Differences Between CME and CIR Geomagnetic Storms

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NASA Image from STEREO gallery
Overview of the Problem

• Space weather implications
• Solar wind and magnetospheric coupling
• The culprits: CIR and CME interplanetary disturbances
• Key differences between CIR and CME geomagnetic storms
• Summary, Conclusion, & References
Space Weather Implications

A key question of our space weather program is our ability to predict occurrence of CIR and CME’s and how they create geomagnetic storms using satellite observations.

• Punch line:
  • CIR driven storms create more problems for space based assets while CME driven storms cause more problems for Earth-based electrical systems (Borovsky and Denton, 2006).
Solar Wind and Magnetospheric Coupling

• Why do CIR and CME’s create different storms?
  • Geomagnetic storms are driven primarily from electric field input from reconnection: vBs, were v is the solar wind speed and Bs is the southward magnetic field in GSM coordinates (Dungey, 1961).
  • CIR and CME have differing morphology, duration and temporal profiles with respect to v and Bs.

• Problems: Identification of disturbances and ‘geoeffective’ analyses differ between authors.
CME Characteristics

• Occur predominately during solar maximum, are mostly radial structures, and drive storms ~ days.

• Typically are composed of 3 parts:
  • Forward Shock: If the speed differential between the remnants of the coronal ejecta and the slow, upstream solar wind is greater than the magnetosonic wave speed (50–70 km/s), a forward shock is formed. Typical shocks of Mach 2-3 are observed, on the order of minutes.
  • Sheath region: between the shock and the cloud the field and density are compressed and turbulent, ~ 9-24 nT (dependant on the Mach of the shock), timescale on the order of hours.
  • Magnetic cloud: slow varying (~ day), strong magnetic fields (10-25 nT), low density, low ion temperature as compared to background solar wind.
Graphical view of ICME

Figure 2 from Gonzalez et al., 1999.
CIR Characteristics

• Occur predominately during the descending phase of solar cycle, are nearly azimuthal in profile, and last up to a week.
• Lack of sudden impulse (no forward shock at 1 AU) but can contain the typical 3 phases of a magnetic storm.
• They are characterized by strong magnetic fields ~ 30 nT (due to high and low speed stream compression)
• Bz fluctuates throughout interval (due at least in part by intense Alfvén wave activity embedded in high speed streams see Smith et al., 1995).
Graphical View of a CIR

Figure 4 from Tsurutani et al., 2006.

Figure 6 from Gonzalez et al., 1999.
Key Differences: What is Important?

- **Everything!** This class is interested in forecasting space weather so all aspects are important:
  1. Dst: morphology, strength (i.e., Ring current)
  2. Solar energetic protons
  3. Preconditioning of magnetosphere
  4. Solar wind parameters (important for PS)
  5. Plasma sheet properties (density and temperature)
  6. Spacecraft surface charging
  7. Radiation belt energization and dynamics
  8. Great auroras
  9. Ionospheric effects (GIR, equatorial bubble in topside ionosphere, etc…)

→ In fact there are at least 21 differences between CIR and CME storms (Borovsky & Denton 2006).
(1) Dst: Features and Duration

**CME:**
- Can create strong strength storms (Dst < -100 nT)
- Initial phase: caused by forward shock, \( \tau \sim \text{min-hrs.} \)
- Main phase: initiated by a southward IMF and enhances nightside convection thus ring current increases, \( \tau \sim \text{hrs.} \)
- Recovery: when the ring current begins to decays, \( \tau \sim \text{days.} \)

**CIR**
- Due to highly oscillatory nature of the Bz GSM field, the resultant storms are weak to moderate in Dst, less than 100 nT.
- *Initial phase*: caused by an increase in ram pressure from the HCSPS but density increase is gradual, rarely a sudden impulse is observed.
- *Main phase*: caused by CIR
- *Recovery phase*: high speed stream contains Alfvenic waves which create intense AE increases (called HILDCAAs)
Figure 3 from Gonzalez et al., 1999.

Figure 5 from Tsurutani et al., 2006.
(2) Solar energetic protons

Solar energetic particle events are enhanced fluxes of subrelativistic and relativistic ions that have durations of hours to days. They are known to be associated with flares and interplanetary shocks (Borovsky & Denton 2006).

- Sometimes accompany CME (with shocks) driven storms, but rarely with CIRs at Earth (because shock hasn’t typically steepened yet—one SEP was observed during CIR but was due to flare in late 1999/early 2000, see McPherron catalog).
(3) Calm before the storm:

**CME:**
- 37% of storms had a calm reported by Denton et al. [2006] which studied 68 CME driven storms.

**CIR**
- 67% of storms (Borovsky & Steinberg 2006).
- Tend to have an extended interval (1-2 days) of extreme geomagnetic calm (Kp ≥ 1).
- Due to Russell-McPherron effect: a sector reversal just upstream of the CIR stream interface.

