Time Scale of Solar Effects

Emission Sources:
- X-ray
  - Alert!
  - Sunlit Ionospheric Disturbance
- Radio
  - Alert!
  - Radio Interference due to Radio Waves
  - Due to Energetic Particles
  - Due to Ionospheric Storm
- Energetic Particles
  - Warning!
  - Radiation
  - PCA Event
- Solar Plasma
  - Watch
  - Warning!
  - Alert!
  - Magnetic Storm

(Time 0 is 8 minutes after a solar event)
Contents

1. The forecast of solar flares and CMEs (Lee et al. 2012, Lee et al. 2015, Shin et al. 2015)


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   3.3 Comparison among cone models and a flux rope model (Na et al. 2013, Lee et al. 2015)
   3.4 WSA-ENLIL model with three cone types (Jang et al. 2014)
   3.5 Comparison of 2-D and 3-D CME parameters (Jang et al. 2015)
   3.6 Development of a full ice-cream cone model (Na et al. 2015)
1. Probabilistic Forecast of solar flares and CMEs
(Poster CS-14)

Data & Analysis

- **Data**
  - NOAA’s SRS data
    (McIntosh sunspot group, sunspot area, area change)
  - *Area*: a proxy of magnetic flux
  - NGDC flare catalog
    (C, M, and X-class flare)

- **Sub-groups**

Method

- **Calculating flare occurrence rate**
  (the number of flares / the number of sunspot group ARs)

- **Calculating flare probability**

- **Solar flare probability depending on sunspot group area and its change**
In case of “Increase” sub-groups, the flare probability higher than those of other sub-groups.

This is statistical evidence that magnetic flux emergence is a very important mechanism for triggering solar flares since sunspot area can be a good proxy of magnetic flux.
We point out that the CME probability is high when sunspot area is remarkably changed (Especially, Dkc, Ekc, and Fkc classes).
We find that the occurrence rates of major flares and halo CMEs for 6 active sunspot classes are noticeably higher in the descending phase of solar cycle 23 than those in the other phases.
Previous Studies
Using all flaring data tends to underestimate flares.
Ex) C : 1000, M : 500, X : 100

Our study: Using same 61 numbers of each flare class make the model improve the performance of strong flares. → C : 61, M : 61, X : 61

X-class prediction rate 0%

Improve forecasting performance

\[
|\log_{10}(\text{observed flux}) - \log_{10}(\text{forecasted flux})| \leq 0.5
\]

<table>
<thead>
<tr>
<th></th>
<th>MLR</th>
<th>ANN</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-class</td>
<td>0.707</td>
<td>0.617</td>
</tr>
<tr>
<td>X-class</td>
<td>0.581</td>
<td>0.677</td>
</tr>
</tbody>
</table>
2. Forecast of Solar Proton Events

SPEs having a flux of $> 10$ MeV protons equal to and greater than $10$ particles $\text{cm}^{-2} \text{sec}^{-1} \text{ster}^{-1}$ (the unit: pfu)

SPE forecast
High-priority forecast now cast models for NOAA/SWPC(2003)
### SPE occurrence probability depending on flare parameters

<table>
<thead>
<tr>
<th></th>
<th>E31-E90°</th>
<th>E30-W30°</th>
<th>W31-W90°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>X-class (85)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T&lt; 0.3h</td>
<td>10.8% 9/83</td>
<td>25.3% 19/75</td>
<td>13.8% 11/80</td>
</tr>
<tr>
<td>T≥ 0.3h</td>
<td>19.2% 9/47</td>
<td>32.1% 18/56</td>
<td>44.2% 19/43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>E31-E90°</th>
<th>E30-W30°</th>
<th>W31-W90°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>M-class (81)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T&lt; 0.3h</td>
<td>0.3% 3/1057</td>
<td>0.7% 8/1174</td>
<td>1.5% 15/1005</td>
</tr>
<tr>
<td>T≥ 0.3h</td>
<td>3.6% 11/306</td>
<td>3.5% 13/376</td>
<td>11.7% 31/265</td>
</tr>
</tbody>
</table>

