A Comprehensive Study of Superstorms from 1957 to Present

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Introduction

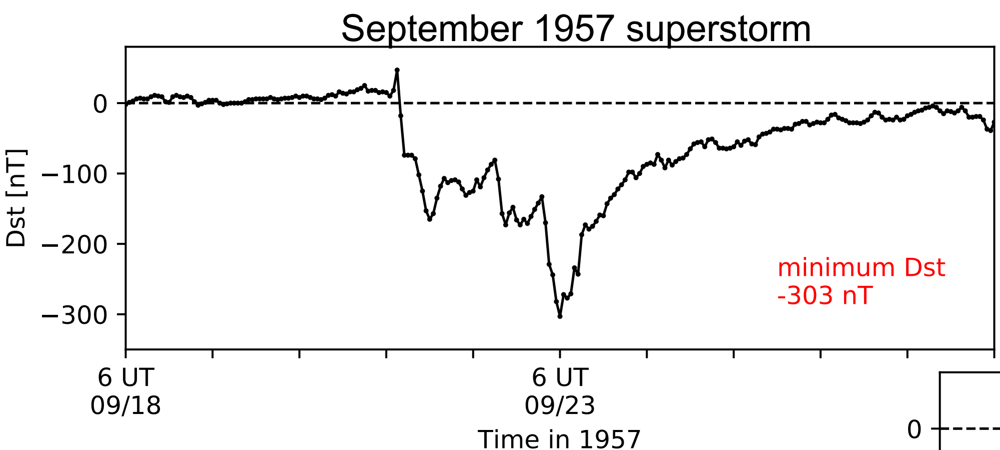
- Superstorm definition: minimum Dst ≤ -250nT.
- Superstorms are relatively rare, but their impacts on the geospace environment can be dramatic. Our scientific understanding of extreme space weather events, particularly their causes and consequences, is incomplete (Riley et al., 2018).
- Numerous research on particular superstorms. Several studies on statistical behaviors of superstorms occurred over a limited time span (Tsurutani et al., 1992, Cliver and Crooker, 1993, Bell et al., 1997, Gonzalez et al., 2002, Dal Lago et al., 2004, …).
- To extend the past studies in both time and scope, we conduct a study of all superstorms, since the introduction of the *Dst* index in 1957 until present**. We investigate the characteristics, solar and interplanetary causes of these storms.**

Methodology – Data Analysis

- Dst index from Kyoto data center, 1957 – present
- Interplanetary: 1-hr and 1-min (if available) OMNI data, 1963 - present
- Sunspot number from SILSO, version 2.0, 1957 – present
- Adjusted daily 10.7-cm solar radio (F10.7) flux from NOAA, 1957 – present
- X-ray flare data from SOLRAD 1968 – 1974, from GOES after 1975
- Comprehensive Flare Index (Dodson & Hedeman, 1971) from NOAA, 1968-1990

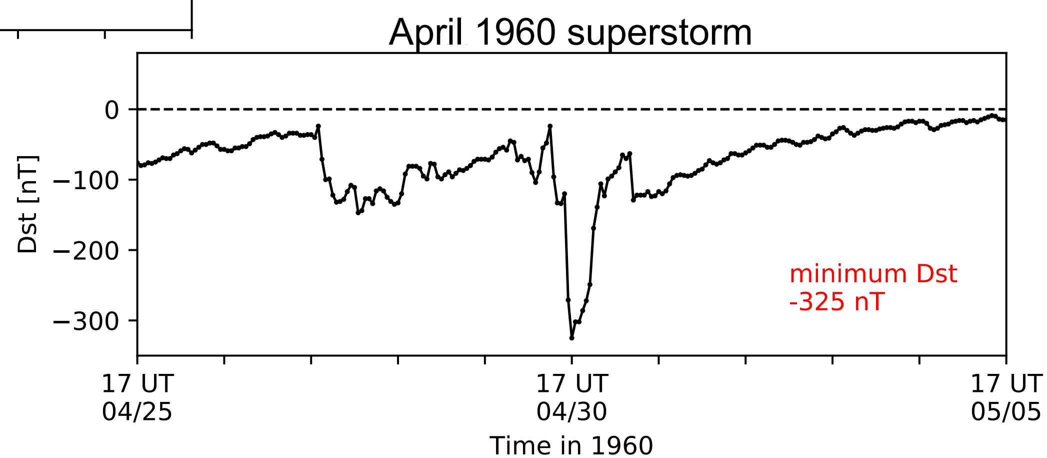
Superstorm Characteristics

- From 1957 to 2018, **39 superstorms** with minimum Dst ≤ −250 nT are identified.
- 87% of the 39 superstorms have a multi-step main phase development or are built upon preceding geomagnetic storm activity, bases on their Dst profiles.



