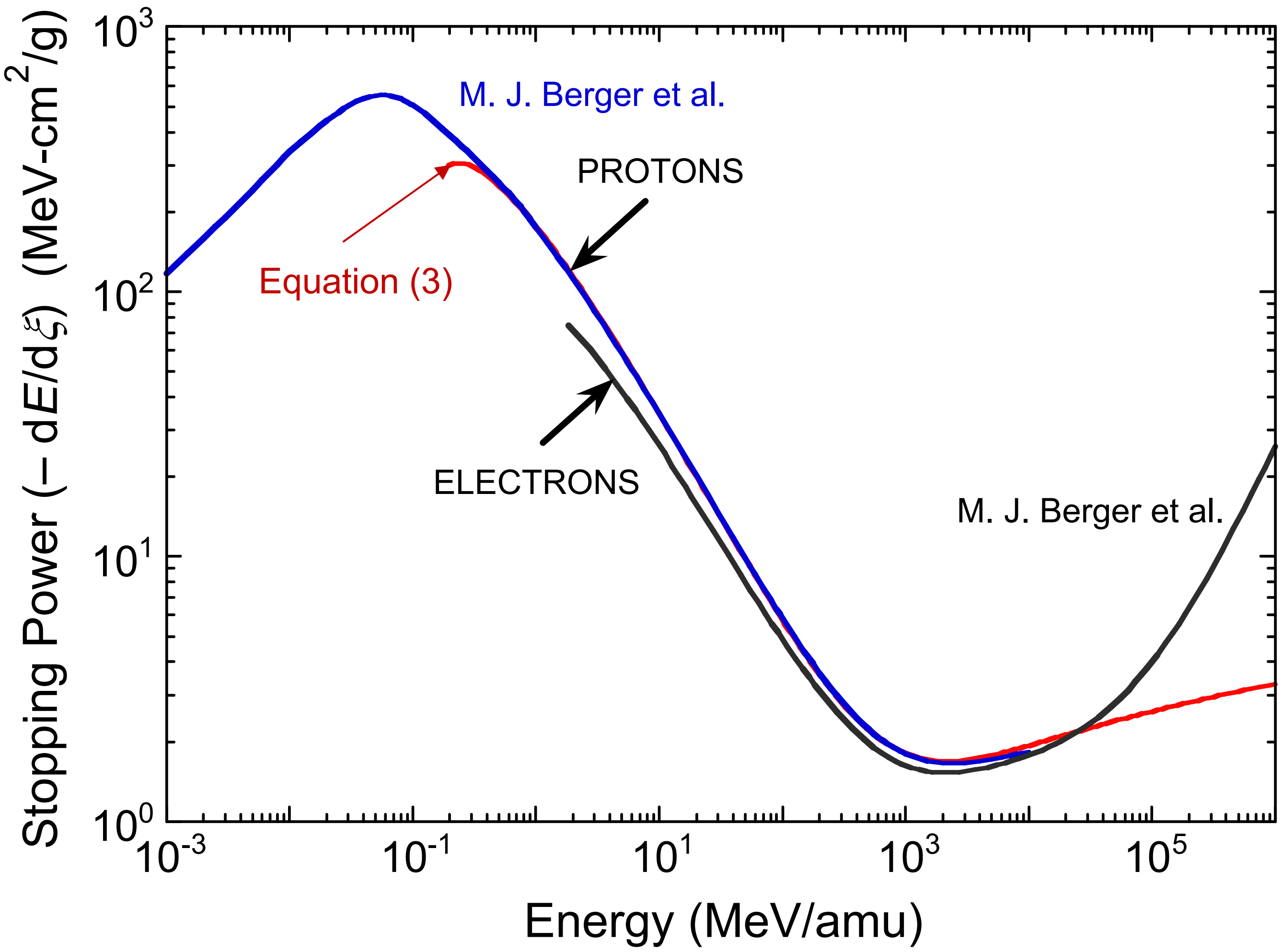
$$-\,dE/(\rho dx) = -\,dE/d\xi = 0.307(Z^2/\beta^2)\bullet(z/m)\bullet[\ln\{2m_e c^2\beta^2/(\bar{I}(1-\beta^2))\} - \beta^2] \quad (2)$$

- For non-relativistic particles ($\beta \ll 1$) the stopping power for protons (Z = 1) reduces to

