African School of Fundamental Physics and Applications

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Cosmic Rays, Neutron Monitors, Solar Cycles & the Heliosphere

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History and Discovery

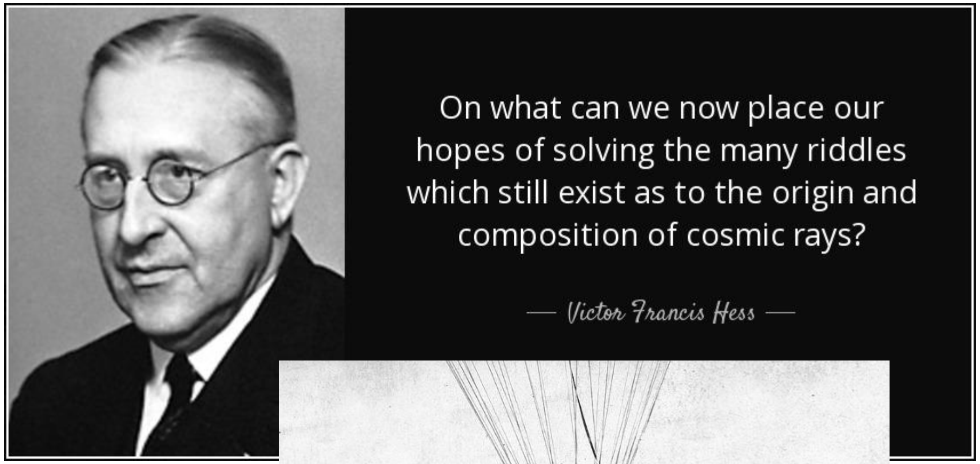
A short history of the discovery of Cosmic Rays

At beginning of 20^{th} Century:

- **Hypothesis:** Natural radioactivity caused by decay of isotopes in crust of Earth
- **Test(s):** Taking instruments up towers to measure ionisation rate
  - Inconclusive due to limited height
- **Q:** How to increase height?
- **A:** Balloon flights!

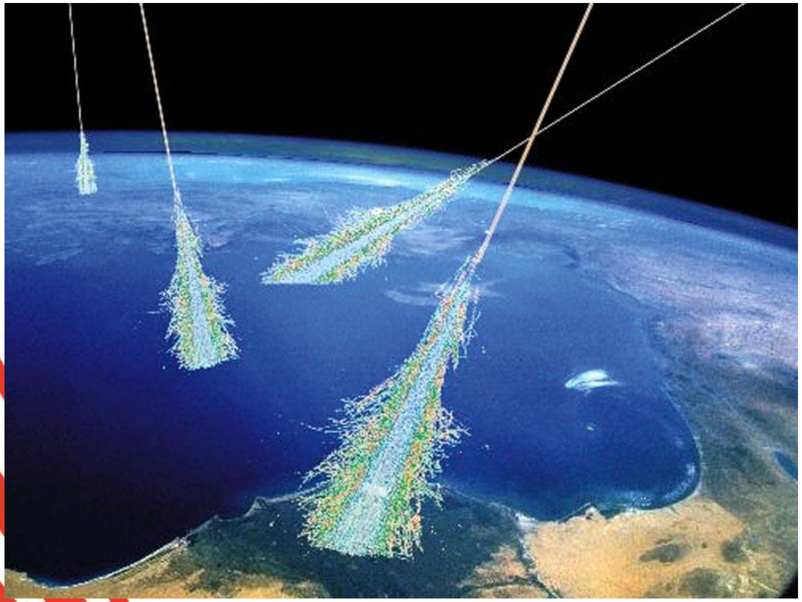
Victor F. Hess

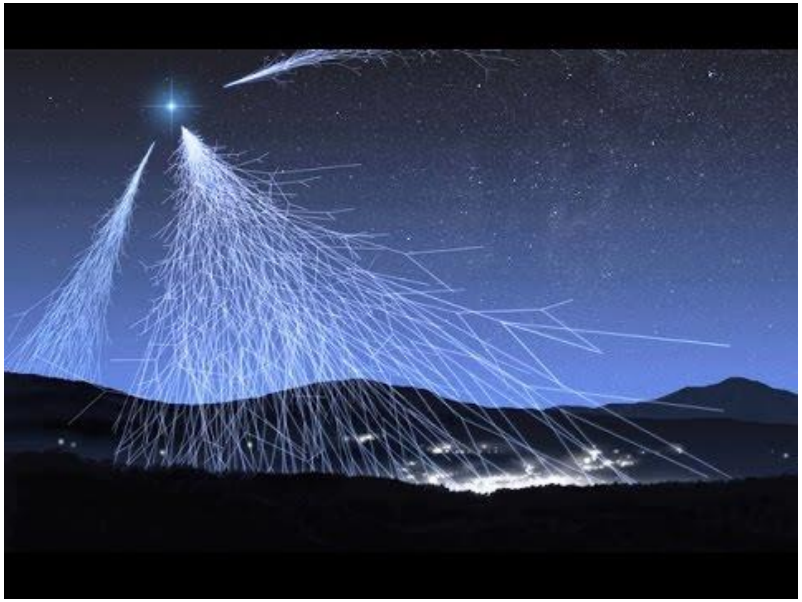
- Balloon flights up to 5.3 km with improved instrumentation in 1911—13
- Results:
  - Radiation levels decreased up to 1 km
  - Thereafter increased sharply until radiation levels at 5 km were twice that at sea level
  - **Conclusion:** Radiation from outer space
  - Millikan named them “Cosmic Rays” (ionising rays from the cosmos)
- Hess shared Nobel prize for discovery with Carl David Anderson



Cosmic Rays (CR)

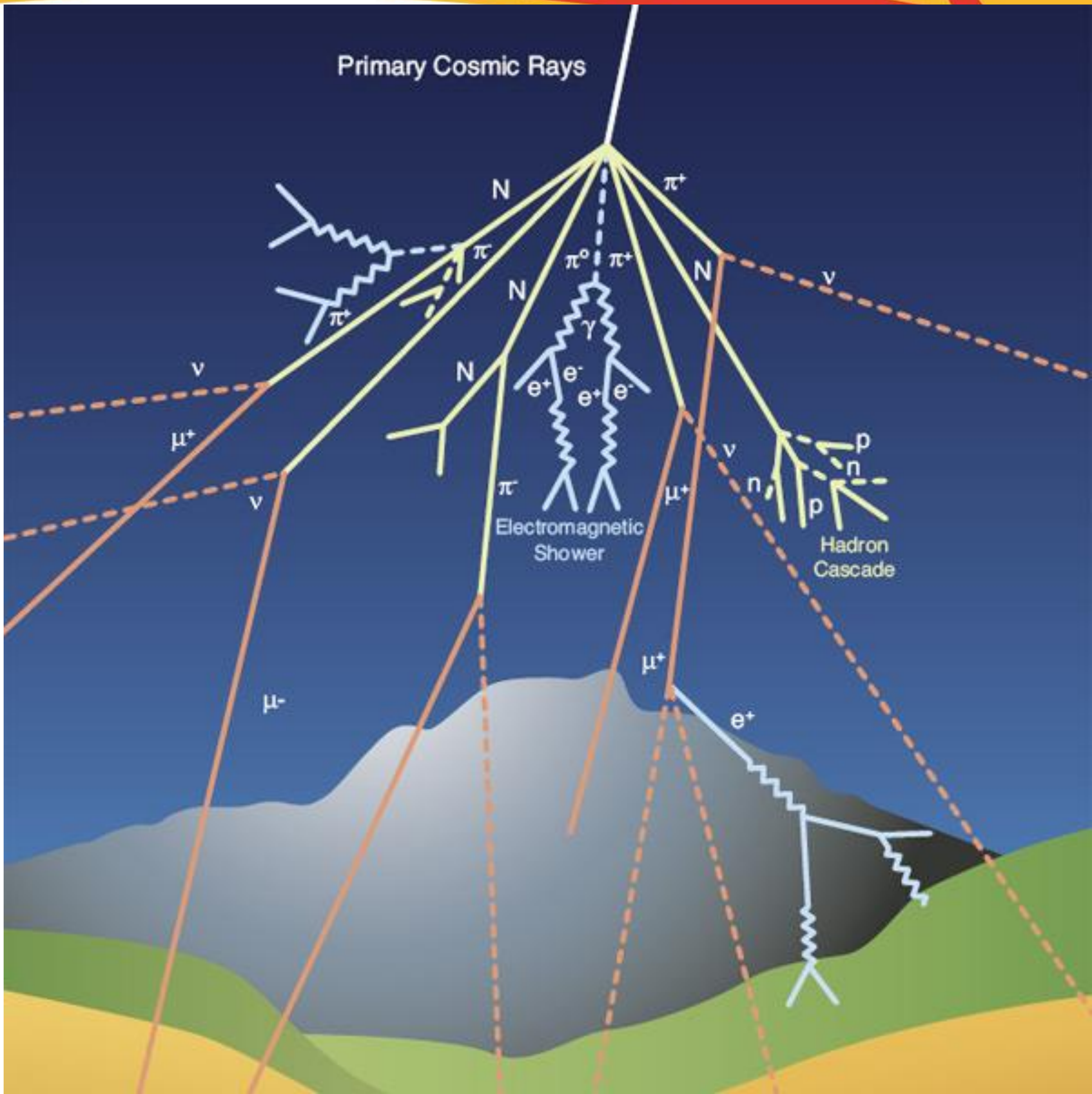
- Misnomer: Not rays, but charged particles
- Measured atmospheric radioactivity not actually caused by CR, but by secondary particles produced by CR interactions in upper atmosphere





