Solar Transients

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<table>
<thead>
<tr>
<th>source</th>
<th>typical duration</th>
<th>energy source</th>
<th>$E$ ($\gamma$-ray)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGF</td>
<td>milliseconds</td>
<td>$E$-field</td>
<td>$10^{30}$ erg</td>
</tr>
<tr>
<td>GRB</td>
<td>milliseconds–minutes</td>
<td>gravity</td>
<td>$10^{35}$ erg</td>
</tr>
<tr>
<td>SGR</td>
<td>milliseconds–seconds</td>
<td>$B$-field</td>
<td>$10^{44}$ erg</td>
</tr>
<tr>
<td>TDE</td>
<td>days–years</td>
<td>gravity</td>
<td>$10^{39}$ erg</td>
</tr>
<tr>
<td>solar flare</td>
<td>minutes</td>
<td>$B$-field</td>
<td>$10^{30}$ erg</td>
</tr>
<tr>
<td>SN/nova</td>
<td>minutes–years</td>
<td>nuclear</td>
<td>$10^{40}$ erg</td>
</tr>
<tr>
<td>accreting BH/NS</td>
<td>seconds–days (variable)</td>
<td>gravity</td>
<td>$10^{36}$ erg s$^{-1}$</td>
</tr>
<tr>
<td>AGN</td>
<td>hours–days (variable)</td>
<td>gravity</td>
<td>$10^{48}$ erg s$^{-1}$</td>
</tr>
</tbody>
</table>

Table 1. High-energy transients. TGF, terrestrial $\gamma$-ray flash; GRB, $\gamma$-ray burst; SGR, soft $\gamma$ repeater; TDE, tidal disruption event; SN, supernova; BH, black hole; NS, neutron star; AGN, active galactic material.
Solar Flares and associated Coronal Mass Ejections (CMEs)

• Solar flares duration ~10s of sec to 10s min
• X-ray classification – according to their energies - moderate to intense flares are C, M, and X classes
• In general, intense flares are associated with ejection of magnetic field and mass

Solar Flares

• Solar flare is a violent explosion in Sun’s atmosphere
• Spans EM frequencies from radio to X-ray
• Caused by release of energy stored in twisted magnetic field lines. Rapid conversion of this energy into the kinetic energy accelerates particles to high energies (primarily e, p, and He)
• Large increase in X-ray flux and high-energy particles can affect satellites
• Energy release accelerates protons in solar wind and cause disturbances in Earth’s magnetic field.

An X-ray image of an intense X9 flare taken from the GOES-13 satellite. The flare was actually intense enough to damage the imager.
Solar flares: Emissions and Energies

Solar flares are rapid localised brightening in the lower atmosphere.

More prominent in X-rays, UV/EUV and radio…. but can be seen from radio to 100 MeV

Coronal Mass Ejections (CMEs)

- Large eruptions of coronal plasma
- Originate from active regions in Sun associated with solar flares
- Solar minimum: ~1/week
  - Coronal streamer belt near the solar magnetic equator
- Solar maximum: ~ 2-3 /day
  - Active regions, latitudinal distribution is more homogeneous.
- Involve mass ~10^{12} – 10^{13} kg
- Fast: Speed ~100 – 4000 km/s
Solar Transients Affect Earth

- CMEs, CIRs, and solar flares can affect the Earth’s magnetosphere and ionosphere.

- Their effects can be severe enough to cause damage to satellites and power systems.
Solar Flare and Radio Emission Height

Hard X-ray emission is generally fairly localized despite the large volume involved in the full flare.

Temporal and Spatial Development
X-ray spectrum of solar flares

Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spectrum

Hinode (Solar-B) Magnetic Field Twisting
December 9-14, 2006
Hinode (Solar-B) SOT
December 13, 2006
July 14, 2000
A powerful X-class flare eruption

Ooty Callisto – Solar Radio Spectrum
X3.4/4B Flare on 13 Dec 2006

Frequency (890 – 45 MHz)

02:30 UT

890 MHz

03:15 UT

45 MHz
Significant CMEs & their Consequences

Cycle 23 – 24 CMEs from SOHO/LASCO

Gopalswamy, 2006; 2010

m2 – Metric type II
MC – Magnetic Cloud
EJ – Ejecta
S – Interplanetary shock
GM – Geomagnetic storm
Halo – Halo CMEs
DH – Type II at $\lambda$ 10-100 meters
SEP – Solar Energetic Particles
GLE – Ground Level Enhancement

Plasma impact  Energetic electrons  Energetic protons

p≈0.3%

p<10^{-4}
Fast CMEs – Speed Distribution

<table>
<thead>
<tr>
<th>Category</th>
<th>Number of CMEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All identified CMEs</td>
<td>18000 (1996 to 2014)</td>
</tr>
<tr>
<td># CMEs with V ≥ 1000 km/s</td>
<td>539</td>
</tr>
<tr>
<td># CMEs with V ≥ 1500 km/s</td>
<td>131</td>
</tr>
<tr>
<td># CMEs with V ≥ 2000 km/s</td>
<td>39</td>
</tr>
<tr>
<td># CMEs with V ≥ 2500 km/s</td>
<td>9</td>
</tr>
<tr>
<td># CMEs with V ≥ 3000 km/s</td>
<td>2</td>
</tr>
<tr>
<td># CMEs with V ≥ 3500 km/s</td>
<td>1</td>
</tr>
<tr>
<td># CMEs with V ≥ 4000 km/s</td>
<td>0</td>
</tr>
</tbody>
</table>

