Investigation of Active Region Properties for Solar Flare Forecasts

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• Goal
• Terminology
  – Solar Flares
  – Active Regions
  – Sunspots
• Classifications
  – Compactness
  – Penumbra
  – Zurich
• Parameters
  – Helicity
  – NHGV
  – Number of Spots
  – Longitudinal Extent
  – Area
  – Distance
• What I Did
• Cool plots, Results, and Analysis
• Conclusion
My goal is to help improve the way flares are forecasted.

– Space weather events can destroy or interrupt important technology, harm astronauts, and misdirect homing pigeons.
An Introduction to Terminology

http://lwsde.gsfc.nasa.gov/LWS_Space_Weather/SpaceWeatherOverview.html
What are Solar Flares?

- A sudden release of energy stored in twisted magnetic fields.
- Solar flares are classified according to their x-ray peak wavelength.
  - **X-class flares** are big.
  - **M-class flares** are medium-sized.
  - **C-class flares** are small.

<table>
<thead>
<tr>
<th>Flare Class</th>
<th>Class Peak (W/m²) between 1 and 8 Angstroms</th>
<th>Pneumonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>$I \geq 10^{-4}$</td>
<td>Xtreme</td>
</tr>
<tr>
<td>M</td>
<td>$10^{-5} \leq I &lt; 10^{-4}$</td>
<td>Mediocre</td>
</tr>
<tr>
<td>C</td>
<td>$10^{-6} \leq I &lt; 10^{-5}$</td>
<td>Cheesy</td>
</tr>
<tr>
<td>B</td>
<td>$I &lt; 10^{-6}$</td>
<td>Baby</td>
</tr>
</tbody>
</table>

http://www.noaanews.noaa.gov/stories2010/20100119_solarflare.html
### Geomagnetic Storms

<table>
<thead>
<tr>
<th>Category</th>
<th>Effect</th>
<th>Physical Measure</th>
<th>Average Frequency (1 cycle = 11 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G5 Extreme</td>
<td>Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps. HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Kp value* determined every 3 hours</td>
<td>Number of storm events when Kp level was met, (number of storm days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kp&lt;6</td>
<td>4 per cycle (4 days per cycle)</td>
</tr>
<tr>
<td>G4 Severe</td>
<td>Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect protective measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and southern California (typically 45° geomagnetic lat.).**</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kp=7</td>
<td>200 per cycle (130 days per cycle)</td>
</tr>
<tr>
<td>G3 Strong</td>
<td>Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface currents may occur on satellite components, flux may increase on low-Earth orbit satellites, and corrections may be needed for orientation. Other systems: internets and radio may be intermittent and inaccurate**.</td>
<td></td>
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</tr>
<tr>
<td>G2 Moderate</td>
<td>Power systems: high-latitude transformer overloads Spacecraft operations: communication satellite operations are affected drug dosing: orbit predictions. Other systems: HF radio propagation affected in northern latitudes and Alaska (typically 65° geomagnetic lat.) **</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G1 Minor</td>
<td>Power systems: minor impacts Spacecraft operations: minor impact Other systems: minor impacts **</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** For specific locations around the globe, use magnetic latitude to determine likely regions (see www.sec.noaa.gov/NOAA-Scales/)

### Solar Radiation Storms

<table>
<thead>
<tr>
<th>Level</th>
<th>Extent</th>
<th>Event Type</th>
<th>Detailed Description</th>
<th>Flux level of 10 MeV (particles/cm²)</th>
<th>Number of events when flux level was met**</th>
</tr>
</thead>
<tbody>
<tr>
<td>S5 Extreme</td>
<td>Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity), passengers and crew in high-flying aircraft at high altitudes may be exposed to radiation risk.Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious issues on Earth satellites, permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors under navigation operations extremely difficult.</td>
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<tr>
<td></td>
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<td>Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high altitudes may be exposed to radiation risk. Satellite operations: may experience memory device problems and noise in ionosphere systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.</td>
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<tr>
<td>S4 Severe</td>
<td>Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high altitudes may be exposed to radiation risk. Satellite operations: single-event upset, noise in ionosphere systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.</td>
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<tr>
<td>S3 Strong</td>
<td>Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. Satellite operations: infrequent single-orbit upset possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibility affected.</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>S2 Moderate</td>
<td>Biological: none. Satellite operations: none. Other systems: minor impacts **</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1 Minor</td>
<td>Biological: none. Satellite operations: none. Other systems: minor impacts **</td>
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</tbody>
</table>

** Flux levels are 3-month average. A particle is a proton or neutron. ** These events can occur that one day. *** High energy particle measurements (<10 MeV) are a better indicator of radiation risk to passengers and crews.匠师s are particularly susceptible.

### Radio Blackouts

<table>
<thead>
<tr>
<th>Level</th>
<th>Extent</th>
<th>Event Type</th>
<th>Detailed Description</th>
<th>GOES X-ray peak brightness by class and by flux*</th>
<th>Number of events when flux level was met, (number of storm days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5 Extreme</td>
<td>HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth for a number of hours. This results in no HF radio contact with mariners and remote mountaineers. Navigation: Low-frequency navigation signals used by mariners and aviation systems experience outage on the sunlit side of the Earth for many hours, causing loss of position. Increased satellite navigation errors in positioning for several hours on the sunlit side of the Earth, which may spread across the night side.</td>
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<tr>
<td></td>
<td></td>
<td>HF Radio: HF radio communication blackout on the entire sunlit side of Earth for one to two days. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two days. Minor disruptions of satellite navigation possible on the sunlit side of Earth.</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>R4 Severe</td>
<td>HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>R1 Minor</td>
<td>HF Radio: Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. Navigation: Loss of low-frequency navigation signals degraded for brief intervals.</td>
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</tbody>
</table>

* Flux measured in the 0.1-4.0 keV range, in W cm⁻². Based on this measure, but other physical measures are also considered. ** More frequencies may also be affected by these conditions.

