What we can learn from the ISEST WG4 Campaign Study of Sun-Earth events?

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Introduction

WG 4 (Campaign Events)

Objectives:

♦ To understand cause-effect chain of Sun-Earth activity
♦ To develop space weather prediction capability

Task: To study selected events (T, U, P categories)

Present report

♦ Analysis of possible flux rope structure in the 11 events
♦ Consideration on key factors in the cause-effect chain (CME initiation, ICME propagation, geoeffectiveness, etc.)
♦ Report for 4 (5) selected events (Marubashi et al., 2017)

Final comments

♦ Difficulties in REAL predictions (cf. retrospective study)
## ISEST/MiniMax WG4 Event List

<table>
<thead>
<tr>
<th>ID</th>
<th>Dates</th>
<th>Solar Events</th>
<th>Solar Wind</th>
<th>Dst</th>
<th>Type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2012 July 12-14</td>
<td>X1 flare, CME</td>
<td>Shock, MC</td>
<td>-127</td>
<td>T</td>
<td></td>
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<tr>
<td>2</td>
<td>2012 Oct. 4-8</td>
<td>CME (stealth?)</td>
<td>Shock, MC</td>
<td>-105</td>
<td>P/U (solar source?)</td>
<td></td>
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<tr>
<td>3</td>
<td>2013 Mar. 15-17</td>
<td>M1 flare, CME</td>
<td>Shock, MC?</td>
<td>-132</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2013 June 1</td>
<td>CME?</td>
<td>Shock, CIR?</td>
<td>-119</td>
<td>P (strong storm?)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2015 Mar. 15-17</td>
<td>C9 flare, CME</td>
<td>Shock, MC</td>
<td>-223</td>
<td>P/U (super storm?)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2015 June 21-24</td>
<td>2 M fls, CMEs</td>
<td>Shock, MC</td>
<td>-204</td>
<td>T?</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2012 Mar. 7-9</td>
<td>X5 flare, CME</td>
<td>Shock, MC</td>
<td>-131</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2012 July 23-24</td>
<td>2 fls, EPs</td>
<td>STEREO-A (Carrington-type), T?</td>
<td></td>
<td></td>
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<tr>
<td>9</td>
<td>2012 Jan. 6</td>
<td>CME, West-Limb</td>
<td>No storm, GLE at Earth</td>
<td>P/U</td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td>2014 Jan. 7-9</td>
<td>X1 flare, CME</td>
<td>Shock, No MC</td>
<td>-----</td>
<td>P/U (MC deflection)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2014 Sep. 10-13</td>
<td>X2 flare, CME</td>
<td>Shock, MC</td>
<td>-75</td>
<td>P/U</td>
<td></td>
</tr>
</tbody>
</table>

Type: T = Textbook, P = Problem, U = Understood

Only **yellow-highlighted** events are reported.
Event No. 5: March 15-17 storm (The largest in Cycle 24)

Question: What caused such an intense storm?

Previous studies
Kamide & Kusano (2015), SpW: Superposition of two storms
Kataoka et al. (2015), GRL: Intensification due to pileup effect
Liu et al. (2015), ApJL: GS reconstruction of two MCs
Gopalswamy et al. (2015) IE Symp: Comparison with statistics
Wang et al. (2016), JGR: Fitted to cylindrical flux rope
Cho et al. (2017), JKAS: Fitted to toroidal flux rope
Marubashi et al. (2016), EPS: Toroidal flux rope, Dst development

In this talk
Cylinder vs torus: Torus model provides better interpretation.
Dst analysis: The prolonged southward IMF caused the strong storm.
Different MC intervals were suggested by previous studies.

