Solar energetic particles and coronal interplanetary radio bursts

Nat Gopalswamy
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA

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Energy release on the Sun
Solar eruptions
Noise storms
SEPs (ions, electrons)
In situ detection of particles
Inferred from electromagnetic emission

Electrons KeV to 100s of MeV, protons of keV to tens of GeV from the Sun
Coronal thermal particles have an energy of ~175 eV

impulsive SEP events associated with jets
Jets are similar to CMEs, except open field line are involved
Confined Flare: No mass motion

- Microwave burst, X-rays $\rightarrow$ nonthermal electrons propagating toward the Sun
- No metric radio bursts $\rightarrow$ no electrons away from the Sun
- No Interplanetary radio emission
- No SEP event
Eruptive Flare: CME involved

- Radio bursts $\rightarrow$ nonthermal electrons propagating away from the Sun
- X-ray emission $\rightarrow$ electrons propagating toward the Sun
- Interplanetary type II
- Large SEP event
Interplanetary Shock and Radio Burst

CME & IP radio bursts
- SGRE ends when Type II ends
- CME at ~65 Rs when type II & SGRE end
- Large distances also indicated by the ending frequency of type II (~200 kHz)
- Copious >100 MeV particles from STEREO-B

>100 MeV protons

Gopalswamy+ 2018

Ajello+ 2021
Type II burst, SEP Event, and SGRE Events linked by CME-driven shocks

Gopalswamy et al. 2018; 2021
We suggest that energetic protons are accelerated in the shock front just ahead of the expanding loop structures observed as mass ejections.

Kahler, Hildner, & Van Hollebeke (1978)

Skylab CME on January 15, 1974

Studied 16 Skylab CMEs; 14 had SEP events
Found correlation between CME speed and SEP intensity

“...We suggest that energetic protons are accelerated in the shock front just ahead of the expanding loop structures observed as mass ejections.”

Kahler, Hildner, & Van Hollebeke (1978)

Rao et al. 1967 for ESPs; Cliver et al. 1982 for GLEs; Cane et al. 1988; Reames 1990
The images illustrate solar phenomena observed during the period of 2000/11/08.

1. **GOES X-Rays**
   - The X-ray spectrum is shown with a time series from 22:00 to 02:00 on 2000/11/08.
   - The graph plots intensity against time, with different X-ray energy bands indicated.

2. **Type II and Type III Solar Emissions**
   - The emissions are evident in the solar images.
   - Type II emissions are associated with shock waves, while Type III emissions are related to electron acceleration.

3. **WIND/WAVES Observations**
   - The spectral analysis of the emissions is displayed with a color-coded intensity scale.
   - Peaks are marked for Type II and Type III emissions.

4. **Additional Images**
   - Two additional images show the solar surface, highlighting the regions of emissions.

These observations are crucial for understanding solar activity and its impact on space weather.
SEP Intensity, Energy Range, Spectrum

Intensity

Fluence Spectrum

2005/01/20: $\gamma = 2.13$
2006/12/13: $\gamma = 2.07$
2001/04/12: $\gamma = 2.66$
2004/04/11: $\gamma = 4.50$

Spectrum
Particles hit the airplane material and produce secondaries, which affect crew and passengers in polar route.

GOES provides Proton flux for >1 MeV to >100 MeV.
Hard Spectrum Events are more hazardous

CME Kinematics determines the spectral shape

Gopalswamy et al. 2016
Double Whammy: Geomagnetic Storms & SEPs

Some times eruptions occur in quick succession maintaining elevated level of particle radiation Gopalswamy et al. 2005

Transformer oil heated by 10° in Sweden; 50,000 people in Malmo had power blackout

Two halo CMEs: 10/28 and 10/29 2003
The MARIE Slayer: 2003 Oct 28 Halloween Storm

Oct 26 - 29, 2003

Safe mode

2003/10/28
11:12 UT

0.1
1
10
100
1000

Day of Year 2003

Zeitlin+2010

10/26 SEP

A1

A2

2003/10/28

HEND SCIH
GRS ULD
MARIE A1
MARIE A2
The MARIE instrument on Mars Odyssey observed the radiation levels on the way to Mars and in orbit, so that future mission designers could plan the trips of human explorers to Mars.

