Understanding the Sun via gamma-ray lines

Albert Y. Shih (NASA/GSFC)
2021 June 7
Solar ion acceleration

- Solar eruptive events (SEEs) accelerate both ions and electrons
  - Both flares and CMEs accelerate particles
  - Particle acceleration is efficient: up to tens of percent of the released magnetic energy
- Accelerated ions can be characterized through the gamma rays they produce (see next slide)
  - Compact sources associated with flare loops
  - Diffuse source from particle precipitation

(modified from Temmer et al. 2010)
Solar gamma rays

Accelerator

- Electrons
- Protons, alphas, heavy ions
- Neutrons

Bremsstrahlung

Nuclear de-excitation, positron-annihilation, pion-decay emission

Neutron-capture

Neutrons

Corona

Photosphere

Thermalization

Time delay of ~ 100 seconds
Spatial separation of < 1 arcsec
≤10 MeV spectroscopy

Composite *RHESSI* spectrum for 2002 July 23 X4.8 flare

- Thermal plasma emission
  - Plasma temperature
  - Plasma abundances
- Relativistic bremsstrahlung continuum from electrons
  - Electron energy spectrum
  - Electron angular distribution
- Nuclear de-excitation lines
  - Ambient abundances
  - Accelerated abundances
  - Ion energy spectrum (∼3–10 MeV/nuc)
  - Ion angular distribution
- Neutron-capture line (2.223 MeV)
  - Accelerated ions (∼20 MeV/nuc)
- Positron-annihilation line (511 keV)
  - Ambient conditions such as temperature

(Lin 2011)
Instruments for gamma-ray lines

- **SMM/GRS** (spectroscopy)
  - NaI scintillators → a few % FWHM

- **RHESSI** (spectroscopy and imaging)
  - HPGe detectors → <1 % FWHM
  - Fourier-transform imaging via tungsten bi-grid collimators → 35 arcsec angular resolution

- **Fermi/GBM** (spectroscopy)
  - NaI and BGO scintillators
Where are ions accelerated?

- RHESSI imaged flare footpoints for a gamma-ray line (2.2 MeV neutron-capture line)
- These compact sources contain all of the spectroscopically observed 2.2 MeV line flux
  - \( \sim 20 \text{ MeV/nuc ions confined to flare loops} \)
  - \( \sim 20 \text{ MeV/nuc ions not precipitating from the CME shock} \)
- Offset between ion footpoints and electron footpoints indicate differences in acceleration/transport

(Hurford et al. 2006)
How is ion acceleration coupled to electron acceleration?

Similar energy content in ions (●) and electrons (◇) as observed by *SMM/GRS*

Proportional acceleration of ∼20 MeV/nuc ions and >300 keV electrons

(Ramaty et al. 2000) (Shih et al. 2009)
Where does the energy in ions get deposited?

- The positron-annihilation line narrowing in a flare indicates changes in interaction region
  - Broad line: density of $\sim 10^{14} - 10^{15} \text{ cm}^{-3}$ at $\sim 10^5 \text{ K}$
  - Narrow line: density of $\geq 10^{15} \text{ cm}^{-3}$ at $< 10^4 \text{ K}$, still ionized
- A couple of flares have shown ambient abundances that evolve from photospheric-like to coronal-like (not shown)

(Share et al. 2004)
Future needs for solar gamma-ray measurements

• Any observations whatsoever!
  • Ions contain ~half of the energy released into particles
  • Ions may have a significant role in flare heating

• High angular resolution and high image quality
  • Ion acceleration/transport versus electron acceleration/transport

• High sensitivity
  • Evolution in large flares
  • Small flares
  • Signatures of sub-MeV ions
Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS)

- Balloon mission funded under the NASA Heliophysics LCAS program
- PI: Pascal Saint-Hilaire (UC Berkeley)
- Capabilities
  - <1% FWHM spectral resolution
  - 12.5 arcsec angular resolution with high image quality
- Implementation
  - HPGe detectors with 3D position sensitivity
  - Coded aperture is a grid of tungsten-copper slats
  - 8-meter grid-spectrometer separation

(Hurford et al. 2006)
GRIPS implementation

3D position-sensitive HPGe detectors (3D-GeDs)
- 7.5cm × 7.5cm × 1.5cm detectors
- 149 strips on each face (0.5-mm pitch)

Multi-pitch rotating modulator (MPRM)
- W/Cu slit/slat pitch ranges from 1 to 13 mm
- MPRM rotates at 10 rpm
**GRIPS status**

- **GRIPS** has had one Antarctic flight
  - \(~10^6\) seconds in January 2016
  - The Sun produced 21 small (C-class) flares, with no appreciable gamma rays
- **GRIPS** recently funded for a second Antarctic flight
  - Instrument needs to be rebuilt following recovery

The **GRIPS** field team in front of the instrument
Compton Spectrometer and Imager (COSI) SMEX

- Astrophysics SMEX mission undergoing a Phase A study
- PI: John Tomsick (UC Berkeley)
- Capabilities
  - <1% FWHM spectral resolution
  - Compton-imaging angular resolution usable for background rejection
- Implementation
  - **GRIPS**-like HPGe detectors with 3D position sensitivity
- High-energy astrophysics missions can make groundbreaking measurements of the Sun: most recently, *Fermi* and *NuSTAR*
- Two COSI talks on June 9
  - 12:30pm, 309.04: “The Compton Spectrometer And Imager: Audacious Advancements In Mev Astronomy” by Terri Brandt
  - 4:50pm, 324.05: “COSI: From Data to Images and Spectra” by Andreas Zoglauer
Solar Maximum Energetic Ion induced Gamma Ray Line Spectrometer (SMEIGLS)

- ISS-borne instrument proposal pending selection under the Heliophysics FORT program
- PI: Lee Mitchell (NRL)
- Capabilities
  - High effective area
- Implementation
  - Compact array of bright scintillators

<table>
<thead>
<tr>
<th>Instrument</th>
<th>511 keV</th>
<th>2.2 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area$_{pp}$</td>
<td>FWHM</td>
</tr>
<tr>
<td>SMEIGLS</td>
<td>268 cm$^2$</td>
<td>24 keV</td>
</tr>
<tr>
<td>Fermi/GBM</td>
<td>120 cm$^2$</td>
<td>70 keV</td>
</tr>
<tr>
<td>RHESSI</td>
<td>27 cm$^2$</td>
<td>2 keV</td>
</tr>
<tr>
<td>SMM/GRS</td>
<td>175 cm$^2$</td>
<td>41 keV</td>
</tr>
</tbody>
</table>
Additional possibilities

• Other astrophysics gamma-ray missions
• Space-borne version of GRIPS
  • \( \sim 5 \) arcsec angular resolution
• Direct gamma-ray imaging, although with FOV concerns
  • Fresnel lenses
  • Laue lenses
• The next Heliophysics Decadal Survey is around the corner!
  • The previous Decadal Survey studied the Solar Eruptive Events (SEE) 2020 mission concept, which included a gamma-ray instrument
Summary

• Solar gamma-ray lines (≈0.5–10 MeV) are vital for understanding:
  • Ion acceleration at the Sun
  • Energy transport into the chromosphere

• We aspire for improved observations!
  • Platform: balloons to orbital spacecraft
  • Solar science: primary to ancillary

• See also the poster right now, 127.05: “New Solar-Flare Particle Acceleration And Interaction Studies Using Gamma Rays” by Gerry Share