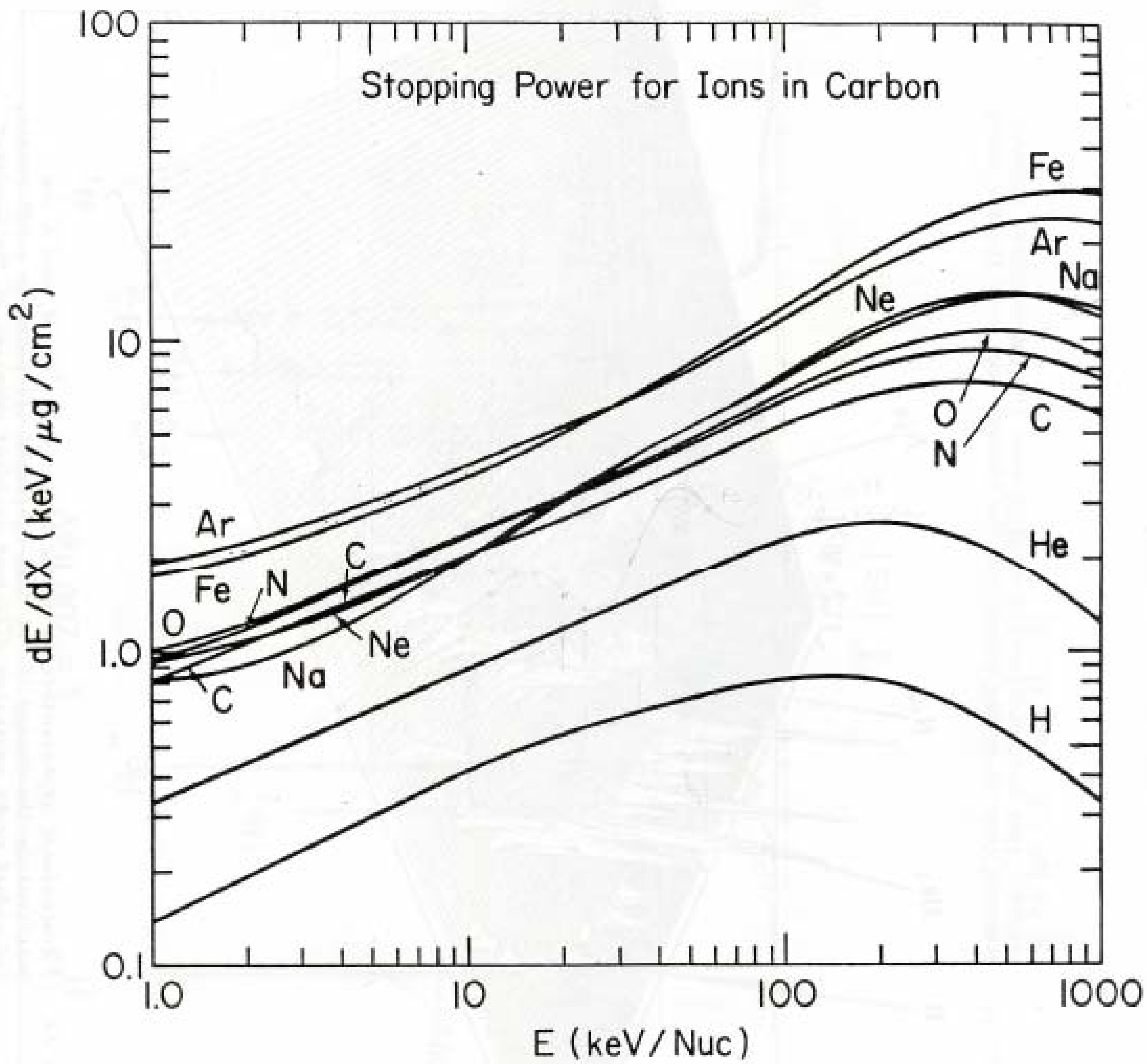
$$-\,dE/d\xi = 0.153(m_p c^2/E)\bullet(z/m)\bullet[11.93 - \ln(z) - \ln(m_p c^2/E)] \quad (3)$$