One of the October 2003 SEP events rendered MARIE inoperative. It is ironic, as MARIE was designed to measure the radiation environment at Mars.

Radiation Assessment Detector (RAD) on board the Curiosity rover (Mars Science Laboratory) indicates that a 360-day round trip would add a dosage of ~660 mSv. (Zeitlin et al. 2013)

This is ~66% of astronaut’s entire career exposure limit (1000 mSv)
Curiosity provides Radiation info for a Mars Trip

Radiation Assessment Detector on Mars Science Laboratory (RAD/MSL)

RAD mounted on the top deck of Curiosity rover

Data collection:
6 December 2011 to 14 July 2012
1.84 mSv/day due to GCRs
Total: 660 mSv; 5.4% due to SEPs
S/C Anomaly & SEPs

Iucci et al. 2005
Range of Phenomena: 2005 May 13 CME

Source Location
N11E12

Halo CME

Sun

1689 km/s

ESP 100 → 3000 pfu

Type II Burst

SW Shock

in-situ “view” of the CME
SEP Intensity vs. CME Speed

- SEP Intensity correlated with CME speed → strong evidence for acceleration by CME shocks
- Large Scatter
  - Source and Environmental factors
  - Connectivity
  - CME interaction

Kahler 2001

Mewaldt 2008
More on Connectivity: CMEs Associated with Type II Bursts and SEPs

Sources of CMEs associated with type II bursts at f < 14 MHz (Decameter-hectometer and longer wavelengths)

- Type II bursts from the western hemisphere are likely to be associated SEPs due to better magnetic connectivity.
- Type II bursts from the eastern hemisphere are associated with SEPs that do not arrive at Earth (e.g., STEREO B).

Type II bursts and SEPs are due to the same shocks

Gopalswamy et al. 2008 Ann Geo
CMEs producing Large SEP Events

- SEP Events are caused by fast and wide (energetic CMEs)
- Typical energy of these CMEs \( \sim 10^{32} \) erg
- Shock-driving capability of CMEs key for SEPs
Shock Source: coronal mass ejections

Type II burst starts exactly at the time the shock appears in the corona at 1.19 Rs (this is the leading edge method)

We can probe the coronal medium as well as the shock structure by combining type II and EUV/coronagraph observations

\[
\frac{df}{dt} = 0.28 \text{ MHz/s}; \quad \frac{1}{f} \frac{df}{dt} = \frac{(0.28/175)}{s^{-1}}
\]

\[
V = 600 \text{ km/s}; \quad L = 189,000 \text{ km}
\]
Where does the shock form? Or What is the shock/CME height when the type II bursts starts?

CME starts at 5:34 at 1.13 Rs; Type II starts at 5:36 when the CME at 1.17 Rs; shock 1.19 Rs

\[ f_p = 150 \text{ MHz} \Rightarrow n_p = 2.8 \times 10^8 \text{ cm}^{-3} \]

Gopalswamy et al., 2012 ApJ
It Matters Where the Shocks Form

![Graphs and data visualizations related to solar events and particle fluence.]
SEP Intensity, Energy Range, Spectrum

Intensity

Spectrum

Fluence Spectrum

GOES11: 2000/11/08 23:35
8.7-14.5 MeV 84-200 MeV 420-510 MeV
15-40 MeV 110-220 MeV 510-700 MeV
30-82 MeV 220-420 MeV >700 MeV

GOES15: 2013/09/30 00:25
8.7-14.5 MeV 84-200 MeV 420-510 MeV
15-40 MeV 110-200 MeV 510-700 MeV
30-82 MeV 220-420 MeV >700 MeV

2005/01/20: γ = 2.13
2006/12/13: γ = 2.07
2001/04/12: γ = 2.66
2004/04/11: γ = 4.50
Solar Cycle Variation

![Solar Cycle Variation Graph](image-url)
Locations of CMEs that Produced SEP Events

- More SEP events around solar maximum
- GLE events are very rare
- Paucity of high-energy SEP events in cycle-24
Extreme SEP Events

Miyake et al. 2012; Mekhaldi et al. 2015

Usoskin et al. 2013
Summary

• The large SEP events are caused by energetic CME-driven shocks
• Radio bursts are indicative of electron acceleration; also accompanied by ion acceleration (SEPs)
• The SEP spectrum is important in assessing their space weather impact
• Flare reconnection also causes particle acceleration, but the contribution to SEPs in space is unclear
• Most SEP events are produced during solar maximum (when there is high level of magnetic energy available for powering CMEs)
• There are not many high-energy SEP events in cycles 24 and 25 – consequence of a weak heliosphere
Notes