Air showers

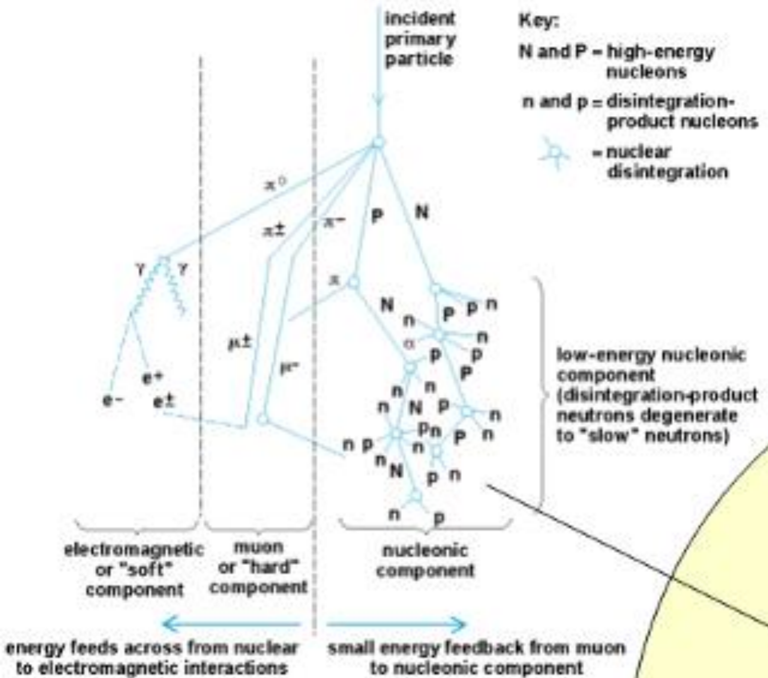
- CR interacts with air molecule
- Produces a cascade of elementary particles
  - Electromagnetic shower
  - Hadron cascade
- Focus on latter, esp. the energetic neutrons as means of detecting CR