- Gopalswamy et al.
- Wang et al., Kataoka et al.
- Liu et al. (2 MCs)
- Cho et al. (2017)
Causative solar eruption (commonly accepted)

(a) Full halo CME in LASCO C3 image
(b) Flare ribbons in AIA 304 image
(c) PIL where the main eruption occurred
   arrow: orientation of the horizontal field component (for positive helicity)
(d) Filament eruption in Hα image

Halo CME: March 15, 01:48 UT (LASCO C2)
C9.1 flare: 01:15 UT, S22W25 (AR 12297)
Geometry of interplanetary flux rope (torus-fit)

Spacecraft crossed near the eastern flank (consistent with the eruption in the western hemisphere), where the magnetic field is southward throughout passage. Thus, prolonged southward field attacked the Earth!
Comparison: cylinder vs torus model

cylinder model
Fit is not so good as torus-fit. Axis orientation (280°) is largely different from PIL orientation. Spacecraft passes near the western edge of flux rope. Thus, cylinder-fit is unacceptable.
Analysis of Dst Development

According to Burton et al. (1975)

\[
\frac{dD_{st}^*}{dt} = Q - \frac{D_{st}^*}{\tau} \quad (D_{st}^*: \text{modified})
\]

Solution is given as:

\[
D_{st}^*(t) = e^{-t/\tau} \cdot \left[ D_{st}^*(0) + \int_0^t Q_{sw} \cdot e^{t/\tau} dt \right]
\]

- Two-step development is NOT the reason for the intense Dst.
- Prolonged southward Bz is essential.

Consideration on chain link

- Flux rope axis: parallel to AR PIL
  - flux rope formed: parallel to PIL
  - Rotation effect: insignificant both in corona & in solar wind

- IFR deflection effect:
  - toward SE plane: required
  - E-W direction: not clear (because the size is unknown)
  - If had deflected a bit to WEST, then IFR would not hit Earth.
  - If had deflected to EAST, then IMF changed S-W-N (shorter duration of Bz < 0.)

- Prediction?
  Even if we could predict the shape of the IFR, it is IMPOSSIBLE the encounter geometry!
Event No. 11: 2014 September 12-13 storm

Question: Why the storm was so weak? (originally P)

Causative solar eruption (originally suspected)

10 September, X1.6 flare, Sep 10/17:21 (start)
    in AR 12158 (N11E05), start: 17:21 UT
A full halo CME : 18:21 UT first appearance in LASCO C2 FOV
Both right-handed (R) and left-handed (L) models reproduce the observation.

Spacecraft passage: southern edge (L) northern edge (R)

Bz > 0 throughout the S/C passage
FACT: a multi-onset event of two separate eruptions:
Eruption 1 at N15 E07, CME 2 (18:00 UT): faint one
Eruption 2 at N17 E03, CME 1 (18:12 UT): prominent one

CME 1 did not hit the Earth.
CME 2 is the origin of the September 10 flux rope.
(Required polarity change is satisfied, and axis parallel to PIL.)
FACT: 2 eruptions and 2 CMEs (one to N, one to S)

CME1: from the western eruption, denser, moved toward the Earth

CME2: from the eastern eruption, lower density, may be a shock, moved to south
Consideration on chain link

- Flux rope formation, source eruption
  - prominent CME from smaller flare
  - faint CME from larger flare

- 2 CMEs: one hit the Earth, the other not

- Flux rope (L) axis: parallel to PIL
  - flux rope formed: parallel to PIL
  - Rotation effect: insignificant
    both in corona & in solar wind

- IFR deflection
  - very large (CME 2), very small (CME1)
  - If the Earth hit a little East, Bz > 0
  - If CME 1 deflected a little more southward, Bz changed E-S-W

- Prediction?
  Again, IMPOSSIBLE to predict the Earth hitting point?
Event No. 1: 2012 July 12-14 Event (Textbook type)

Solar eruption from Dudik et al., 2014

Flare: 2012 July 12, 16:42 (Max)
S14W01 (AR 11520)
2N/X1.4
Full halo CME at 16:48 UT
flux-rope structure from cylinder-fit

Note: Southward field observed throughout the passage, while the PIL at source suggest roughly N-E-S polarity change.
The peculiar encounter explains. The tilt of cylinder axis: 325 Eastward deflection suggested from the axis tilt.
Eastward propagation

Source: S14W01

Moestl et al. (2014)
Hu et al. (2016)
Reconstruction by Grad-Shafranov eq.