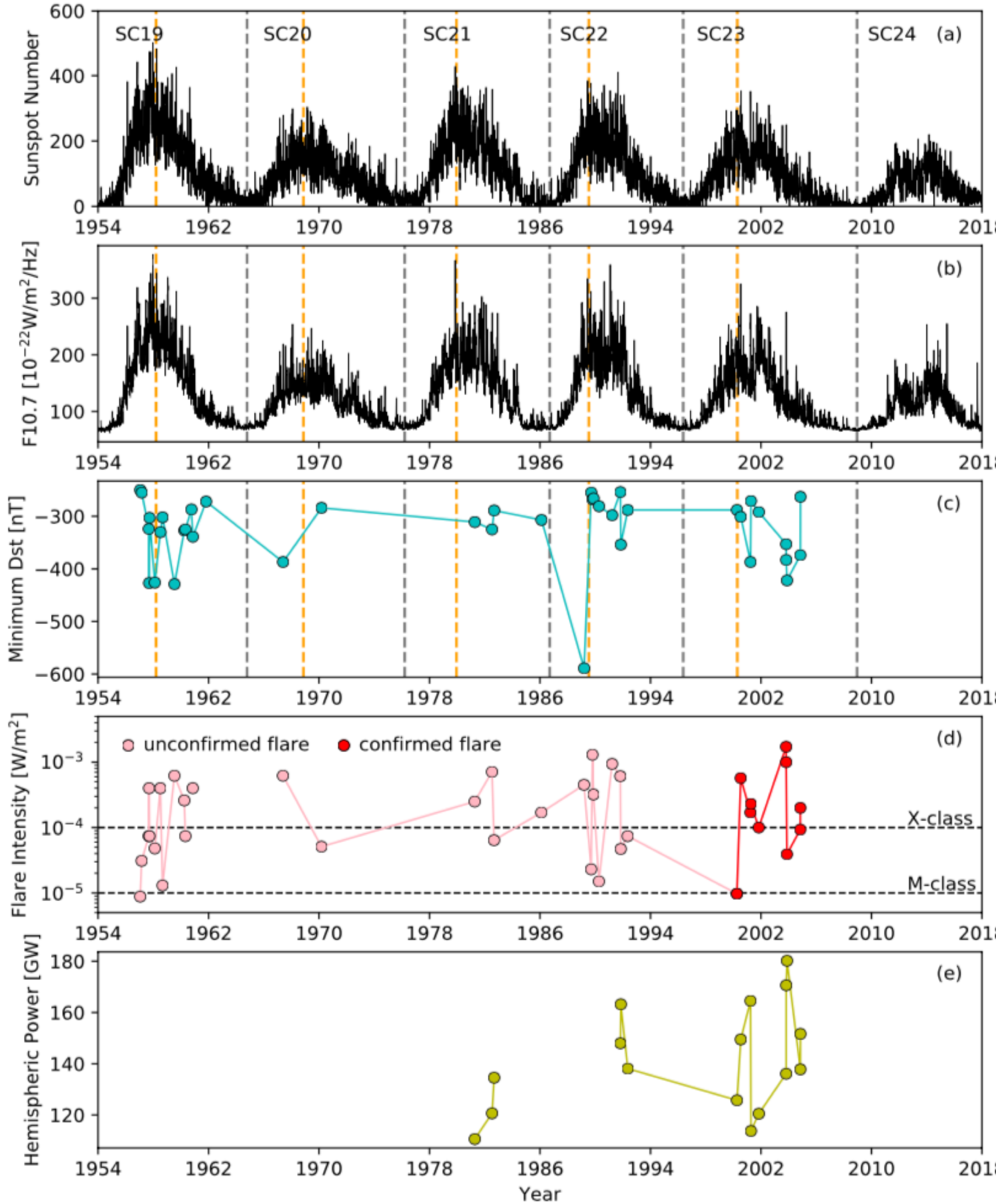
Multi-step main phase development (Type II superstorm)

Built on preceding geomagnetic activity (Type III superstorm)



Type I superstorm is defined as the *Dst* monotonically decreases from a positive value to its maximum negative value.