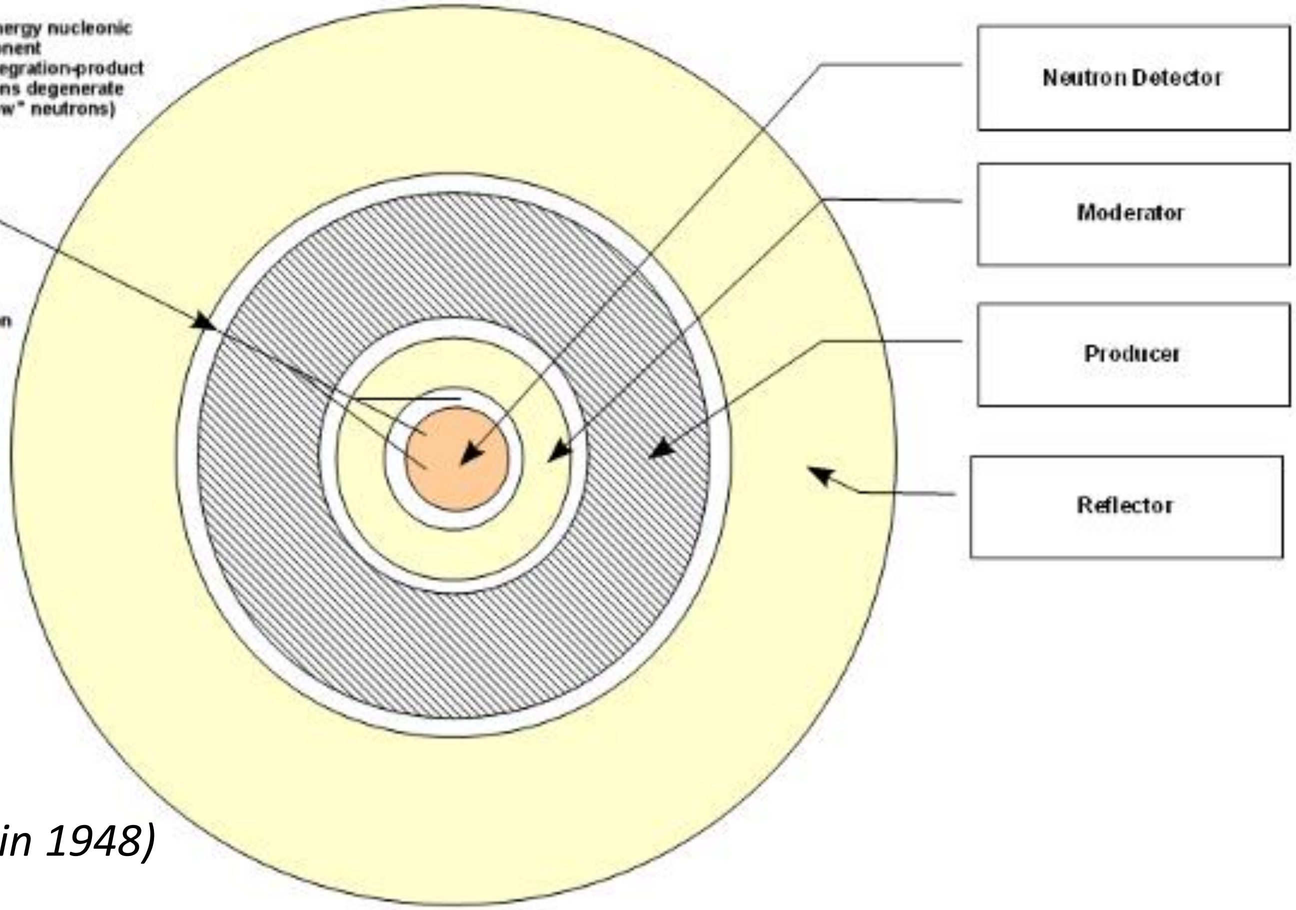


Neutron Monitors

Instruments to measure high-energy particles impacting the Earth from space

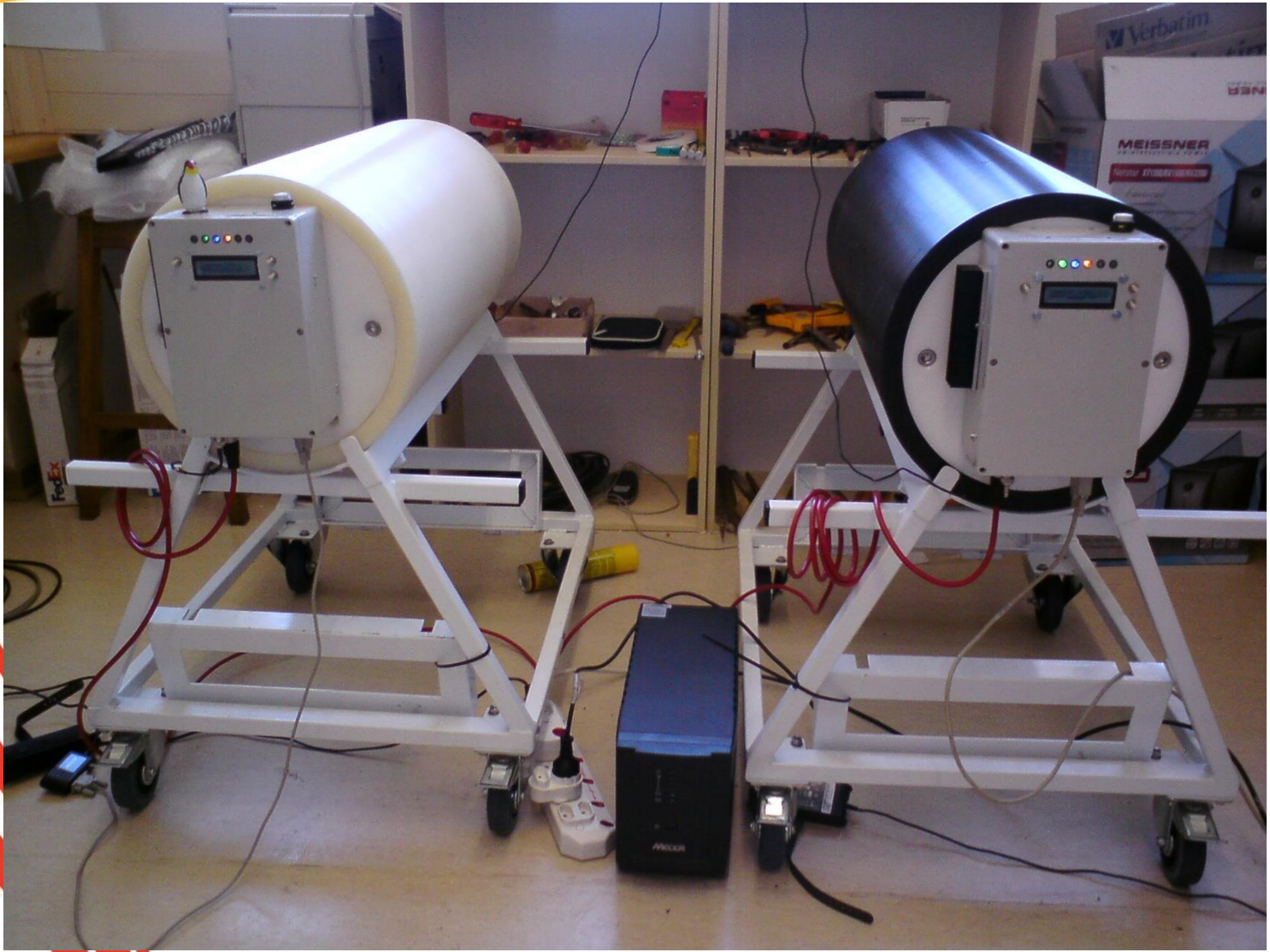
Basic design



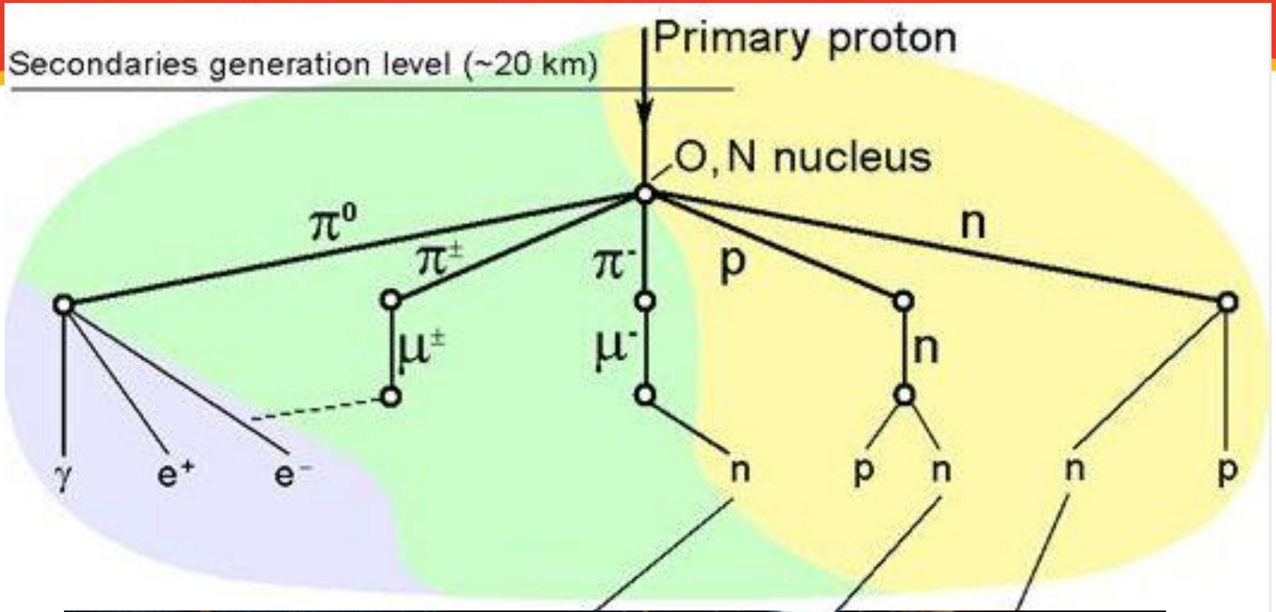


(Invented by John A. Simpson in 1948)

Mini-Neutron Monitors



Neutron Monitor Arrays



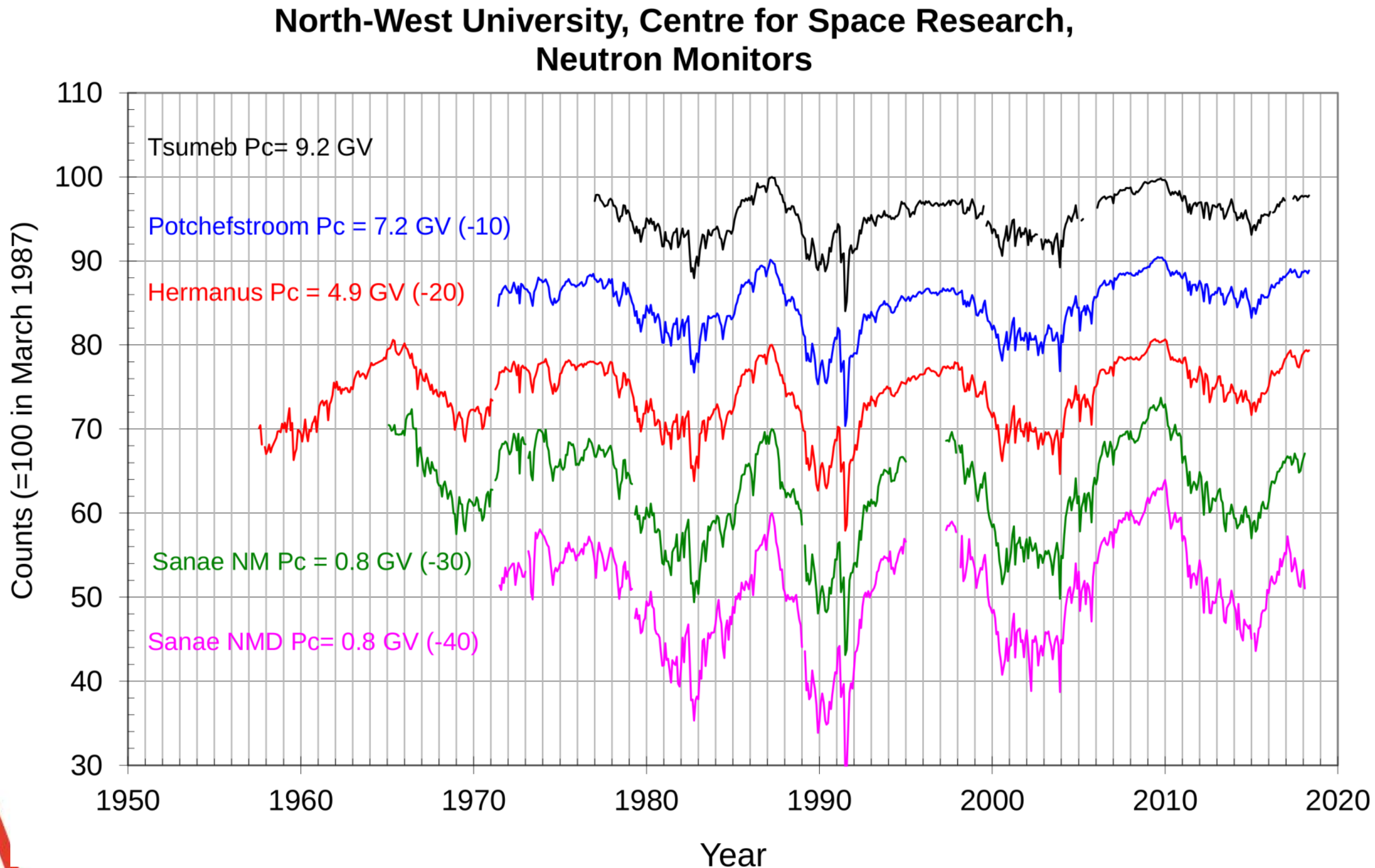
How it works

- Reflector:
  - outer shell of proton-rich material to stop low energy neutrons from outside (paraffin/polyethylene)
- Producer:
  - fast neutrons that get through reflector interact with dense material to produce more lower energy neutrons (lead)
- Moderator:
  - Proton-rich material slows down secondary neutrons to increase likelihood of detection
- Proportional Counter:
  - neutrons interact with gas nuclei causing nuclear reactions that in turn causes energetic charged particles that ionise gas producing electrical signal ($n + {}^{10}B \rightarrow \alpha + {}^{7}Li$ or $n + {}^{3}He \rightarrow {}^{3}H + p$)

Where to find them?

Potchefstroom (SA), Hermanus (SA), SANAE (Antarctica), Tsumeb (Namibia), etc, etc