Elevation = -44 (GSE - 44)
Azimuthal ang. = 232 (52)

Perhaps, this is a wrong result caused by relaxing requirement for application of this method.

Consideration on chain link

- Flux rope (L) axis: parallel to PIL
  - flux rope formed: parallel to PIL
  - Rotation effect: insignificant
    both in corona & in solar wind

- IFR deflection
  - Eastward deflection: clear
  - Northward/Southward deflection: Not clear
    (Size is unknown)

- Southward magnetic field throughout passage:
  Interpreted by the peculiar encounter

- Prediction?
  The peculiar encounter: impossible to predict?
Event No. 6: 2014 Jun 21-24

Minimum Dst = -204 nt (Second biggest storm in Cycle 24)
TB? case with M2.7 flare, halo CME on 21 June, and IFR (MC)

Solar eruption suggested within WG 4

SDO/HMI 2015 June 21 02:00
SDO/AIA094 2015 June 21 01:44
C3: June 21/04:05 UT

This is the only event that deviates from the general feature seen in other vents as described below.  <Unsettled>
Two flux rope structures from torus-fit

Both models reproduce the ACE observations.

IFR Axis orientation: inconsistent in either of fits.
Possible approaches toward resolving the problem

(1) Other possible IFR intervals?
   Liu et al. (2016): two separate flux ropes (not shown)

(2) Possibility of other solar source event(s)? This requires:
   Careful survey of CMEs
   Large deflection of the June 21 CME (avoid Earth hitting)

(3) Attributing to IFR rotation during propagation to Earth
   May be needed are:
   A different flux rope model (obtained L type: no good)
   A different solar source event
   Precise interpretation about how it rotated
Possible supporting evidence for approach (2)

Comparison of the ACE and Wind observations

ACE

B

Bx

By

Bz

18 00 06 12

One structure

WIND

Suggested is ....
Some smaller-scale structure penetrates the IFR. Wind passed through it. ACE passes very near the boundary.
IPS observations shows: the IFR (shock) appears earlier than the flare (June 21/01:42)
What’s more about other solar wind quantities needed?

**Magnetic field intensity**: magnetic flux comparison, Sun and 1 AU

**Solar wind velocity**: not addressed (relation with IFR is weak)

From Qiu et al., ApJ (2007) Other works exist (Hu et al., Gopalswamy et al.)

Global shape of IFR, Distribution of poloidal flux along the axis: necessary but unknown
Summary

We have seen the flux rope structures and their solar origins for the WG 4 campaign events.

It seems possible (at least in principle) to predict magnetic structures of ICMEs from solar observations.

We recognize many problems that need further studies.

- CME-source eruption correspondence: still unclear
- ICME propagation: strongly affects IMF at Earth

We strongly recognize the difficulty of prediction: we may “correctly” predict the shape of ICMEs, but what we need is “precise” geometry.
Thank you
For
your attention!
<table>
<thead>
<tr>
<th>ID</th>
<th>Solar Wind (IP Flux Rope)</th>
<th>Solar Source Region</th>
<th>Helicity</th>
<th>tilt</th>
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<tr>
<td></td>
<td><strong>S/C</strong></td>
<td><strong>Model</strong></td>
<td><strong>R/L</strong></td>
<td><strong>IFR tilt</strong></td>
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<td>ACE</td>
<td>torus</td>
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<td>247</td>
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</table>
統計結果: (1) 磁気ロープ軸が発生域のPILに平行、(2) helicity rule

Solar Eruptions → Initiation & Evolution → CMEs → Magnetic structure → ICMEs → Propagation (velocity) → Magnetic Storms

- Source PIL
- IP flux rope
- Magnetic structure
- Propagation (velocity)
- Deformation
- Deflection
- Rotation

- Sun
- Corona
- IP Space
- Earth

- SOHO
- SDO
- STEREO
- Radio
- ACE
- Wind
- GCS
- FF-FR
- GS-eq
- MHD
- Dst model