Solar Cycle Dependence



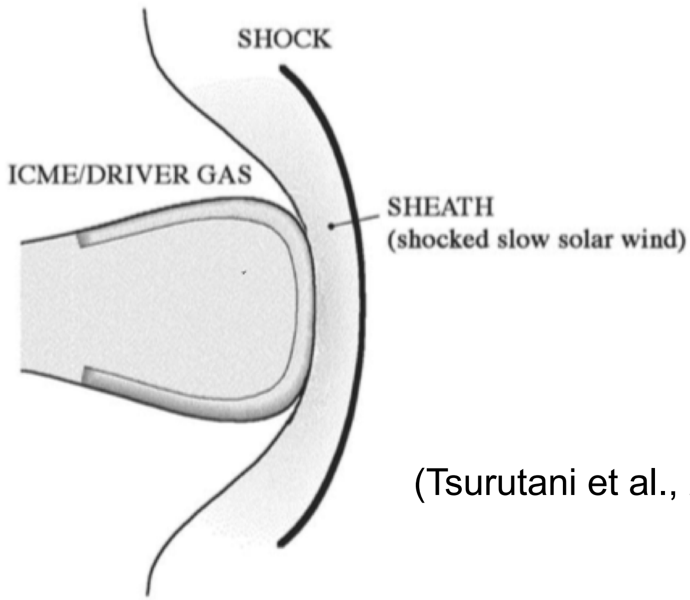
46% superstorms occurred during a solar maximum phase, 44% occurred during a declining phase.

Only 2% occurred during a solar minimum phase.

Interplanetary Structures

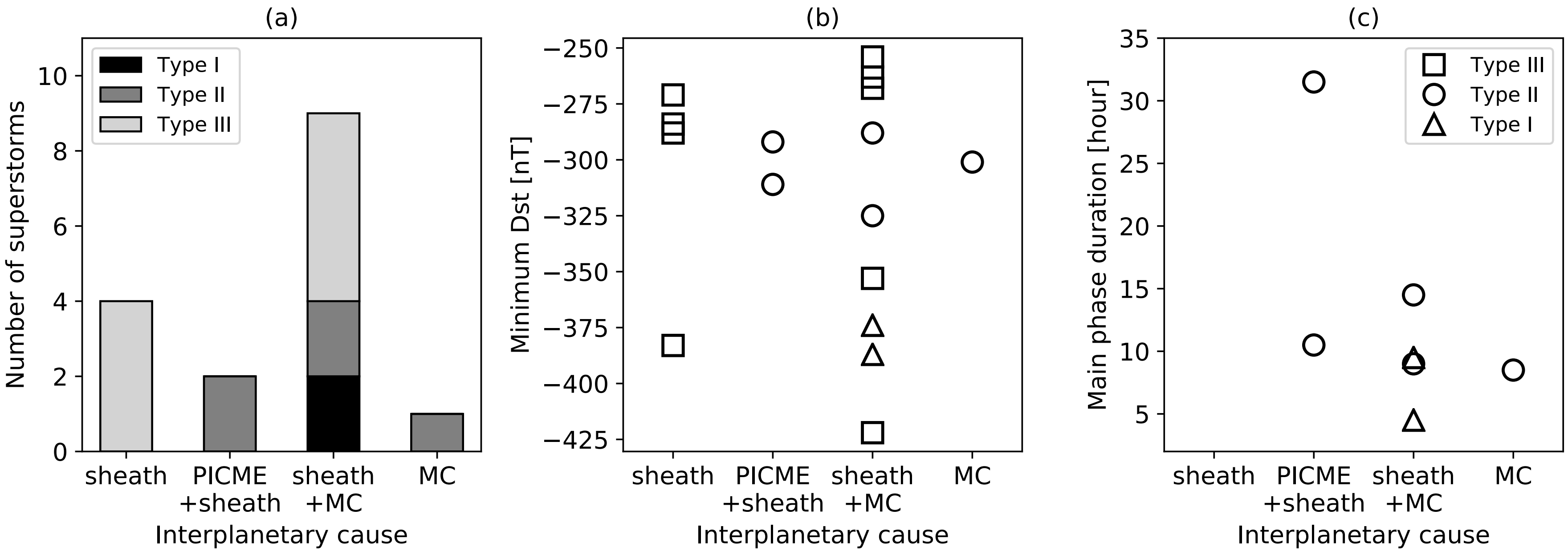
Four interplanetary phenomena that can have large southward magnetic fields:

- sheaths anti-sunward of ICMEs (Tsurutani et al., 1988)
- magnetic clouds (MCs) within ICMEs (Burlaga et al., 1981)
- filaments within ICMEs (Burlaga et al., 1998; Kozyra et al., 2014; Lepri & Zurbuchen, 2010)
- Corotating Interaction Regions (CIRs) associated with high speed stream/slow speed stream interactions (Smith & Wolf, 1976; Tsurutani et al., 1995).



