Space-based Observations of Gradual SEP Events

Astronomy and Astrophysics Group

Daniel Keerie

Gradual SEP Events

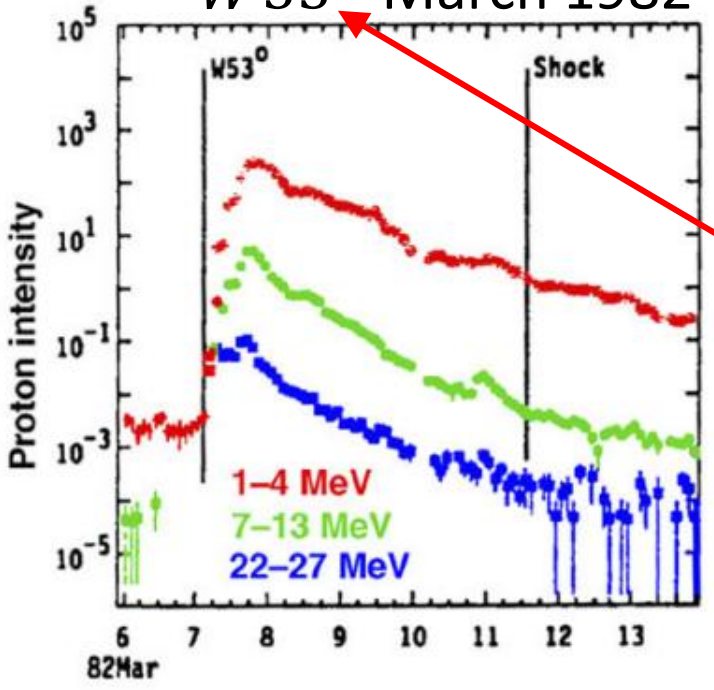
- **Solar energetic particle (SEP) events** arise due to solar magnetic activity.
- Events are broadly categorised as either **gradual** or **impulsive**.
- Gradual events occur when **shock waves** are produced by **fast coronal mass ejections (CMEs)** moving faster than the local Alfvén speed:

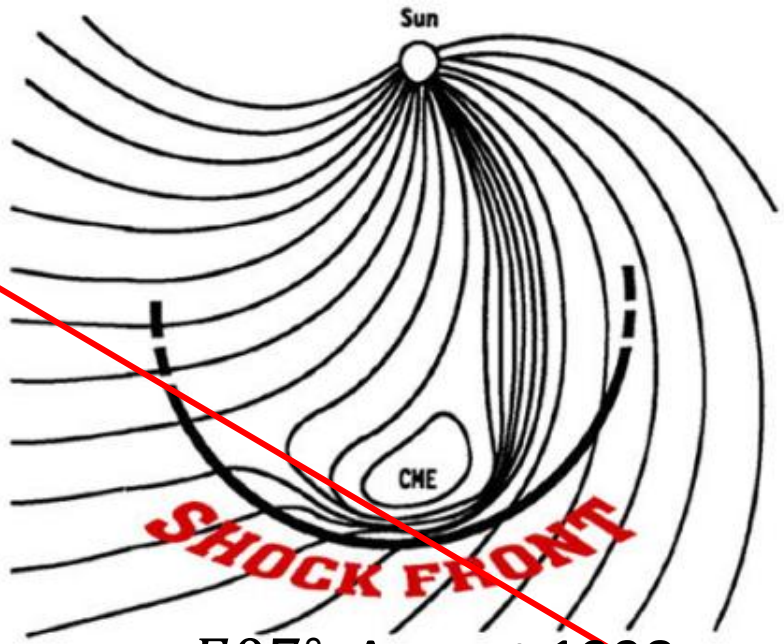
$$v_A = \frac{B}{\sqrt{\mu_0 \rho}}$$

Speed at which magnetic waves propagate through a plasma

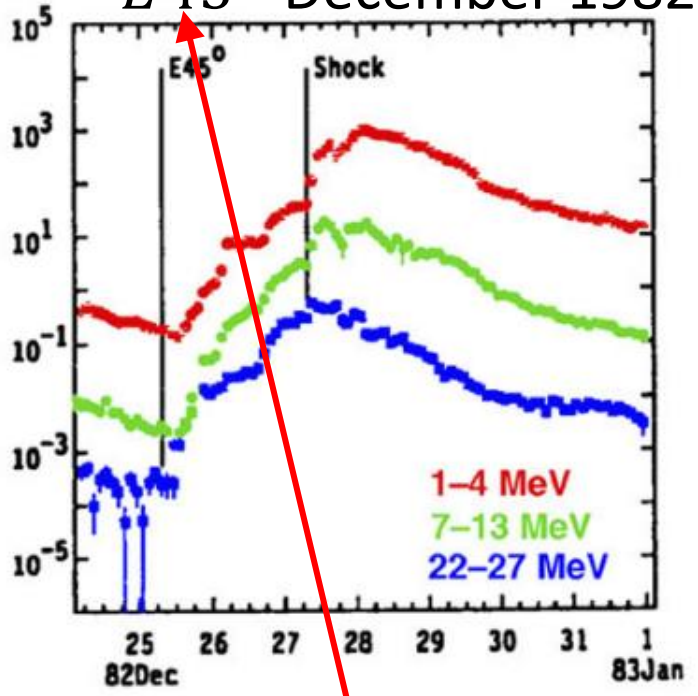
- These shock waves scatter protons, electrons and heavy ions, increasing **particle velocities** and **intensities**.
- Typical characteristics of particles in gradual SEP events include:
  - **Energies** of a few keV up to MeV dependent on CME velocity
  - **Intensities** following a power-law distribution in energy
- Gradual events produce **high particle intensities** and cause the vast majority of **space-weather effects**.

$W53°$ March 1982

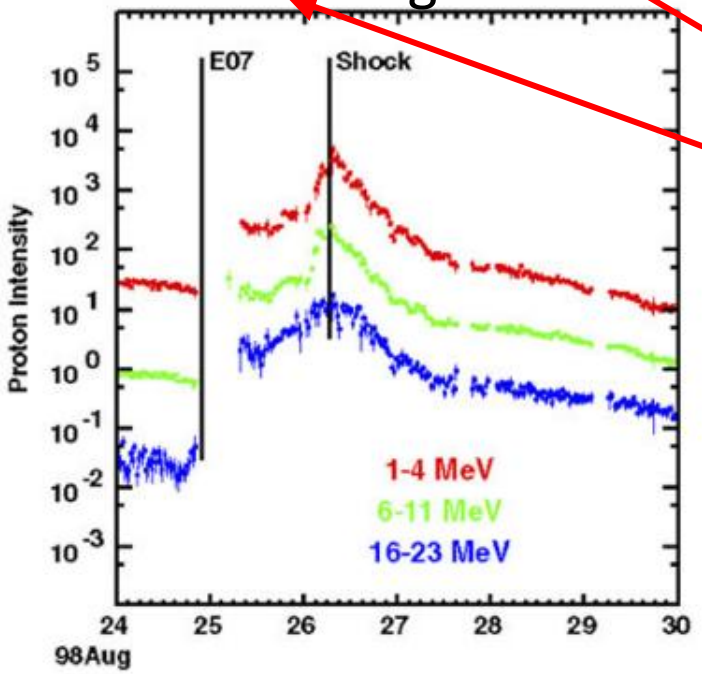




$E45°$ December 1982



$E07°$ August 1998



Typical gradual event proton intensity profiles obtained from analyses of over 200 events (Desai & Giacalone 2016, Reames 1999).

Intensity profiles vary depending on observer solar longitude.