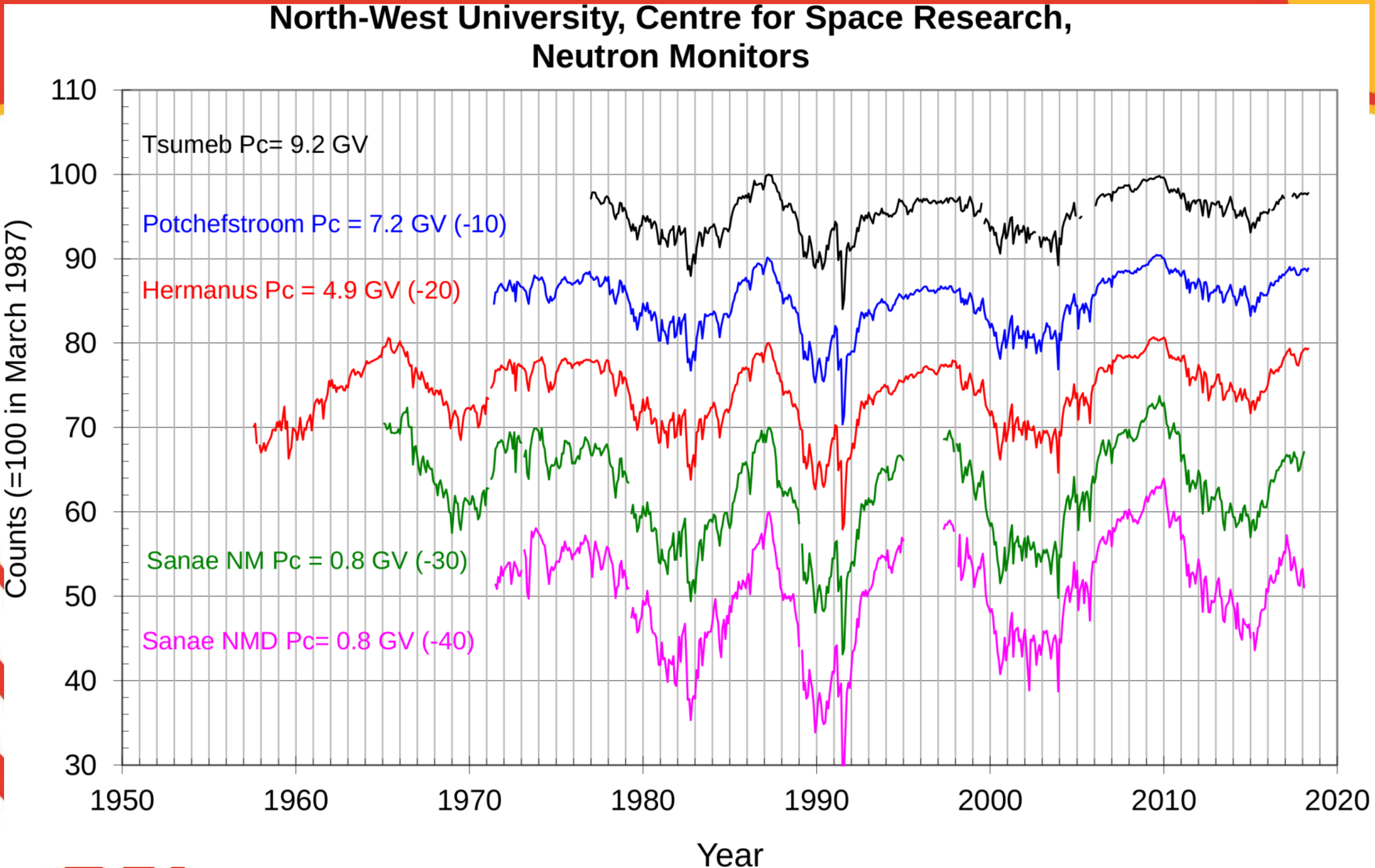
Pieter Stoker



Need many NM arrays

- To measure Anisotropy:
  - View different directions in space – anisotropy determined
  - Diurnal variations
- To measure Energy Spectrum
  - Geomagnetic field screens off charged cosmic-ray particles more strongly in equatorial regions than, e.g., polar regions
  - Only higher energetic CR can easily penetrate across B-field lines, while lower energy particles are screened off.
  - In polar regions even relatively low energy CR can penetrate deep into atmosphere

Energy dependence



Particle rigidity: $P = {}^{pc}/_{q} = {}^{pc}/_{Ze} = r_L B$

What it Measures

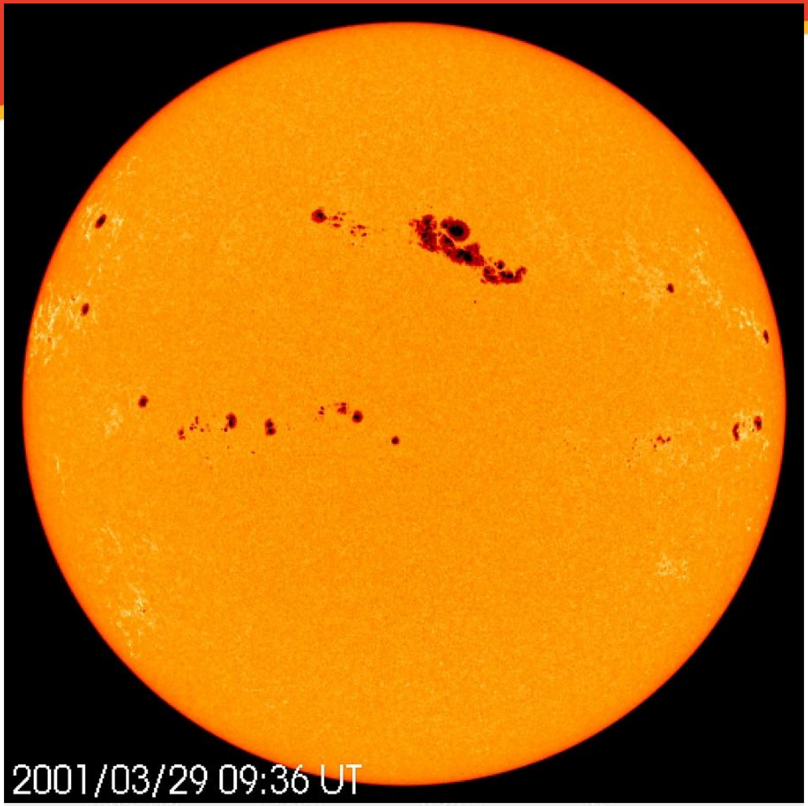
NM Data interpretation:

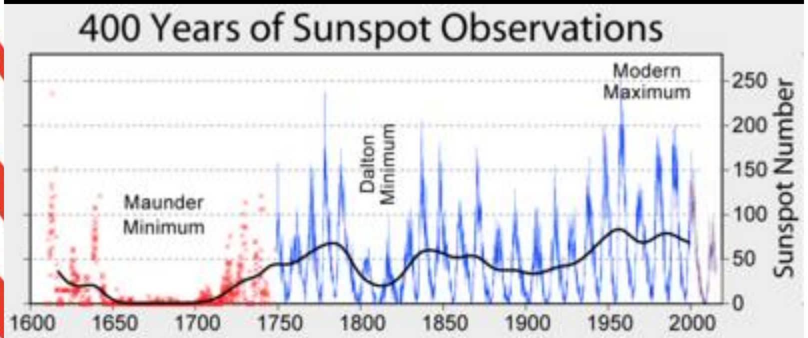
- Measures mainly **Galactic** cosmic rays:
  - Solar Cycle – “solar modulation” (11 & 22 year cycles)
  - Forbush Decreases – decrease in intensity after solar flare (named after Scott E. Forbush)
  - Ground level enhancements – a few times a decade Sun emits (relatively) high-energy solar particles that can be detected at ground level

Heliospheric Physics

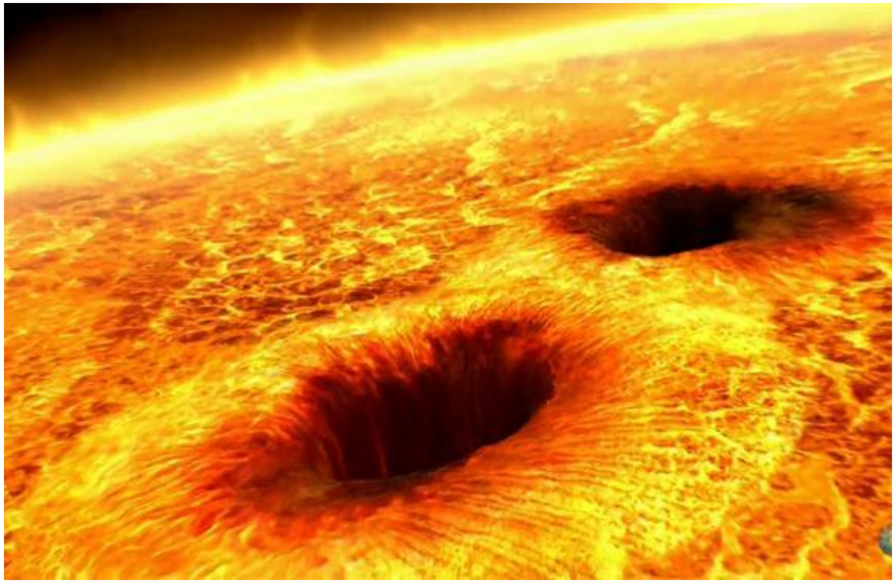
Interpretation of clues to Heliospheric Physics from neutron monitor data and beyond