(Tsurutani et al., 2003)

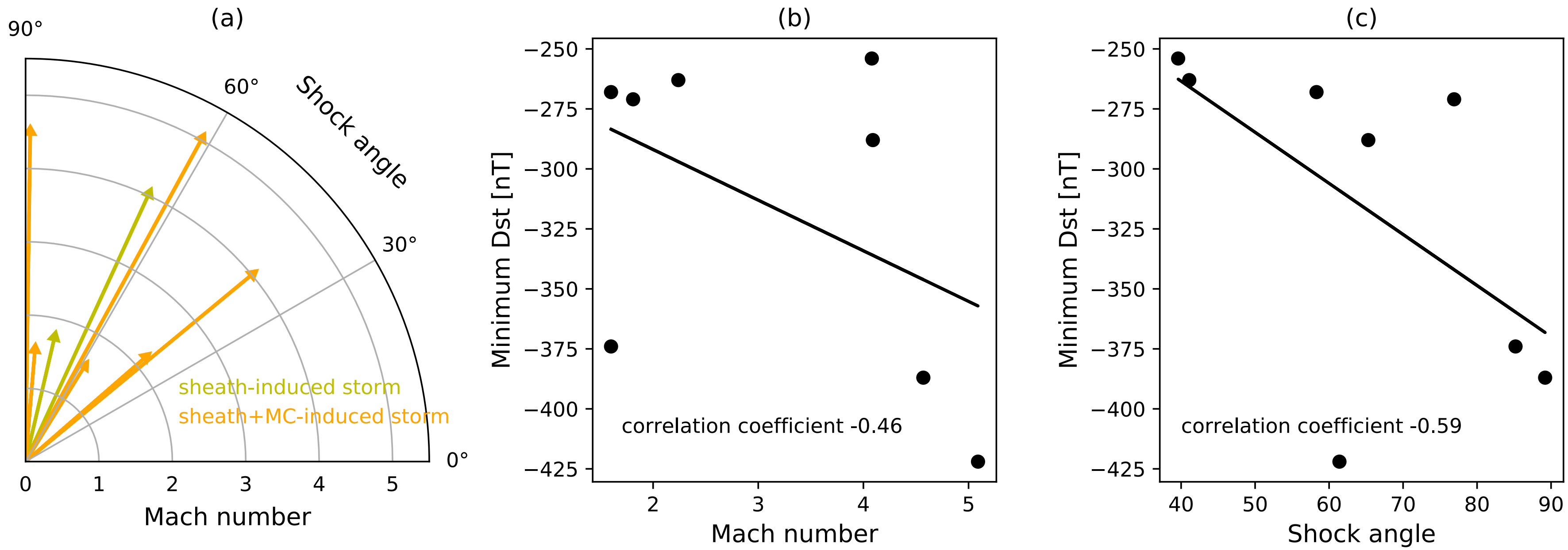
Interplanetary Causes



PICME: Preceding ICME

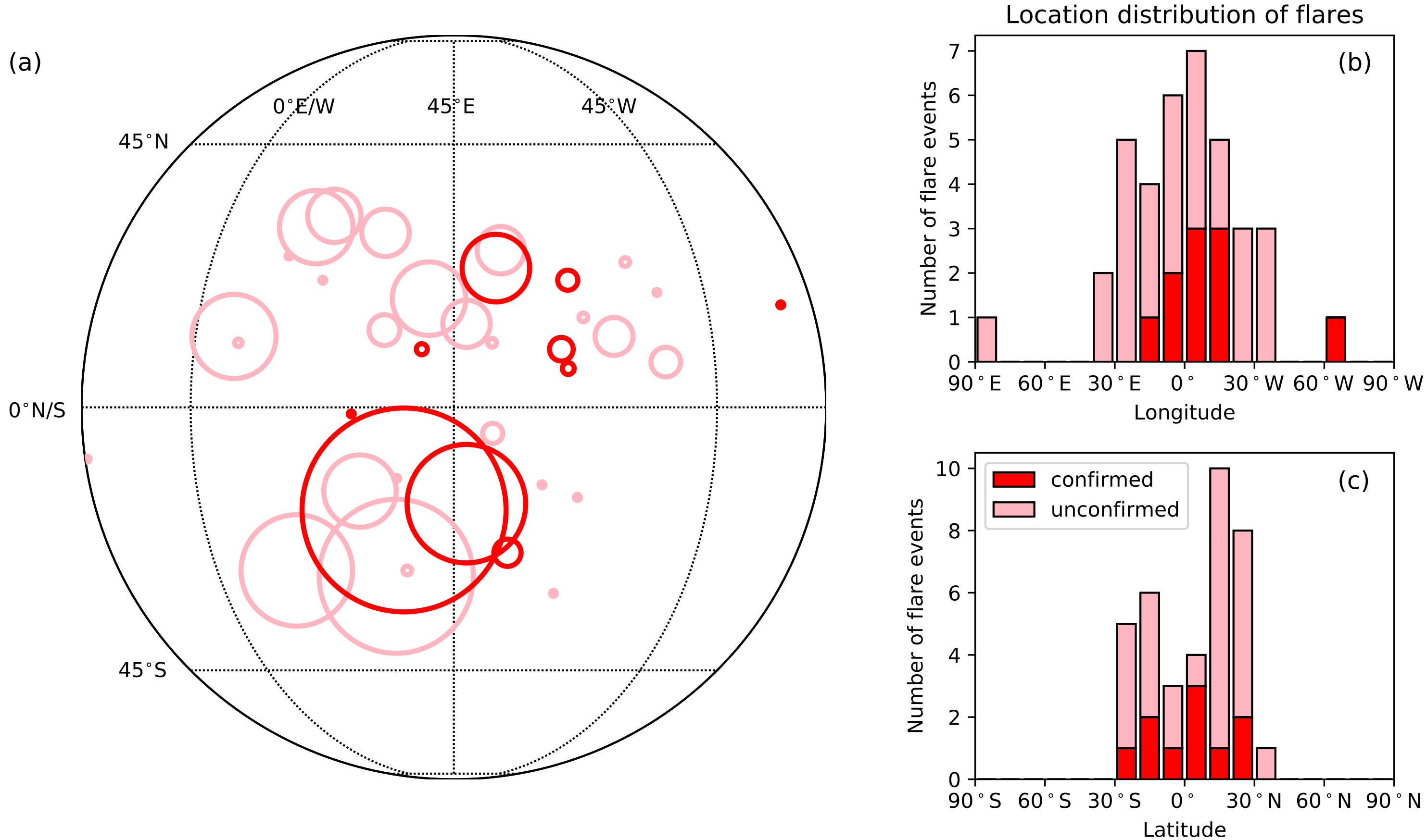
- All superstorms are caused by magnetic clouds within ICMEs or the upstream sheaths of ICMEs or both, and no superstorms are caused by filaments within ICMEs or solar wind structures related to CIRs.
- 95% of the superstorms are solely caused or partially caused by the sheath anti-sunward of an ICME, indicating the importance of the sheath structure in driving superstorms.
- Little relation between the type of the interplanetary cause and the superstorm strength.