Important because the magnetosphere fills up with dense plasmaspheric plasma and a dense LLBL plasma which can lead to a stronger ring current. Interesting that this occurs during CIR storms which are already weak storms!
(4) Solar wind parameters for CME and CIR superposed at shocks and stream interfaces respectively.

Fig. 3, Kataoka and Miyoshi et al., 2006
(5a): Plasma Sheet Density

- Using LANL/MPA instrument at geosynchronous orbit Denton et al., 2006 studied the plasma sheet ions and electrons (.1-.03-45 keV) for CME and CIR driven storms.

- CME enhanced density spreads to all local times and returns to prestorm levels ~ 2 days.

- CIR enhanced density does not spread in local time and returns to prestorm levels with ~ 24 hrs even though Dst is similar.

Figure 3. The hot ion and hot electron densities for the three data sets used in the study: (a) and (b) Group A - all 78 ICME events, (c) and (d) Group B - 45 ICME events with minimum Dst > -100, and (e) and (f) Group C - 32 CIR events, as a function of epoch time and local time.

Denton et al., (2006)
(5b): Plasma Sheet Temperature

CME

• Size of the storm may play a role in modulating temperature.

CIR

• The temperature is much higher than for CME driven storms, especially for electrons.

Figure 4. The hot ion and hot electron temperatures for the three data sets used in the study; (a) and (b) Group A - all 78 ICME events, (c) and (d) Group B - 45 ICME events with minimum Dst > -100, and (e) and (f) Group C - 32 CIR events, as a function of epoch time and local time.

Denton et al., (2006)
(6): Spacecraft potential

Measured voltages of geosync-orbit LANL satellites with respect to ambient plasma

CME

- Spacecraft potential is very slightly elevated during storm.

CIR

- Spacecraft potential is highly elevated in magnitude, effect lasts for days

Figure 6. Same as Figure 5 except we remove all times when the spacecraft is in the Earth’s shadow. The magnitude of the potential is much greater for the CIR events, compared with ICME events, and the elevated spacecraft potential lasts for a longer time.

Denton et al., (2006)
(7a) Radiation Belts

Enhanced relativistic electrons (> MeV) in the outer radiation belt can cause severe spacecraft problems. - ** We note that enhanced ULF Pc5 waves are also observed and thought to be related (Borovsky & Denton, 2006-see bottom Figure).

CME driven storms:
• Less severe

CIR driven storms
• Can be severe, enhanced fluxes peak during declining solar cycle.
(7b) Formation of new radiation belt

- Usually caused by the capture of SEP ions during strong compression of the magnetosphere, but new inner electron belt has also been created from large compression of a SSC.
- CME driven process not related to CIRs.
(8): Aurora

• **Great auroras** are predominately due to CME driven storms and peak during solar maximum

• **HILDAAs**: low intensity aurora over the entire oval is observed during CIR driven storms in the recovery phase.
(9a) Ionospheric Effects

CME affect:

- GIR: geomagnetically induced currents which are hazardous to Earth based electrical systems.
  - Caused by rapid intensification of ionosphere currents that are driven from shock compression of the magnetosphere or a substorm.
  - Occur predominately during solar max and/or the early declining phase

Brodsky & Denton, 2006
(9b) Ionospheric Effects: Unknown

- Large equatorial bubbles due to penetration electric fields
- SAPS: subauroral polarization stream
- AKR disappearance with dense plasma sheet appearance
- Injection of cool dense plasma sheet material into night side
- Plasmaspheric plumes
Summary

• CME driven storms are brief, have denser plasma sheets, have stronger Dst perturbation, sometimes have SEP events, can produce new radiation belts, great auroras, geomagnetically induced currents, and topside ionosphere equatorial bubbles (i.e., M-I coupling effects).

• CIR driven storms have longer durations, have hotter plasma sheets (thus stronger spacecraft charging), and produce higher fluxes of relativistic electrons.

• CIR driven storms are more hazardous to spacecraft while CME storms are more damaging to Earth based systems.

→ Note that Dst alone is a poor indicator of the behavior of a storm!
Conclusions: CME & CIR-driven Storms

Fig.1: Kataoka & Miyoshi, 2006
References

• Cane, H.V. et al., Coronal mass ejections interplanetary ejecta and geomagnetic storms, GRL, Vol. 27, No. 21, Nov. 1, 2000.
Magnetosheath Plasma-β & Sawtooth Injections

• Plasma $\beta_{\text{ram}} < 1$
  • The field lines have difficulty draping thus squeeze the MS into a flattened shaped which may create sawtooth injections (Borovsky & Denton 2006).

Fig. 5 -Borovsky & Denton, 2006