11-year sunspot cycle

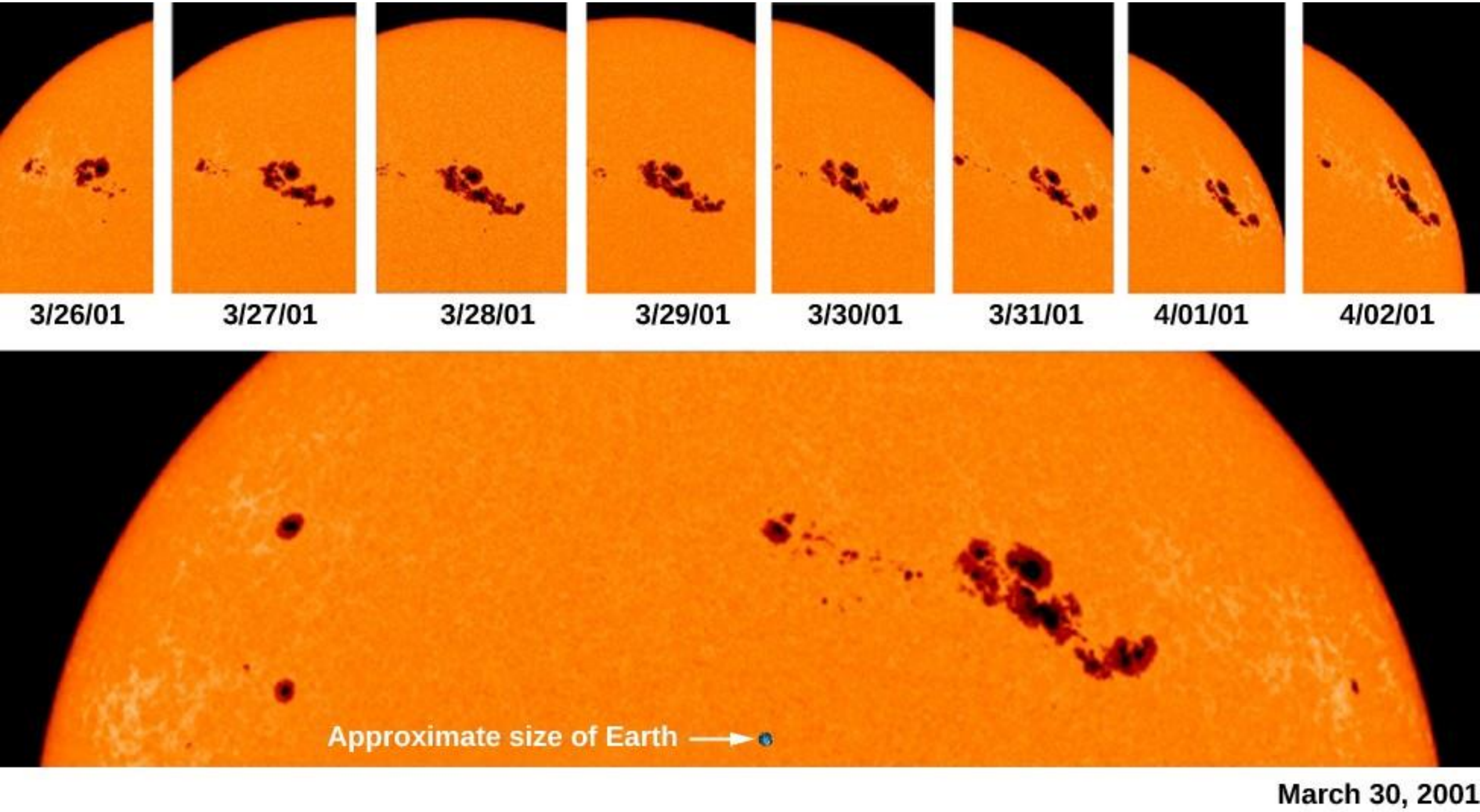




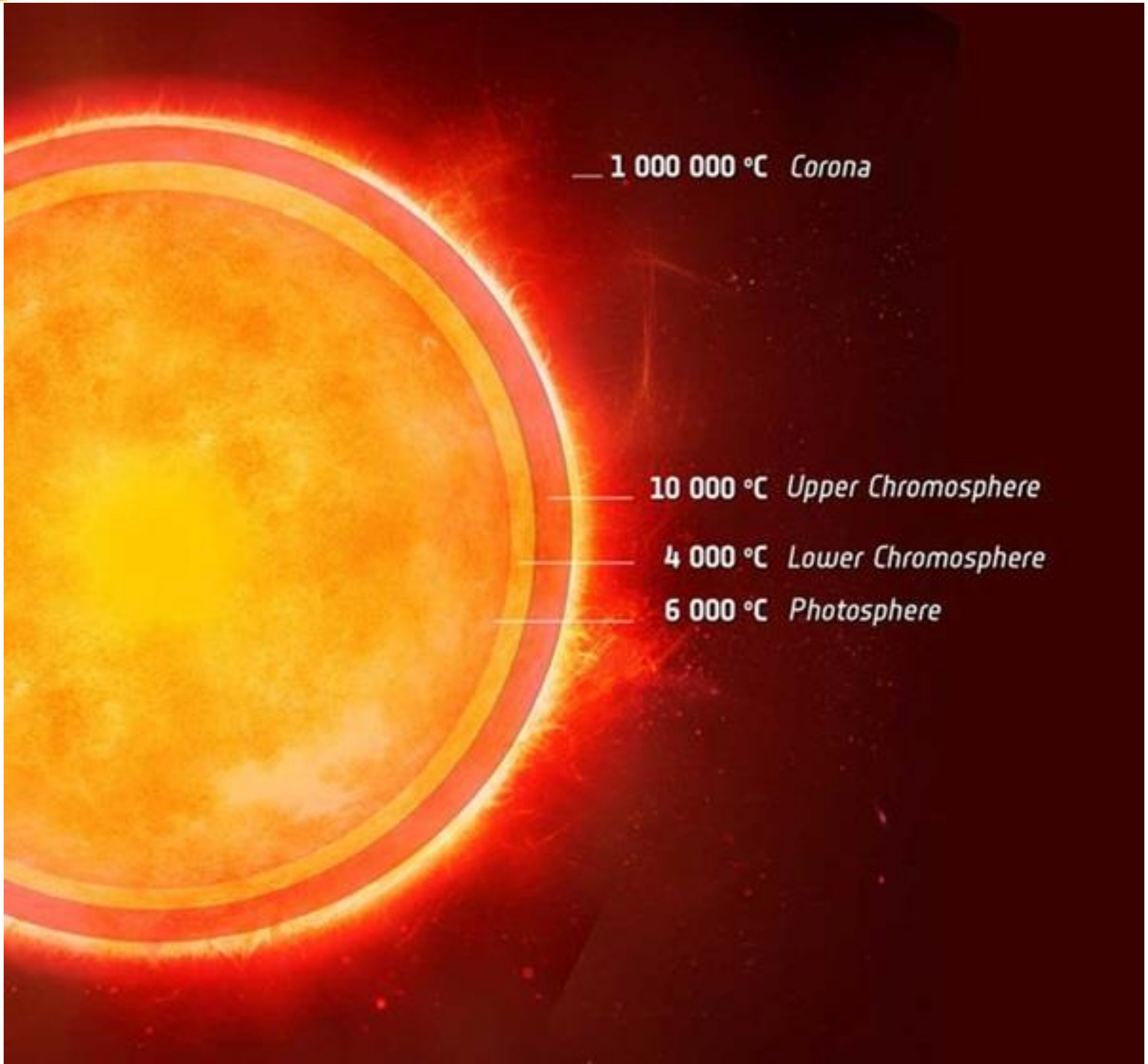
Solar maximum – sunspot number peaks
Solar minimum – almost no sunspots