Solar Super Flares

Description of a Singular Appearance seen in the Sun on September 1, 1859

R.C. Carrington

Carrington Flare (1 Sep 1859, at 11:18 am)

- It was so bight – The first flare record! (observed by Richard Carrington, England)
- White-light flare (~5 min)
- Just before dawn, very bright aurora appeared at many places (e.g., Cuba, Bahamas, Jamaica, El Salvador, Hawaii, etc.)
- E ~ factor × 10^{32} erg
- Largest geo-magnetic storm (>1000 nT) in past 200 years

http://science.nasa.gov/science-news/science-at-nasa/2008/06may_carringtonflare/

Magnetic storm on 13 March 1989 caused Quebec blackou

Intense solar flare X4.6

Intense geo-magnetic storm ~ 540 nT

http://www.stelab.nagoya-u.ac.jp/ste-www1/pub/ste-nl/N
Super flares ..... 

If a Carrington-class flare occurs now, what will happen?

- Troubles to communication satellites (900+!)?
- Whole earth blackout?
- Long-time communication disruption?
- Humans in space would be in peril?
- Total loss of $30 – 70 billions?

Rate of occurrence of solar flares, microflares, nanoflares
Rate of occurrence of solar flares, microflares, nanoflares

Super flare – will it occur on our Sun?
Stellar flares

- **Young** stars and **close binaries** are known to produce **superflares**, $10^{33} - 10^{38}$ erg, than the largest solar flares (X5 to X10 class ~$10^{32}$ erg).
- Such stars **rotate fast** (10 -100 km s$^{-1}$) and the magnetic field of a few kG is distributed in large regions on the stellar surface.
- In contrast, the Sun slowly rotates (~2 km s$^{-1}$) and sparsely has large spots.

‘Superflares’ erupt on some Sun-like stars’

Flares on our Sun are thousands of times punier than those on similar stars – Kepler observations suggest

- **Could superflares occur on the Sun today?**
- Maehara et al (2012) : As most of the superflare stars in his study seem to sport starspots much larger than those on the Sun, for unknown reasons.
- The Sun could have rotated once every few days in its youth, and this churning should have led to the release of magnetic energy in superflares. "It probably happened quite often when the Sun was quite young,"
A typical superflare observed by Kepler

What causes variation of stellar brightness?
Likely due to rotation of a star with a big star spot

Maehara et al. (2011)
• Period of the brightness variation
  Rotation period of star

• Amplitude of the brightness variation
  Area of starspots involved

Energy-frequency distribution

- Power-law distribution with the index of -2.3 +/- 0.3
  - The frequency distribution is similar to that of solar flares.

\[
\frac{dN}{dE} \propto E^{-a}
\]
\[
a \approx 2.3 \pm 0.3
\]

The discovery of 2 superflare stars similar to the Sun
(Nogami et al. 2014, submitted to PASJ)
Intense Solar Transients
Look for large sunspots

Thank you
Transients ....

- Terrestrial $\gamma$-ray flashes (TGF) are due to decay of electric fields above thunderclouds – relativistic electron interact with nuclei of atoms in the atmosphere and produces $\gamma$-ray via bremsstrahlung
- $\gamma$-ray bursts (GRBs) – intense radiation produced at cosmological distances $z \sim 2$
- Soft $\gamma$-ray repeaters (SRBs) – emits bursts of X-rays and $\gamma$-rays – due to rearrangement of magnetic field in magnetars (pulsar with magnetic field $\sim 10^{15}$ G)
- Tidal disruption events (TDEs) – caused by tidal disruption of stars (e.g., close to massive black holes at centre of galaxies)
- Solar flare – an explosion in the solar atmosphere due to the sudden release of magnetic energy in the corona – flares occur in active regions around sunspots – can be quite energetic, up to $10^{-4}$ Lo, releasing energy across the full electromagnetic spectrum from radio to high-energy $\gamma$-rays

X3.4/4B Flare and associated CME on December 13, 2006
14 July 2000 Event – X-ray and Solar Energetic Particles

X-ray profiles
Flares produce X-rays; gamma-rays, UV light burst and very fast wind flow which can inject protons into the trapping region (even create ‘second proton belt’)

Solar Cosmic Rays
Particles ($p$, $e$, and $He$) are emitted during ‘solar storms’
- energies $>10$ MeV/nucleon
- access to open magnetic fields of polar cap. (even create ‘second proton belt’)

Bastille Day Event
Coronal Mass Ejection on July 14, 2000