• Atomic mass unit (amu) = 1/12 the mass of 12C
• It is close enough to nucleon masses
• MeV per nucleon in indistinguishable from MeV per amu for SEP studies
• Total energy $W = AM_u \gamma$ ; $M_u = m_u c^2 = 931.494$ MeV
• $\gamma = (1 - \beta^2)^{-1/2}$; $\beta = v/c$
• Kinetic energy $\varepsilon = AM_u (\gamma - 1)$
3He-Rich Events

Flare-accelerated particles at 1 AU

$\text{3He/4He} > 0.1$ (solar wind $5 \times 10^{-4}$)

No CME association with $^3$He-rich events

$^3$He-rich events associated with type III radio bursts produce by flare-accelerated electrons escaping into the IP space

Other heavy ions and the Fe/O-ratio enhanced

Enhancements of other heavy ions and Fe/O uncorrelated with $^3$He/$^4$He
Shock Acceleration


\[
dJ/dE \propto E^{-\gamma}
\]

Simple shock acceleration predicts independence of charge-to-mass ratio (Q/A)

Shock lifetime and size limit the maximum energy of particles

**Diffusive shock acceleration (DSA):**
- Quasi-parallel shock ($\theta_{BN} \leq 45^\circ$)
- Particles scattering between up- and downstream magnetic fluctuations (1st order Fermi acceleration)
- Slower acceleration rate
- Efficient scattering requires enhanced level of turbulence/waves

**Shock drift acceleration (SDA):**
- Quasi-perpendicular shock ($\theta_{BN} \geq 45^\circ$)
- Induced electric field \(E = V \times B\) at shock front
- Fast acceleration rate
- Higher maximum energy

\(\theta_{BN}\) is the angle between the shock normal and the direction of the upstream magnetic field

Decker 1988
Streaming-limited Intensities of SEP Events

- Plateau in lower energies after initial rise
- Tens of MeV protons cause Alfvén waves, which throttle the lower energy particles (protons, He, Fe, O)

Max intensity ~400 H per (cm² s sr) in the energy range 5-20 MeV

Reames & Ing 2010
Overview

• What are solar energetic particle events?
• Coronal mass ejections (CMEs) and SEPs
• Brief History
• Radio bursts and shocks
• Properties of SEP-producing CMEs
• Height of shock formation
• Eruptive and confined flares
• Solar Cycle Variation of SEP events
What are Energetic Particles?

- Speed of 2 MK protons: $129 \text{ km/s} = 4.3 \times 10^{-4} \text{c}$ \hspace{1cm} [V(kT/m)]; $T = 2 \text{ MK}$; $\varepsilon_{th} = 175 \text{eV}$
- Speed of 2 MK electrons: $5547 \text{ km/s} = 0.018 \text{c}$ \hspace{1cm} $c = \text{speed of light}; m= \text{mass}$
- 2 MK corresponds to an energy of 175 eV
- Nonthermal particles are energetic: $V >> V_{th}$ or $\varepsilon >> \varepsilon_{th}$
- Electrons KeV to 100s of MeV, protons of keV to tens of GeV from the Sun (1 GeV protons have a speed of $\sim 0.875c = 260,000 \text{ km/s}$)
- Electrons and ions are detected by particle detectors; electrons are also inferred from their nonthermal radio emission
- Events involving emission of nonthermal particles are known as solar energetic particle (SEP) events. electrons, protons, He, Heavy ions
- Space weather community also uses the term solar proton events (SPEs) to specifically refer to energetic protons
SWx Sources: Solar Cycle Variation

- SWx in Cycles 24 & 25 is clearly very mild
- CME and sunspot activity have discordant behavior between the two sunspot number peaks
- More fast CMEs during first peak, but a smaller SSN
- X-class flares are more during the second peak
- # of SEP events, magnetic storms similar to CMEs
Properties of CMEs Producing SEPs

• Need to be fast enough to drive a shock
• $V >> V_A \sim B\eta^{\frac{1}{2}}$
• The shock should be magnetically connected to the observer