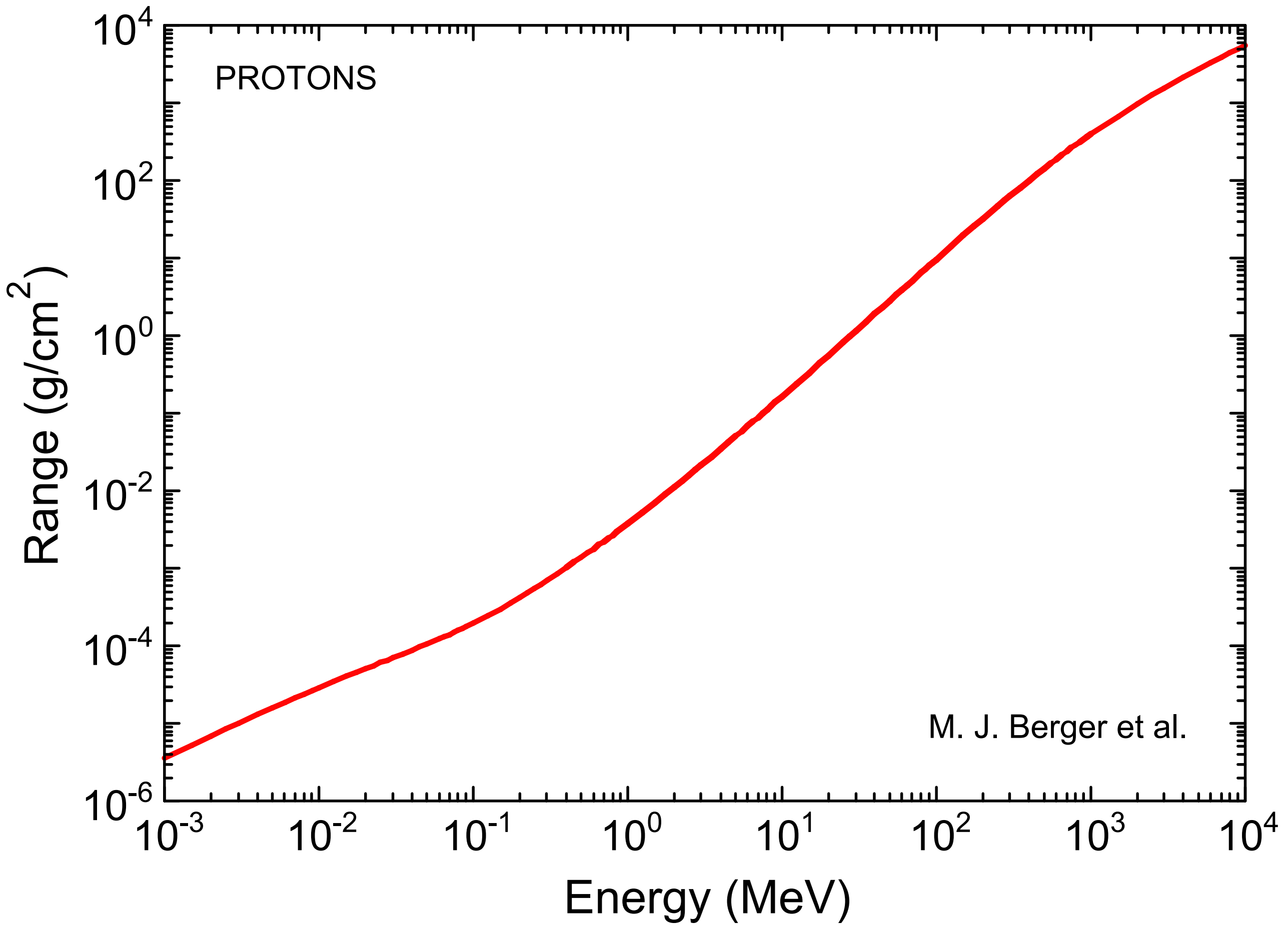
- The dominant energy dependence is contained in the first term of the above equations
  - the dependence on the material (z) is in the ln(z) term and is weak since, to a good approximation, (z/m) ≈ 0.5
  - for the same energy per nucleon E/A the energy loss per g/cm^2 will be less in heavy (high z) material such as copper, than in light materials such as silicon.
- The ionization loss for heavy particles (Z > 1) at some given energy/nucleon E/A above a few hundred keV/nucleon can be obtained by multiplying stopping power of protons at the same energy/nucleon by Z^2.

Comparison a plot of equation (3) for protons traversing Si (z = 14) with a curve based on experimental stopping power data.



Measured energy dependence of the stopping power for the indicated elements in carbon





From the stopping power equation one can compute the *range* of a particle with energy/nucleon E_o/A

The *range* P is defined to be the distance the particle travels in an absorber before stopping and losing all of its energy

$$P = -\int_{Eo/A} (\mathrm{d}E/\mathrm{d}\xi)^{-1}\mathrm{d}E$$