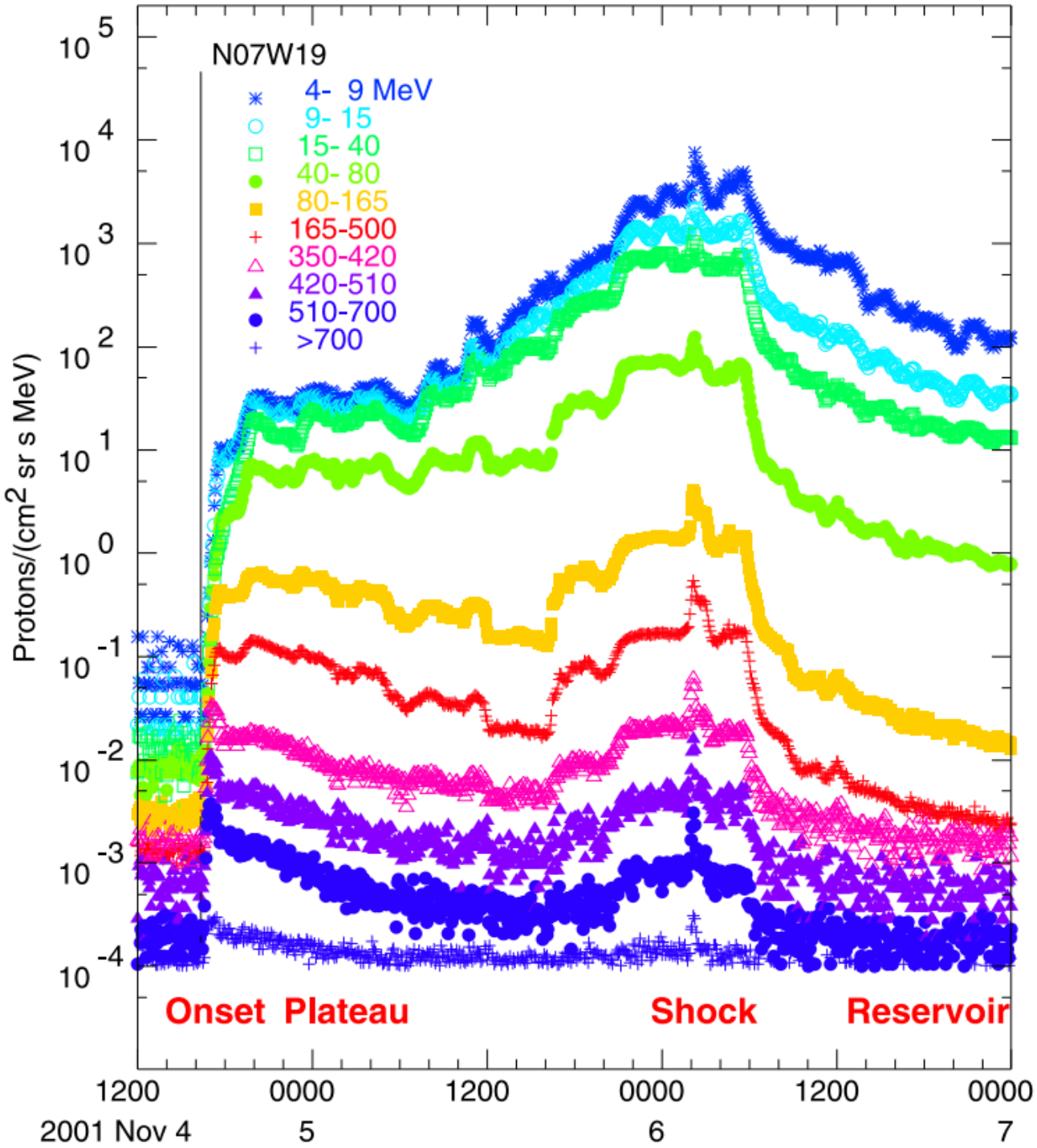
Space-based Observations

- Proton **intensities** and **energies** are commonly measured.
- Protons are **more abundant** than electrons in gradual events because the effectiveness of **diffusive shock acceleration** is proportional to the particle's **gyroradius**:

$$r_g = \frac{mv_\perp}{qB}$$

- **Type II radio bursts** emitted by shock accelerated electrons can also be observed.
- Measurements are performed at a **variety of distances** e.g. NOAA GOES at $1\ AU$ & Parker Solar Probe nearest approach distance of $0.049\ AU$ on 30/9/24 (NASA PSP).
- **Earth's magnetic field** prevents Earth-based observations of the majority of SEP events. However, the most energetic gradual events can cause **ground level enhancements (GLE)** which can be observed on Earth.

Data obtained by the NOAA GOES network from a large gradual SEP event on November 4th 2001 (Reames 2013).