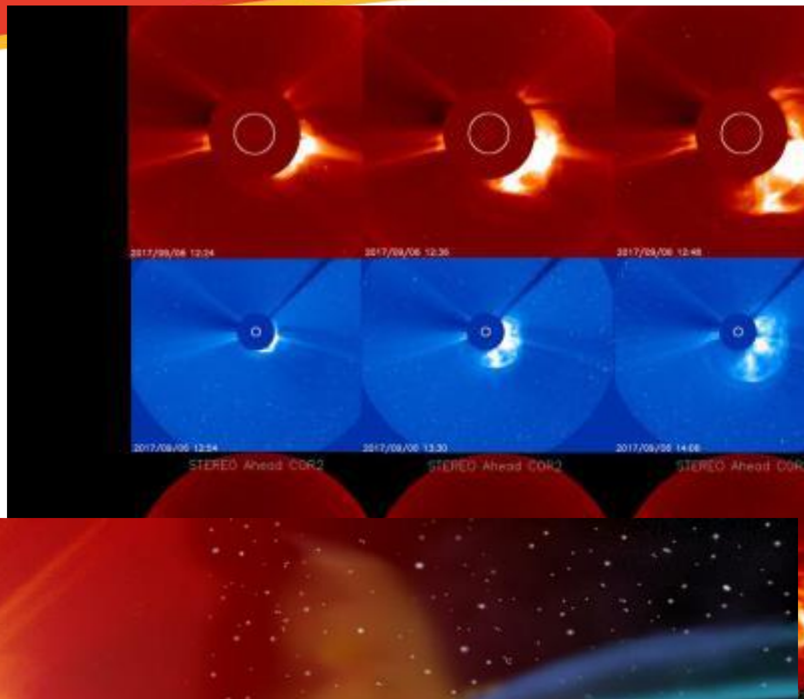
Evidence of 27-day rotation

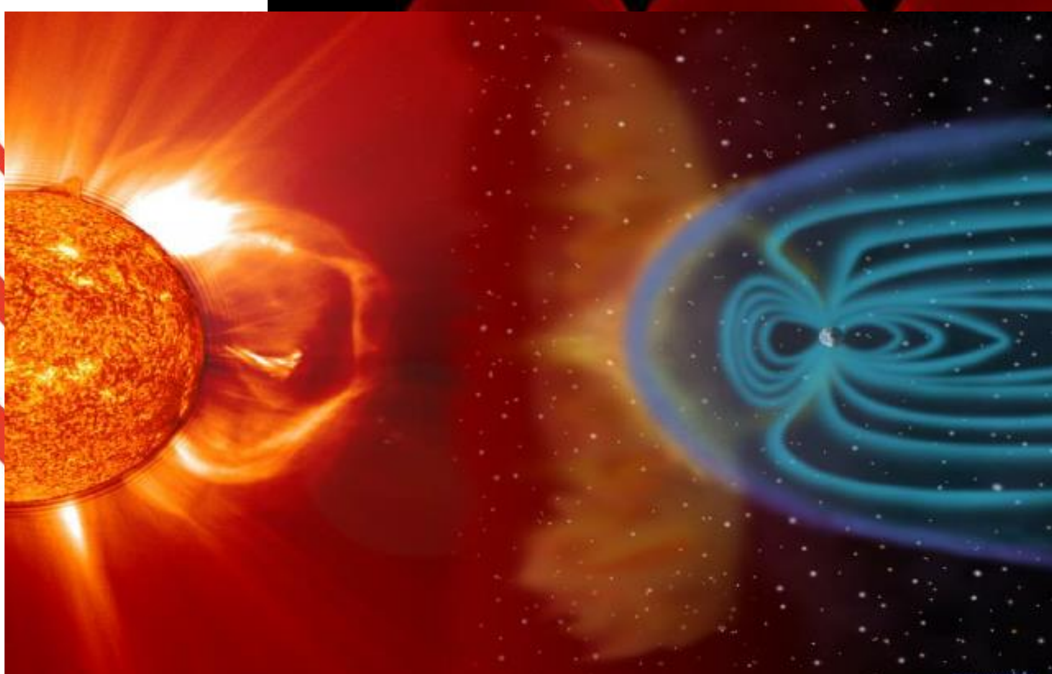


The Sun’s outer layers

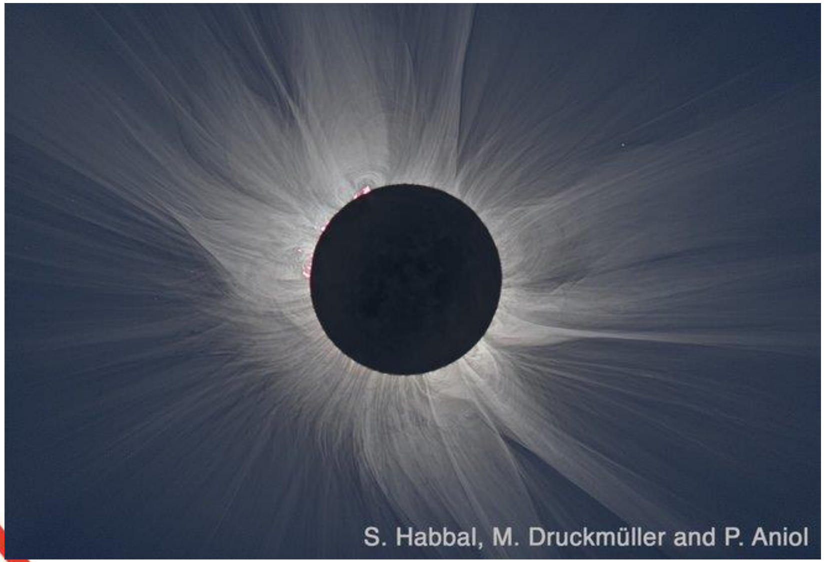


Coronal Mass Ejections (CMEs)





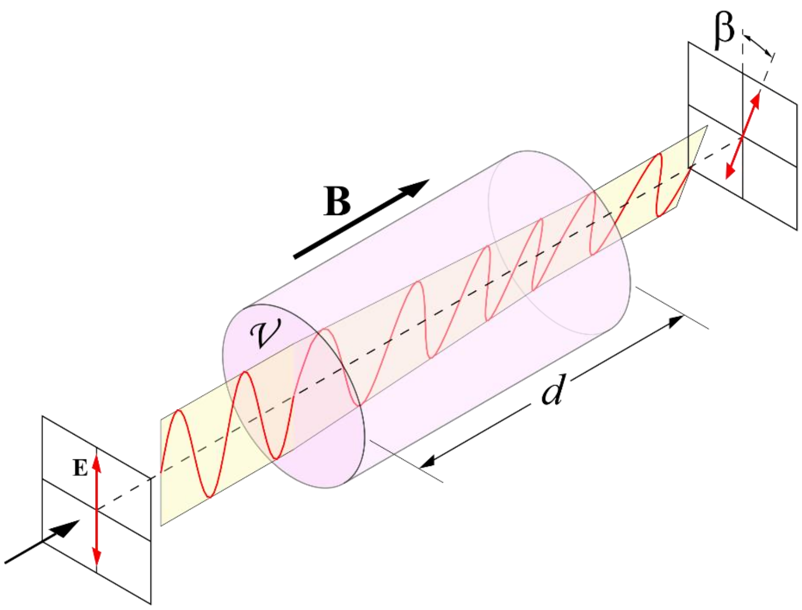
The Solar Wind



- Outflow of hot plasma at "supersonic" speed
- "supersonic": faster than propagation small amplitude of ion-acoustic waves propagating in plasma
- About 400 km/s on average around solar minimum

Faraday rotation

- A magneto-optical interaction:
  - rotation of plane of polarisation proportional to component of B-field in direction of propagation
- Can be used to determine B-field polarity from polarisation state of light propagation parallel to field lines



Salient Properties of Plasmas

- Plasma is the 4^{th} state of matter, i.e, a quasi-neutral ionised gas with collective behaviour
- Can be modelled as a two interpenetrating fluids: an ion-fluid and an electron-fluid.
- Property: due to extreme mobility of the electron fluid, a high quality plasma is a superconductor.
- If a B-field is present in a plasma, relative motion will induce extreme currents in the plasma and nature will, of course, preclude that with the consequence that B-fields can be “frozen” into a plasma with very little relative motion.
- *Thus, if a plasma is flowing, it will “drag” magnetic field lines with it.*
- All sorts of waves can propagation through plasmas: electron-, ion acoustic-, electromagnetic-, magnetosonic-, hydromagnetic waves (a.k.a. Alfvèn waves), etc

Electromagnetic waves propagating through plasmas

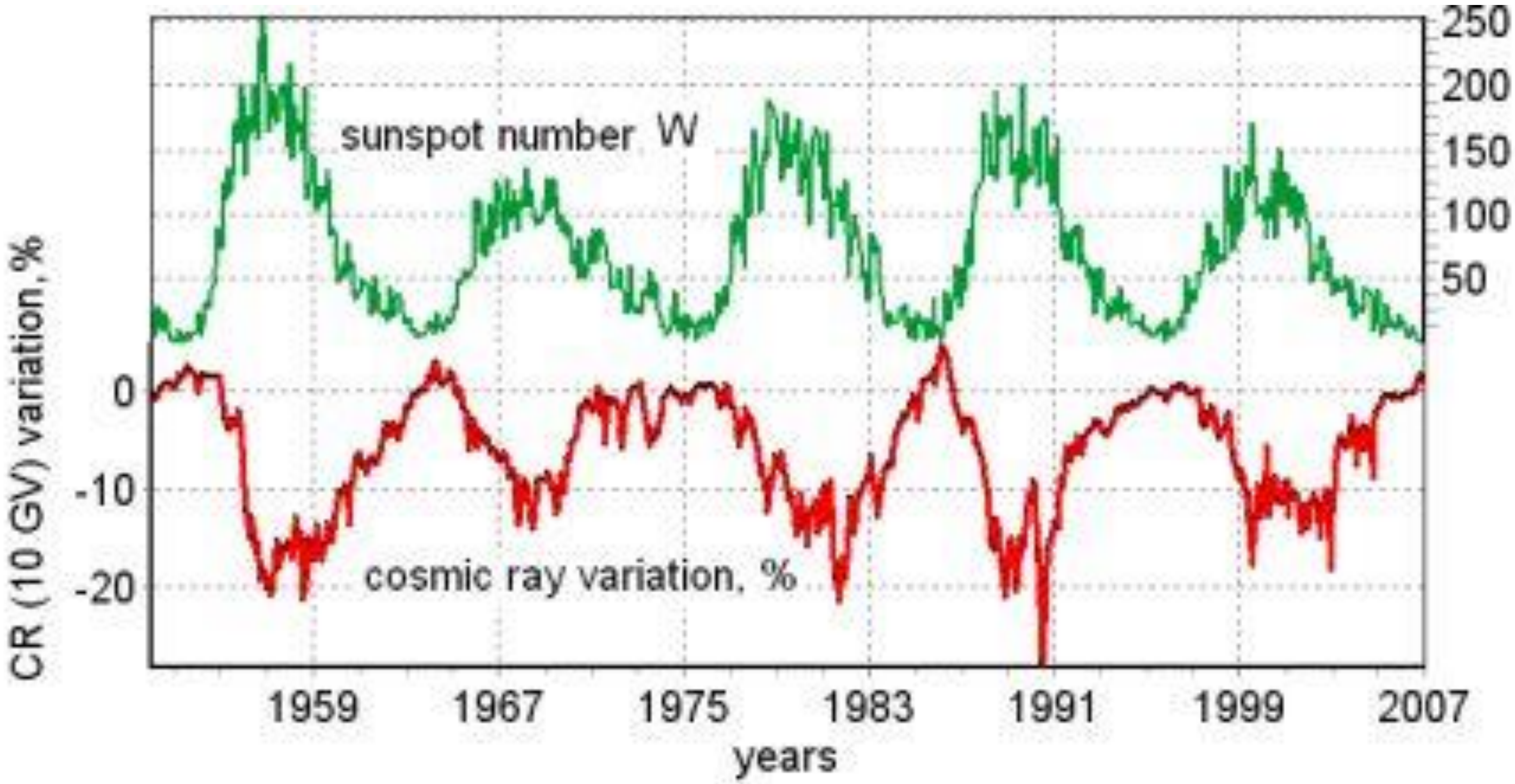
- $\vec{k} \perp \vec{B}_0, \vec{E}_1 \parallel \vec{B}_0$ **(O-wave)**
  - with dispersion relation:
    $$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$$
- $\vec{k} \perp \vec{B}_0, \vec{E}_1 \perp \vec{B}_0$ **(X-wave)**
  - with dispersion relation:
    $$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2}$$
- $\vec{k} \parallel \vec{B}_0$(**R-wave**, *right circ. pol.*)
  - with dispersion relation:
    $$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 - (\omega_c/\omega)}$$
- $\vec{k} \parallel \vec{B}_0$(**L-wave**, *left circ. pol.*)
  - with dispersion relation:
    $$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 + (\omega_c/\omega)}$$

with

k =propagation number, ω =wave frequency, c =speed of light,
$\omega_c = \frac{eB}{m}$ =the electron cyclotron frequency,
$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m}}$ =the plasma frequency,
$\omega_h^2 = \omega_p^2 + \omega_c^2$ =the upper hybrid frequency,
n_e =the electron number density, e =the elementary charge, m =the electron mass and ϵ_0 =the permittivity of free space.