URL: www.swpc.noaa.gov/NOAA-Scales
March 1, 2005
What is an Active Region?

- A part of the solar atmosphere where you can observe:
  - sunspots
  - faculae
  - flares
- Active regions are the result of enhanced magnetic fields.
- Will use interchangeably with “sunspot.”

Magnetic gradient field of sunspot
http://www.aip.de/image_archive/Sun.Sunspots.html
What are sunspots?

- An area seen as a dark spots on the photosphere of the Sun.
  - Concentrations of magnetic flux.
  - Appear dark because they are cooler than the surrounding photosphere.
  - Larger and darker sunspots sometimes are surrounded (completely or partially) by penumbras. The dark centers are umbrae.
- Classification
  - The Modified Zurich Sunspot Classification System
  - Devised by McIntosh
  - White-light characteristics of a sunspot group.
  - A 3-letter designation: Zpc

Classification of Sunspots: Compactness

- c:
  - x: a single spot
  - o: open
  - i: intermediate
  - c: compact

Classification of Sunspots: Penumbra

- p:
  - x: no penumbra
  - r: rudimentary
  - s: small (<2.5 degrees north-south diameter), symmetric
  - a: small, asymmetric
  - h: large (>2.5 degrees north-south diameter), symmetric
  - k: large, asymmetric

Classification of Sunspots: Modified Zurich Classification

- **Z:**
  - **A:**
    - small single sunspot or very small group of spots
    - same magnetic polarity
    - no penumbra
  - **B:**
    - bipolar
    - no penumbra
  - **C:**
    - elongated
    - bipolar sunspot group
    - one sunspot must have a penumbra
    - penumbra longitudinal extent < 5°
  - **D:**
    - elongated
    - bipolar sunspot group
    - penumbra on both ends of the group
    - 5° < Penumbra longitudinal extent < 10°
  - **E:**
    - elongated
    - bipolar sunspot group
    - penumbra on both ends
    - 10° < penumbra longitudinal extent < 15°
  - **F:**
    - elongated
    - bipolar sunspot group
    - penumbra on both ends
    - 15° < penumbra longitudinal extent
  - **H:**
    - uni-polar sunspot group
    - with penumbra

Some Other Factors

• Helicity
  – The amount of twist in the plasma flow below the surface of the Sun.
  – NOT magnetic helicity
  – IS hydrodynamic helicity

\[ H = \int \mathbf{u} \cdot (\nabla \times \mathbf{u}) \, d^3r \]

• Normalized Helicity Gradient Variance (NHGV)
  – A parameter designed to capture the large, shrinking spread of helicity values, the overall range of helicity values, and the depth variation of the helicity.

http://www.absoluteastronomy.com/topics/Gradient
http://www.nordita.org/~brandenb/highlights/recent.html
Some Other Factors

• Number of Spots

![Image of sunspots]

- Area of Sunspot Group

\[ A_M = \frac{A_S 10^6}{2\pi R^2 \cos(B) \cos(L - L_0)} \]

- \( A_M = \) sunspot area in millionths of the sun’s visible hemisphere
- \( A_S = \) measured sunspot area (square millimeters or inches)
- \( R = \) radius of solar drawing
- \( B = \) heliographic latitude of sunspot group (degrees)
- \( L = \) heliographic longitude of sunspot group (degrees)
- \( L_0 = \) heliographic longitude of the center of the disk (degrees)

• Distance

\[ y = \cos^{-1}(\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2)) \]

- Subroutine that I wrote
- Co-latitudes (90-latitude)
- Degrees to radians
- Spherical geometry
- Angle times solar radius to get arc distance between sunspots

• Longitudinal Extent

![Image of sunspots with an arrow indicating longitudinal extent]

What I did

• Pieced together a IDL programs
• Wrote an IDL program to
  – measure distance between two active regions and
  – restrict the location of the sunspot to the center of the disk to avoid uncertainties
• Organized lots of data
• Made lots of plots and histograms
• Looked for patterns with respect to NHGV values in the plots and histograms
Cool Plots, Results, and Analysis
Compactness

c, no flare, 0.98

i, no flare, 1.02

c, x-class, 1.24

i, x-class, 1.13
Penumbra
Penumbra

h, no flare, 1.08

Penumbra

h, x-class, 1.15
Zurich

d, no flare, 1

e, no flare, 1.03

d, x-class, 1.13

e, x-class, 1.2
Standard Deviation shows how much variation there is from the average.

http://www.syque.com/improvement/Standard%20Deviation.htm
When Compactness = C, Penumbra class %

When Compactness = C, Zurich class %
**When Zurich = E, Compactness class%**

![Compactness Class Percentage Chart]

**When Zurich = E, Penumbra class%**

![Penumbra Class Percentage Chart]
Conclusion

• The more compact the sunspot group is, the higher the probability of producing an x-class flare.
• Asymmetric penumbra sunspots are more likely to flare in the x-class than symmetric penumbra sunspots.
• Elongated bipolar sunspot groups with penumbra at both ends are more likely to flare in the x-class than single spots, those without penumbra, and uni-polar sunspots.
• Increasing compactness and complexity of a sunspot increases NHGV
• Work-in-progress.
Sources