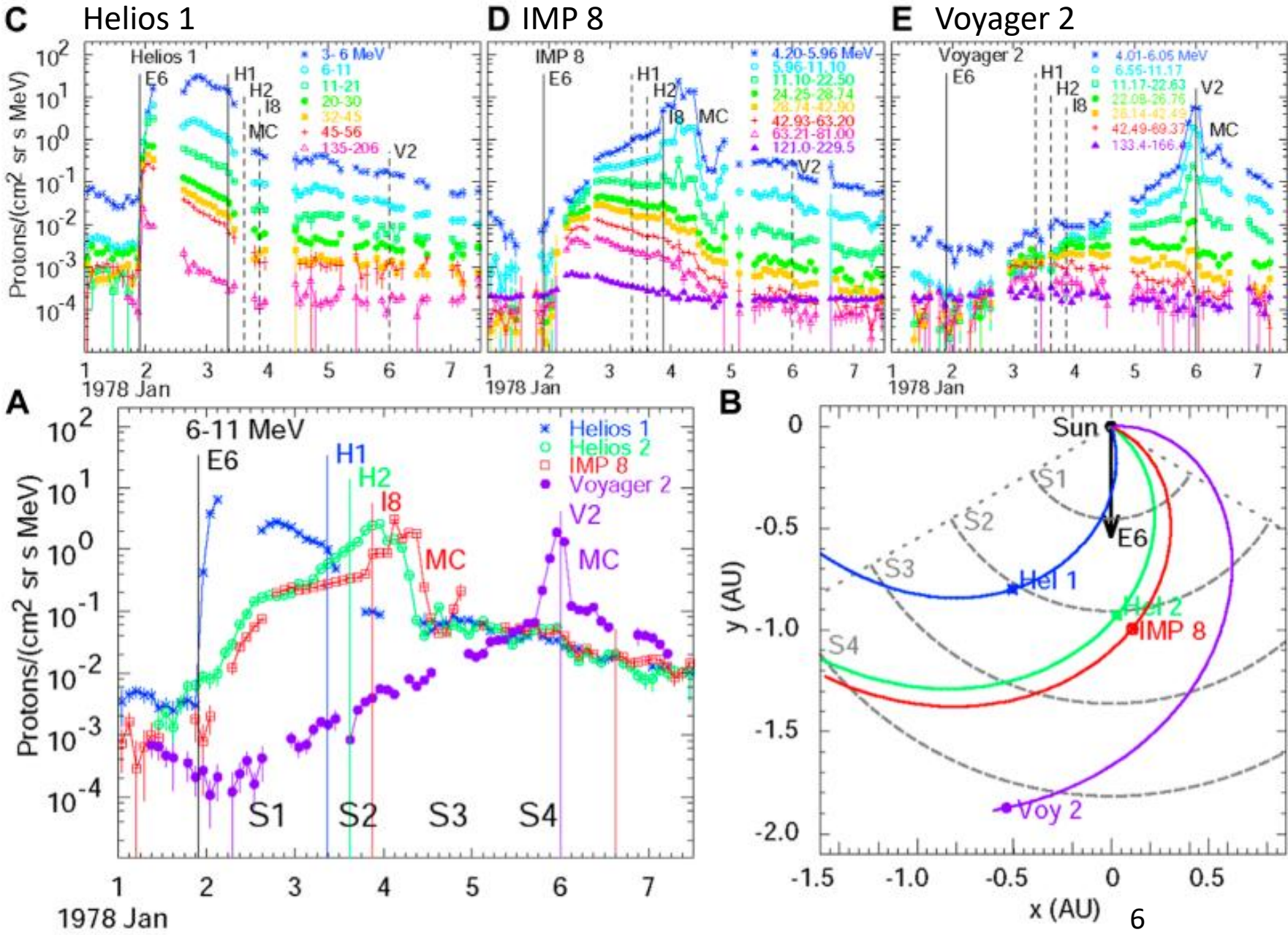


Plot demonstrates the **power law distribution** in proton energies and displays the **gradual decay** phase (reservoir) characteristic of gradual events.