Impulsive time: flare peak time - SPE peak time

(Park et al., 2010)
## SPE occurrence probability depending on CME parameters

- CME speed and angular width (# of SPEs/# of CMEs)

<table>
<thead>
<tr>
<th>CME</th>
<th>400 ≤ V &lt;1000km/s</th>
<th>1000≤ V&lt;1500km/s</th>
<th>V ≥ 1500km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial CME</td>
<td>0.9% (4/434)</td>
<td>8.2% (8/89)</td>
<td>20.7% (6/29)</td>
</tr>
<tr>
<td>(120– 359°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halo CME</td>
<td>5.9% (11/185)</td>
<td>21.3% (19/89)</td>
<td>36.1% (30/83)</td>
</tr>
<tr>
<td>Front CME</td>
<td>400 ≤ V &lt;1000km/s</td>
<td>1000≤ V&lt;1500km/s</td>
<td>V ≥ 1500km/s</td>
</tr>
<tr>
<td>Partial CME</td>
<td>1.8% (4/225)</td>
<td>11.3% (7/62)</td>
<td>27.3% (6/22)</td>
</tr>
<tr>
<td>(120 – 359°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halo CME</td>
<td>9.2% (11/119)</td>
<td>25.0% (17/68)</td>
<td>45.5% (30/66)</td>
</tr>
</tbody>
</table>

(Park et al., 2012)
The relationship between SPE Peak Flux and solar activities

- SPE peak flux and CME speed on longitude

(Park et al., 2012)
SPE occurrence probability depending on flare and CME parameters (Poster CS-13)
- Flare flux, location, CME speed, and angular width

<table>
<thead>
<tr>
<th></th>
<th>Full Halo</th>
<th>Partial Halo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V &lt; 1000km/s</td>
<td>V ≥ 1000km/s</td>
</tr>
<tr>
<td>West</td>
<td>≥M5</td>
<td>33% (6/18)</td>
</tr>
<tr>
<td></td>
<td>F&lt;M5</td>
<td>11% (4/37)</td>
</tr>
<tr>
<td>East</td>
<td>≥M5</td>
<td>0% (0/9)</td>
</tr>
<tr>
<td></td>
<td>F&lt;M5</td>
<td>0% (0/40)</td>
</tr>
</tbody>
</table>

(Park et al., 2014)
We find that most of strong proton events occur when their angular separations are closer to zero, supporting that most of the proton fluxes are generated near the CME noses rather than their flanks.
3. Forecast of Geomagnetic Storms
3.1 CME – Geomagnetic Storm

What CME parameters are important for geomagnetic storms?

Prediction in 2-3 days advance

CME Speed and Location
CME Earthward Direction
CME Field Orientation
How do you know if this CME would produce a geomagnetic storm?
Probability Map of geoeffective halo CMEs:

\[ P(L=0,700\text{km/s}) = 50\% \] (Kim et al. 2005)
Earthward Direction of CME

A new quantitative direction parameter (Moon et al. 2005)

- Degree of symmetry: \( D = \frac{b}{a} \)

\( b/a = 0.64 \)

\( b/a = 0.32 \)
Probability map of geoeffective CMEs
3.2 Geoeffective CME parameters
(Lee et al. 2014)

Super geomagnetic storms (Dst ≤ -200 nT) only appeared in the western region.
Dependence of Halo CME geoeffectiveness on location and magnetic field orientation

<table>
<thead>
<tr>
<th>Dst index</th>
<th>Eastern + Northward</th>
<th>Eastern + Southward</th>
<th>Western + Northward</th>
<th>Western + Southward</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ -50 nT (Moderate)</td>
<td>75% 6/8</td>
<td>81.8% 9/11</td>
<td>66.6% 6/9</td>
<td>83.3% 15/18</td>
</tr>
<tr>
<td>≤ -100 nT (Intense)</td>
<td>12.5% 1/8</td>
<td>36.3% 4/11</td>
<td>44.4% 4/9</td>
<td>55.5% 10/18</td>
</tr>
<tr>
<td>≤ -200 nT (Super)</td>
<td>0% 0/8</td>
<td>0% 0/11</td>
<td>0% 0/9</td>
<td>33.3% 6/18</td>
</tr>
</tbody>
</table>