Interplanetary Shock Analysis



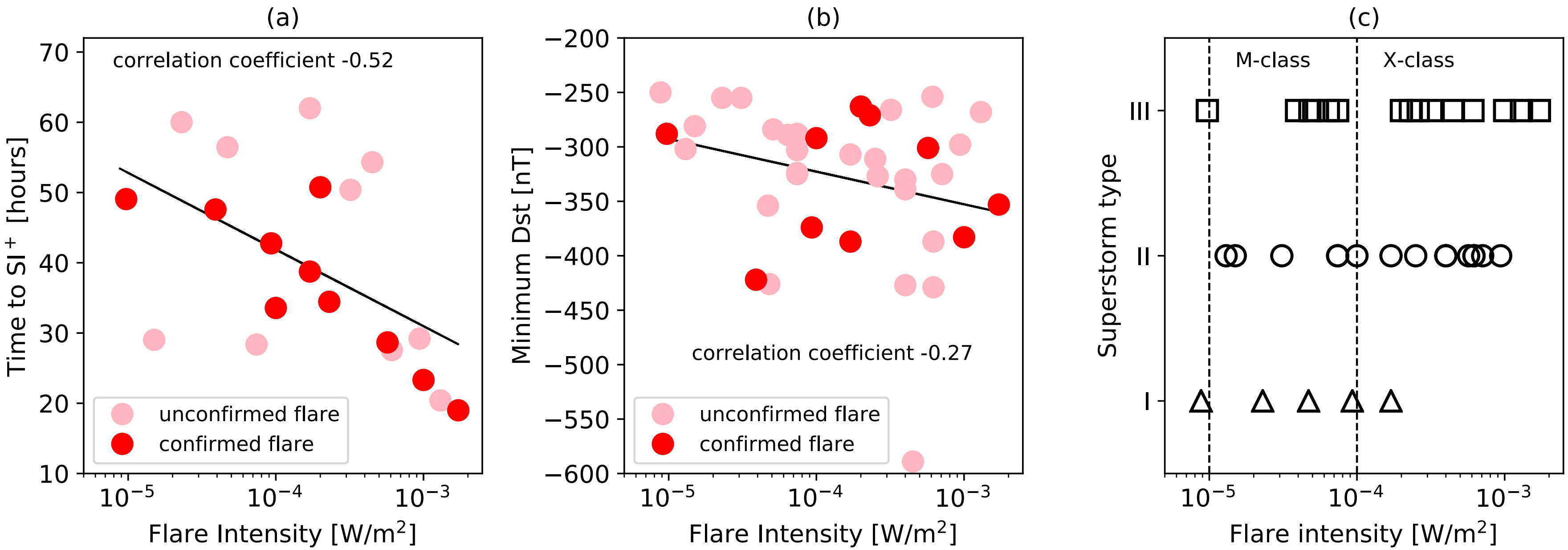
- For eight superstorms that have identifiable interplanetary shocks preceding the ICMEs, the Mach number of the shocks mostly varies between 1 and 5. The highest Mach number is 5.1.
- The shock normal angles were almost all quasi-perpendicular (~>40°).
- Larger shock normal angles correspond to greater intensity superstorms.

Solar Flare Association



- All of the solar flares associated with the superstorms occurred in active regions. These flares were mostly X-class or M-class, and they were mostly located within 30° from the central meridian and the equator on the solar disk.
- A notable exception: a superstorm initiated by a flare nearly at the west limb. This superstorm was driven by the sheath anti-sunward of an ICME.

Flare Intensity Vs Storm Strength



- The solar flare intensity is weakly related to the strength of the associated superstorms, while more intense solar flares tend to induce faster ICMEs that arrive at the Earth in shorter time periods.

Summary of Major Findings

- A majority of the superstorms have a multi-step main phase development or are built upon preceding geomagnetic storm activity.

- For superstorms with identifiable interplanetary drivers during the main phases, all of them are caused by interplanetary structures related to ICMEs. **In particular, the sheath region anti-sunward of ICMEs solely or partially contributes to the main phase development of most superstorms studied.** No superstorms in this study are caused by filaments within ICMEs or CIRs associated with high-speed solar wind streams.

- For the interplanetary shocks anti-sunward of the ICMEs, we have found that **almost all shock normal angles are quasi-perpendicular**, and a larger shock normal angle corresponds to a more intense superstorm.

- For most superstorms we find associations with solar flares, mostly X-class and M-class. Still, a few superstorms could be attributed to disappearing solar filaments. Most associated flares were located in the central meridian or slightly west of it as expected. We obtain a weak relation between the solar flare intensity and the superstorm intensity indicated by the minimum Dst, while a more intense solar flare statistically corresponds to a shorter time delay from the flare occurrence to the sudden impulse of the superstorm.

Conclusion

- This study implies several solar and interplanetary features that are significant for causing superstorms:
  - flares from solar active regions and near-central meridian location of the active region are important.
  - flare intensity affects the speed of the ICME, which determines the time when the superstorm occurs after the flare onset.
  - the angle of the interplanetary shock is crucial for the superstorm intensity.

- What do these results imply for the prediction of future superstorms and those even more intense than the ones included in this study? Can an extrapolation be made?

- Looking to the flare activity does not seem to be a good procedure in order to forecast the intensity of a superstorm, as shown by the poor correlation found between the flare intensity and the superstorm intensity.

- A feature found in this study poses a new problem for predicting a superstorm: how can one predict whether a shock will be quasi-perpendicular or not?

Questions and comments are more than welcome.
Please contact Xing.Meng@jpl.nasa.gov

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- The solar X-ray flare flux data were from the NOAA website (https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-flares/x-rays/), and the Comprehensive Flare Index was obtained from the NOAA website (https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar- features/solar-flares/index/ comprehensive-flare-index/).

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