The R & L waves and Faraday rotation gives ability to measure polarity of solar B-field

Clues:



1. Anti-correlation of cosmic-ray and sunspot cycle
2. Cosmic-ray variation has “sharpish” peak followed by “bluntish” peak
3. 11-year sunspot cycle with suggestion of 22-year sunspot cycle

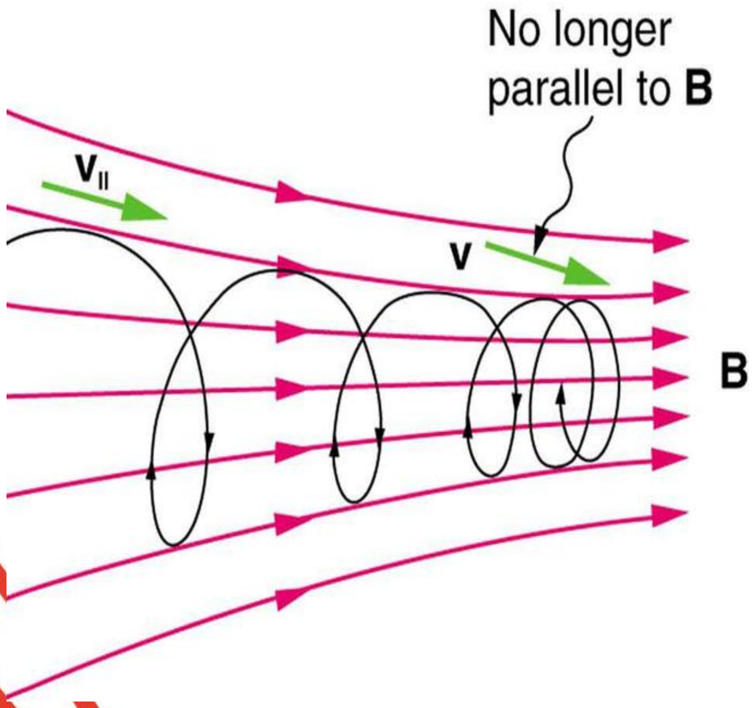
Conclusions from Clues

- What neutron monitors measure are actually energetic CR of Galactic origin and not of Solar origin.
- Modulation by solar wind:
  - At solar maximum, solar wind is stronger and more variable and it opposes Galactic CR from coming close to the Sun
  - At solar minimum the weaker and more even solar wind allows more Galactic CR to be measured
- There are two different types of solar minima
- Forbush decreases occur in correlation with CMEs that temporary reduce Galactic CR by effectively “blowing” some away.
- Polarisation observations of Sun reveal chaotic polarity at solar maximum and opposite polarity states between 2 consecutive solar minima, i.e., at every solar maximum there is a complete magnetic reversal!
    - PHYSICISTS NEEDED EXPLANATION(S):
      - What is the physical system like?
      - A mathematical model is needed.

Magnetic Mirroring and Scattering Centres

Ability of a magnetic field with a gradient in field strength to mirror charged particles

How it works



- $\vec{\nabla} \cdot \vec{B} = 0$ can be integrated to obtain radial component, B_r, that can be used to compute the force parallel to the B-field, $\vec{F}_{\parallel} = -\mu \vec{\nabla}_{\parallel} B$, with $\mu = \frac{1}{2}\frac{mv_{\perp}^2}{B}$ the *invariant* magnetic moment. To keep μ invariant as B increases, we have to have that $v_{\perp}$ must also increase. To keep the total energy of the particle, $E = \frac{1}{2}m\left(v_{\parallel}^2 + v_{\perp}^2\right)$, constant, $v_{\parallel}$ must decrease. If B becomes strong enough, $v_{\parallel}$ will eventually become 0 and change direction.
- "Kinks" in magnetic field lines can change a gyrating particle's pitch angle and it will undergo pitch-angle scattering if the scale length of the "kink" is of the same order as the particle's gyro-radius. These "kinks" are magnetic scattering centres.

The IMF and the Heliospere

The Interplanetary Magnetic Field and the structure of the Heliosphere

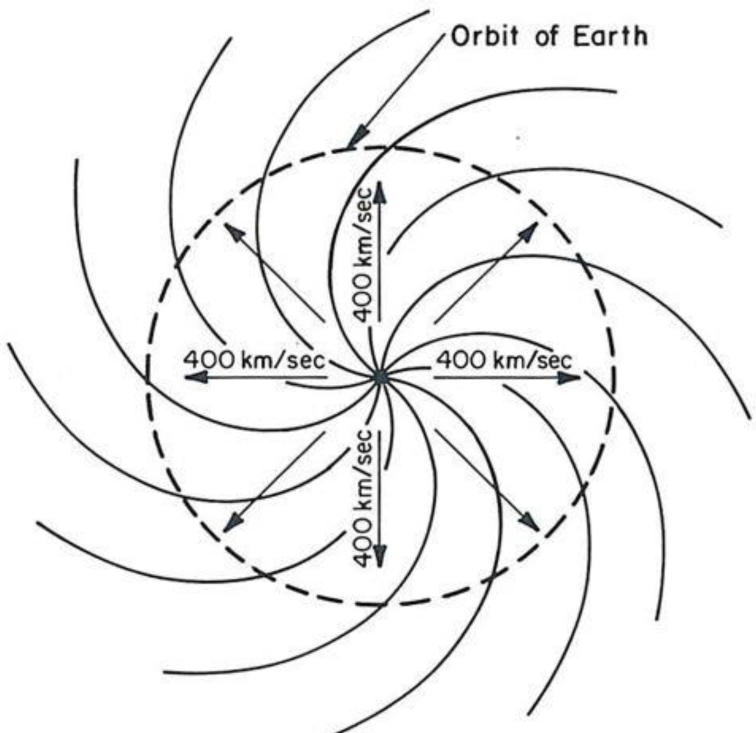
The Parker Spiral Field

(named after Eugene N. Parker)

- Supersonic SW, IMF, TPE

The Parker Spiral Field

- The solar magnetic field is frozen in to the radial outflowing solar wind. Thus, due to the Sun's rotation, the magnetic field lines adopt an Archimedean spiral configuration.
- The angle to the radial direction of the magnetic field depends on distance, latitude and the local solar wind velocity.



Parker (1963)

	ψ(°)	B(nT)
Mercury	21	35
Earth	45	7
Mars	56	4
Jupiter	80	1
Neptune	88	0.2

$\psi =$ "garden hose angle" (angle between field and radial direction)

Parker Spiral Field (math)

$$\vec{B} = B_e \left(\frac{r_e}{r}\right) \cos\psi_e (\hat{r} - \tan\psi \hat{\phi})$$

with magnitude

$$B = B_e \left(\frac{r_e}{r}\right) \frac{\cos\psi_e}{\cos\psi},$$

and garden hose angle

$$\tan\psi = \frac{\Omega r \sin\theta}{V}$$

where V is the radial solar wind velocity, $r_e = 1$ AU the position of the Earth, $\psi_e = 45°$ the garden hose angle at the Earth, $B_e = 7$ nT the field strength at the Earth and (r, θ, ϕ) the relevant polar coordinates.

The Neutral Sheet a.k.a. Current Sheet

- Consider dipole field being dragged out by solar wind.
- In solar equatorial regions, there will be field lines that are of differing polarity a very short distance apart.
- This means that the solar wind dragging the field lines out will create a thin "sheet" where there exist practically a discontinuous swap of polarity known as the "neutral sheet" or "current sheet"
- Using the Heaviside function, H, the Parker field can now be written as