Super geomagnetic storms (Dst ≤ -200 nT) only appeared in the western and southward magnetic field events.♪
3.3 Comparison of cone models and a flux rope model (Poster CS-30, Lee et al. 2015)

**Multi-view**
- STEREO

**Single-view**
- SOHO

**Triangulation**
- GCS

**Ice-cream Cone**

**Direct measurement**
- STEREO

3-D CME parameters: Radial velocity, Angular width, Source location
Comparison of the radial velocities of the CMEs from three geometrical methods
Comparison of the angular widths of the CMEs from three geometrical methods
The WSA-ENLIL model is the three-dimensional MHD numerical code, to simulate corotating and transient SW disturbances in the heliospheres.

3.4 WSA-ENLIL model with three cone types
(First prize of NASA/CCMC contest 2013, Jang et al. 2014)
Travel time error \((T_{model} - T_{obs})\)

(a) WSA-ENLIL Elliptical cone model

MAE = 11.4h
RMSE = 13.5h
Mean = -5.5h

(b) WSA-ENLIL Ice-cream cone model

MAE = 11.5h
RMSE = 13.7h
Mean = -0.7

(c) WSA-ENLIL Asymmetric cone model

MAE = 10.6h
RMSE = 13.2h
Mean = -7.6h

(d) Empirical model

MAE = 8.7h
RMSE = 10.2h
Mean = 1.2h

(Kim et al. 2007)
Comparison between model results and observation

WSA-ENLIL elliptical cone model

WSA-ENLIL ice-cream cone model

WSA-ENLIL asymmetric cone model

RMSE = 213 km/s

RMSE = 164 km/s

RMSE = 172 km/s

RMSE = 30.9 #/cc

RMSE = 25.1 #/cc

RMSE = 30.3 #/cc
3.4 Comparison of CME 3-D parameters with 2-D ones (First prize of NASA/CCMC contest 2015, CS-24)
Comparison of speed-width relationship in 2-D and 3-D

![Graphs showing speed-width relationship in 2-D and 3-D.](image)
Most of the events are closer to the full cone type, which is consistent with Gopalswamy et al. (2009a) and Michalek et al. (2009).

Cone shape parameters: 29 limb events
Input initial parameters: $V_0$, $\alpha_0$, source location $(\phi_0, \theta_0)$, near flare location

Construct a cone for given initial values

Project the cone on the sky plane
&
Select points comprising the outer boundary

Measure projection speeds (every $15^\circ$, 24 points) using the observation data

Minimize the difference between the estimated projection speeds with the observed one.

Output parameters:
$V$, $\alpha$, source location $(\phi, \theta)$,
angle $\gamma = \sin^{-1}(\sin \theta \cos \phi)$
Comparison of Full ice-cream cone model, Triangulation method, and GCS model: Velocity
Comparison of Full ice-cream cone model, Triangulation method, and GCS model: Angular width

- Correlation coefficient (cc) = 0.76
- RMS error = 15°

- Correlation coefficient (cc) = 0.76
- RMS error = 23°
Conclusion

We have developed probabilistic forecast models of major flares and CMEs as well as daily flare peak flux forecast models for strong flares.

We have developed a solar proton (S) forecast model depending on flare parameters (flare strength, duration, and longitude) as well as CME parameters (speed and angular width).

We have presented the probability map of geoeffective CMEs depending on CME parameters.

The geoeffectiveness of CMEs from eastern and western hemisphere is quite different from each other. All superstorms appeared in the western and southward magnetic field events.

We have developed a full ice-cream cone model for CME 3-D parameters, which is more consistent with observations than the other cone types models.