Multi-spacecraft Observations

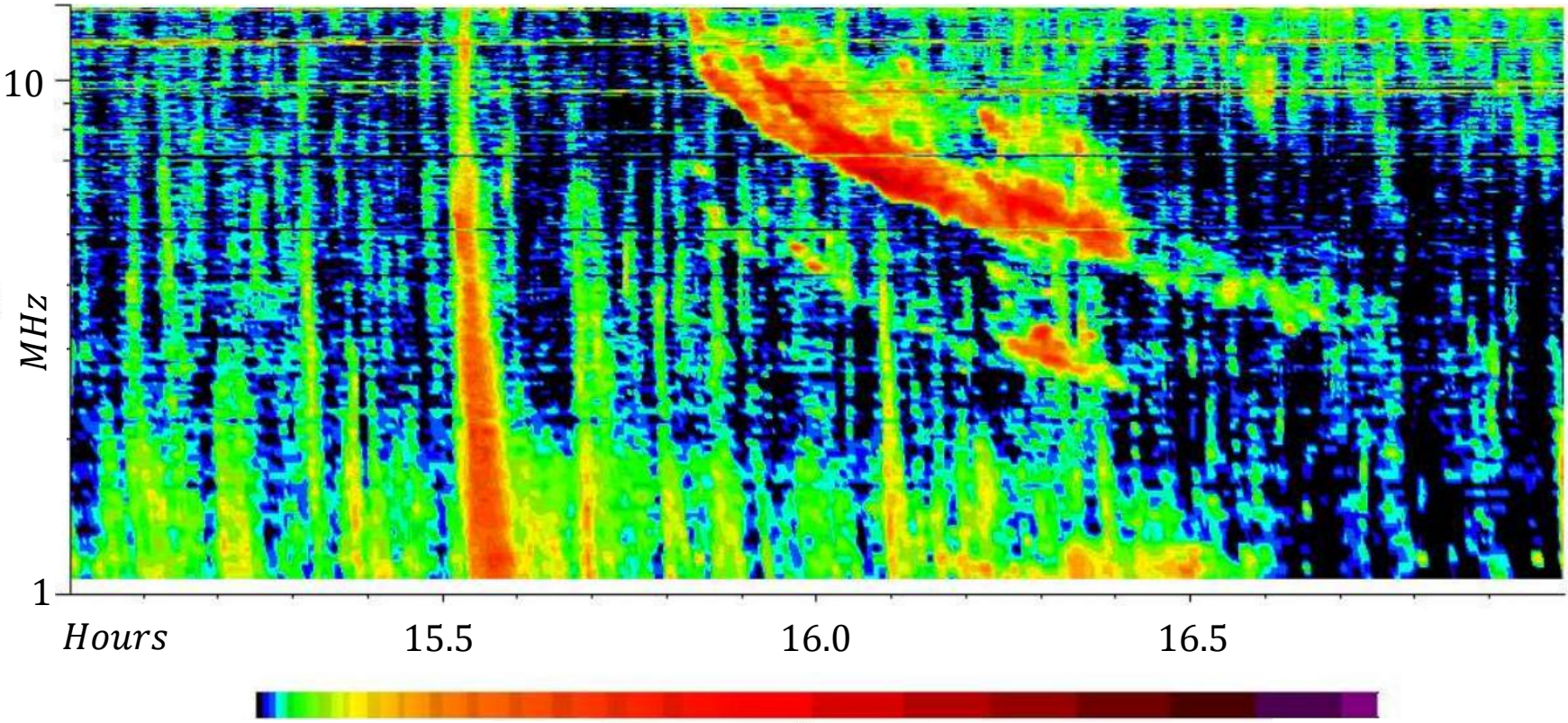
(Reames 2023)

- Using multi-craft observations allows comparison between **different locations** while **increasing the frequency** with which gradual SEP events can be observed.
- Multi-spacecraft observations can determine the **shock nose longitude** and therefore the position of the **highest particle intensities**.
- Proton intensity data measured by four craft during a gradual event on January 1st 1978:



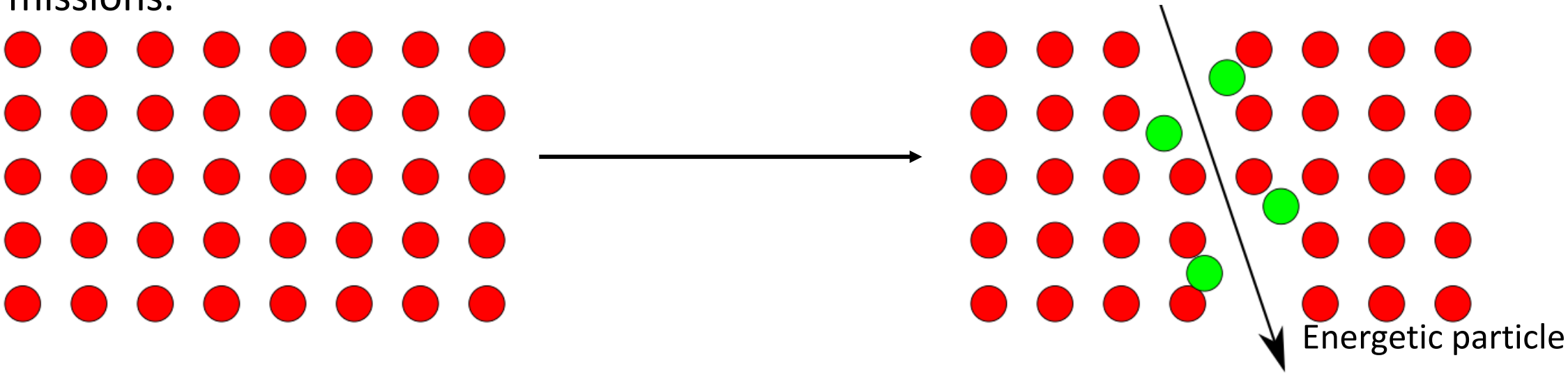
Application of Measurements

- Gradual event properties can be inferred from **proton intensity-time profiles** and compared with **acceleration** and **CME shock formation models**.
- Type II radio burst **frequency** is proportional to the **square root of plasma electron density** and the **shock speed** can be derived from the **frequency drift** $\left({}^{df}/_{dt}\right)$ if we know the plasma **density scale height**.
- Dynamic spectra displaying type II (right) and type III (left) radio bursts. Observation made by the Wind/WAVES RAD 2 receiver on 16/8/2006. Figure adapted from Reid 2011 (Wind).



Challenges in Space-based Observation

- The largest CMEs can span up to 200° in solar longitude thus observing from **one location** confuses **spatial** and **temporal behaviour**. **Multi-craft observations** increase **resolution.**
- **Scattering during transport** alters particle properties.
- High energy SEPs can **damage equipment** and **disrupt communication**.
- **Large temperatures** pose a problem for spacecraft design, especially for near-Sun missions.



Displaced atoms shown in lime green. Figure adapted from Ladbury, R. 2018, 'Radiation Effects: Overview for Space Environment Specialists'.

References

- Apodaca, D. 2024, Parker Solar Probe Completes 21st Close Approach to the Sun, Available at: https://blogs.nasa.gov/parkersolarprobe/2024/10/03/parker-solar-probe-completes-21st-close-approach-to-the-sun/, Accessed: 23/11/2024
- Cliver, E. W. 2008, Proceedings of the International Astronomical Union, 4, 401, doi: 10.1017/S1743921309029639
- Desai, M., & Giacalone, J. 2016, Living Reviews in Solar Physics, 13, 3, doi: 10.1007/s41116-016-0002-5
- Fleetwood, D. M., Winokur, P. S., & Dodd, P. E. 2000, Microelectronics Reliability, 40, 17, doi: 10.1016/S0026-2714(99)00225-5
- Gopalswamy, N. 2011, in Planetary, Solar and Heliospheric Radio Emissions (PRE VII), ed. H. O.Rucker, W. S. Kurth, P. Louarn, & G. Fischer, 325–342 https://ui.adsabs.harvard.edu/abs/2011pre7.conf..325G/abstract
- Kim, K.-H., Kim, G.-J., & Kwon, H.-J. 2018, Earth, Planets and Space, 70, 174, doi: 10.1186/s40623-018-0947-9
- Ladbury, R. 2017, 'Radiation Environment Effects on Spacecraft', https://ntrs.nasa.gov/api/citations/20170010725/downloads/20170010725.pdf, Accessed: 23/11/2024
- Ladbury, R. 2018, 'Radiation Effects: Overview for Space Environment Specialists', https://ntrs.nasa.gov/api/citations/20170012338/downloads/20170012338.pdf, Accessed: 23/11/2024
- Reames, D. V. 1999, Space Science Reviews, 90, 413, doi: 10.1023/A:1005105831781
- Reames, D. V. 2013, Space Science Reviews, 175, 53, doi: 10.1007/s11214-013-9958-9
- Reames, D. V. 2022, Space Science Reviews, 218, 48, doi: 10.1007/s11214-022-00917-z
- Reames, D. V. 2023, Frontiers in Astronomy and Space Sciences, 10, doi: 10.3389/fspas.2023.1254266
- Reid, H. A. S. 2011, PhD, University of Glasgow. https://theses.gla.ac.uk/2370/

In Summary

- Gradual SEP events:
  - Caused by solar magnetic activity
  - Fast CMEs cause shock waves in the interplanetary plasma
  - Particle energies and intensities are enhanced. Source of majority of space-weather
- Observations of type II radio bursts and proton energies and intensities confer properties of gradual events, shaping our understanding
- Multi-craft observations probe the large-scale structure of the CME shock
- Challenges in space-based observations:
  - Large spatial extent of CMEs
  - Distinguishing between acceleration mechanisms and scattering effects
  - Damage to instruments caused by high SEP intensities