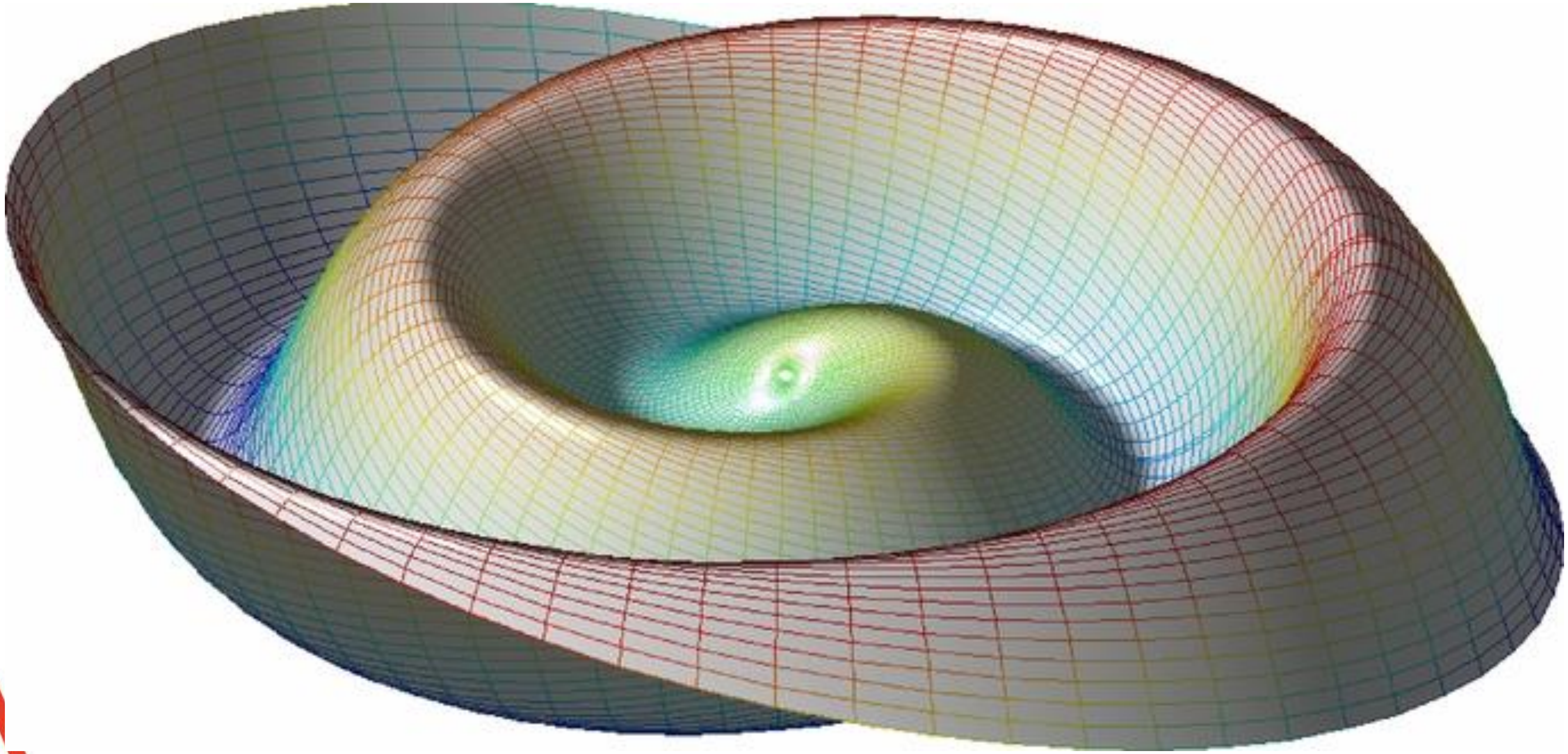
$$\vec{B} = B_e \left(\frac{r_e}{r}\right) \cos\psi_e (\hat{r} - \tan\psi \hat{\phi}) \left[1 - 2H(\theta - \theta_{ns})\right]$$

with $\theta_{ns} = \frac{\pi}{2} + \sin^{-1}\left[\sin\alpha \sin\left(\phi - \phi_{\odot} + \frac{\Omega r}{V}\right)\right]$

and $\phi_{\odot}$ an arbitrary phase constant.

The Wavy Neutral Sheet

If the magnetic equator is at an angle with the rotational equator, the neutral sheet will be take the shape as shown



Particle drifts in the IMF

- Charged cosmic rays moving into the heliosphere will undergo guiding centre drifts due to gradients in the magnetic field strength as well as curvature of the field lines:

$$\vec{v}_R + \vec{v}_{\nabla\|\vec{B}\|} = \frac{m}{q}\frac{\vec{R}_c \times \vec{B}}{R_c^2 B^2}\left(v_\|^2 + \frac{1}{2}v_\perp^2\right)$$

with R_c the radius of curvature.

- In addition, due to swapping gyro-directions across the neutral sheet, depending on the polarity configuration, cosmic rays will either drift into the heliosphere or out of the heliosphere.
- These drifts account for the 22-year cycle in the monitor data.

How to create a mathematical model?

- The magnetic scattering centres cause pitch-angle scattering of CR along field lines with much lower probability of cross-field migration. This is not unlike the process of diffusion.
- The solar wind dragging the field lines with its scattering centres provides not only a mechanism for a tendency of convection/advection of CR, but also provides and energy loss mechanism for CR due to adiabatic cooling.
- Thus, an energy dependent convection-diffusion model can be derived

    (my next lecture)

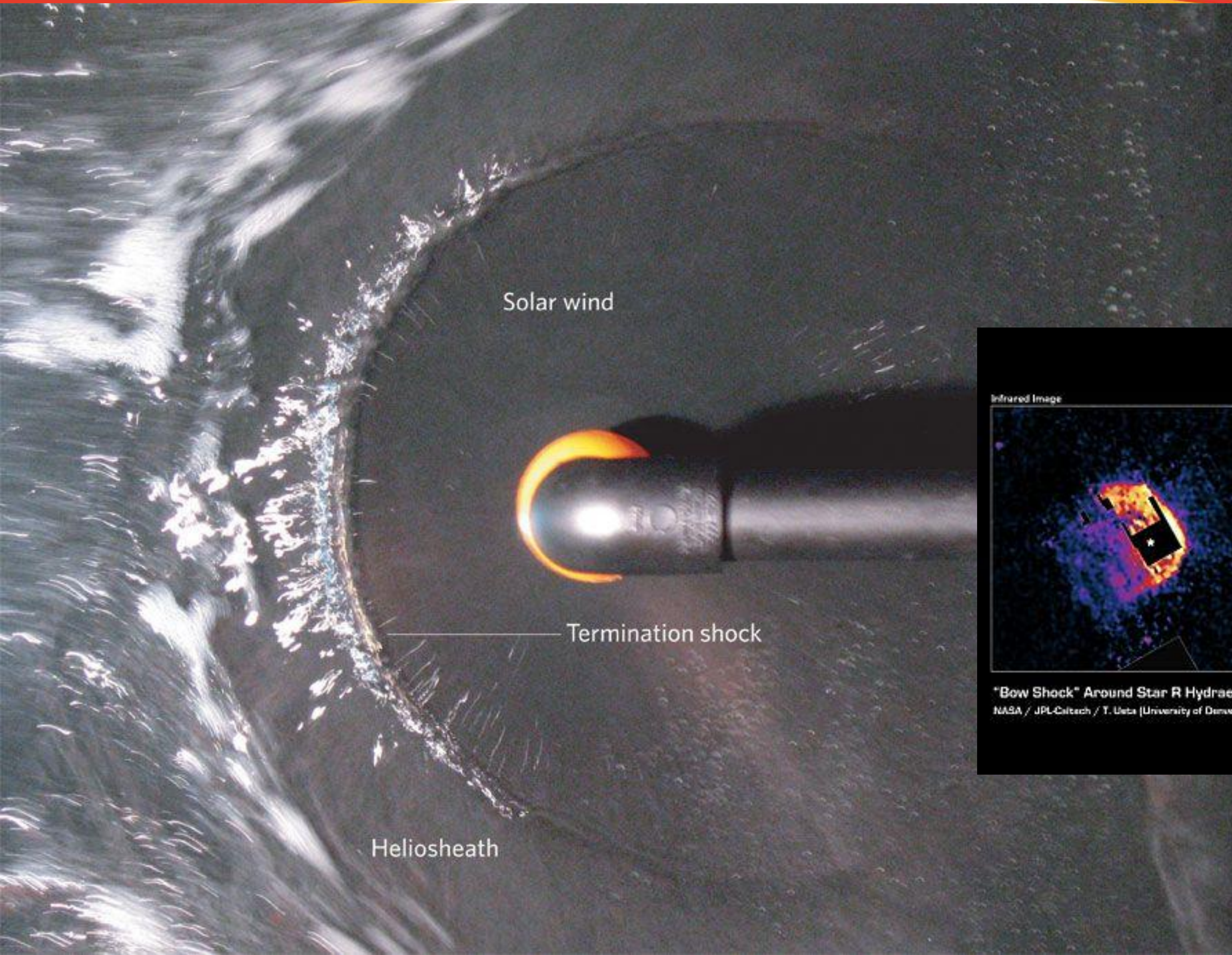
The SWTS and Outer Heliosphere

The Solar Wind Termination Shock, Heliopause, Heliosheath and Bow Shock

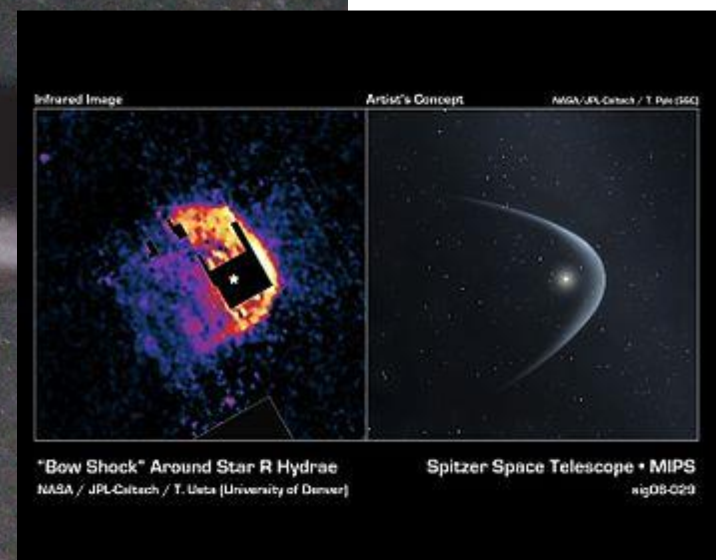
The SWTS and Heliosheath

- At solar minima the smooth outflow of supersonic solar wind plasma causes the formation of a stationary hydrodynamic shock.
- From any treatise of fluids it follows that the only way for a supersonic flow to become subsonic is through a discontinuous transition, or rather, a shock. A plasma that sometimes behaves like a magnetised fluid is no different.
- In addition the flow of interstellar gas and plasma hitting the solar wind outflow and diverting it around our heliosphere causes a “sheath” and bow shock to form around the entire solar system, not unlike a bow shock of a boat.

Analogue:



Experimental Evidence



To be continued…

Thank You