CME Observations – from Sun to impact on Geospace

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Sun: May 8-11, 2024 X-class flares
Earth: May 10-11, 2024 event

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Kp index

Aurorae over Graz, May 11, 2024 © Florian Koller
Solar surface phenomena related to an eruptive event

- **Flare** – bright H-alpha, EUV, SXR, HXR, white-light for strong events (e.g., Fletcher+ 2011)

- **Flare-reconnection-CME feedback:**
  HXR flare <=> CME acceleration; SXR flare <=> CME speed (e.g., Zhang+ 2001, 2004; Chen & Krall, 2003; Maričić+ 2007; Temmer+ 2008, 2010; Schmieder+ 2015)

- **Flux rope** – filament eruption and mass motion (e.g., Schmieder+ 2013)

- **Mass release** – EUV dimming regions (e.g., Hudson & Cliver, 2001; Mandrini+2007; Temmer+ 2017); dimming-CME speed relation see Dissauer+ 2018, 2019;

- **Propagating surface wave** due to lateral (over-)expansion of flux rope (e.g., Patsourakos+2010; Warmuth, 2015)

- **Post-eruptive arcades** – proxy for magnetic structure and reconnected flux (e.g., Green+ 2011, 2015; Gopalswamy+ 2017; Palmerio+ 2018; Tschernitz+ 2018; Scolini+ 2020).

Temmer, 2021 (Living Reviews)
CME properties are set in low corona

*CMEs that start at lower heights also reach their peak acceleration at lower heights.*

Lower coronal heights :: stronger Lorentz force and shorter Alfvén time scales involved in the process (with stronger magnetic field and larger Alfvén speed; see Vršnak et al., 2007).

Bein et al., 2011

*CMEs that are accelerated at lower heights reach higher peak accelerations.*
The lower the starting height, the faster the CME

Distance at which reconnection or instability (disconnection) sets in, i.e., at which height the eruption starts, dictates how strongly CMEs are driven (Bein+ 2011).

Stealth CMEs typically go with the flow, but may produce shocks further out in IP space (e.g., Vrsnak & Lulic, 2000).

see also D’Huys+2014; Nitta & Mulligan 2017; Vourlidas & Webb 2018; Palmerio+2021

Stealth CMEs might cause „problem storms“ due to missed alarms.
Confined events (flare: yes, CME: no) might cause false alarms.
Information support: Type III radio bursts

From Lynch+ 2017; model results based on event from Robbrecht+ 2009
Radio signatures

- Type II: fast CMEs (multiple events – preconditioning effects – density depletion)
- Type III: eruptive flare

See more e.g., in Mann+ 1998; Gopalswamy+ 2001; Vrsnak+ 2002; Zucca+ 2018; Morosan+ 2020;
Structuring of IP space – magnetic “obstacles“ for CMEs

- OMF „shapes“ the heliosphere (HSS, forming SIRs/CIRs), magnetically connects the Sun to the planets, and dominates the motion of energetic particles (Frost+ 2022).
- CHs are assumed to mainly represent the OMF.
- Discrepancy between in-situ and magnetogram OMF estimates; OMF underestimated by factor 2, e.g., Arden, Norton & Sun, 2014; Linker+ 2017; Wallace+ 2019; Linker et al., 2021; Frost+ 2022; Linker+ 2021; Asvestari+ 2024;
- AR outflows might contribute to OMF (vanDriel+ 2012).
- OMF evolution correlates with CH open flux, but not with CH area evolution (Heinemann+ 2024).
- OMF variation might be related to vanishing remnant magnetic field at poles (Heinemann+ 2024) => cycle dependence!

Linker+ 2021
Internal magnetic field

Cappello+ 2024
Internal magnetic field distribution

- Small-scale density structures distributed in different regions of the CME (Cappello+ 2024).
- Blobs might refer to interaction of CME flanks/trailing edge with ambient SW (Cappello+ 2024).
- Global shape of CME from 1AU looks different (see also Howard+2022).
HI data from SoLO and PSP – line-of-sight integrated intensity over different distances

New data reveal the complexity of CME’s internal magnetic field structure, see Cappello+ 2024, in prep.; Rouillard+ 2020; Hess+ 2020; Liewer+ 2021; Wood+; Braga & Vourlidas 2021; Howard+ 2022 …
Local structures versus global appearance

- Space weather forecasting focus: arrival time and speed of shock-sheath and magnetic ejecta
- *Are we consistent in our understanding of different structures and their definitions?* See also ISSI team by C. Verbeke and L. Mays. (e.g., Verbeke+23)
- PSP/WISPR (Vourlidas+ 2016) enables comparative studies in-situ $\Leftrightarrow$ high-resolution WL image data

It needs further investigations and discussions about local vs. global properties and in-situ vs. remote sensing observations.
Expansion behavior of CMEs with and w/o driving clear sheaths

Sheath = high plasma-beta; implications for IMF draping and plasma accumulation (McComas+ 1998; Siscoe & Odstrcil, 2008);

From inner heliosphere to 1 AU both ME types increase in size by ∼47%; at ca 0.75AU strongest size increase; no ICME I type >1.5AU (statistics from > 2000 CMEs, see Larrodera & Temmer 2024);

Other recent studies on CME sheath characteristics: e.g., Mitsakou & Moussas, 2014; Masias-Meza+ 2016; Janvier+ 2019; Lugaz+ 2020; Salman+ 2020, 2021; Temmer+ 2021; Temmer & Bothmer, 2022; [...] See review by Kilpua+ 2017

Larrodera & Temmer 2024
Preconditioning and interacting structures

- High solar activity: multiple CMEs.
- Decay phase: SIRs/CIRs dominate.
- HCS structure varies

Besides interactions, each CME generates perturbations in the smooth outflow of the slow solar wind (preconditioning duration 2-5 days: Temmer+2017).

Interactions (CME-CME, CME-SIR, CME-HCS) cause complex structures (e.g., Gopalswamy+ 2001; Burlaga+ 2002, 2003; Harrison+ 2012).

Interaction events cause most intense geomagnetic storms (e.g., Burlaga+ 1987; Farrugia+ 2006a,b; Xie+ 2006; Dumbović+ 2015)

CME-CME interaction review: Lugaz+2017
Interacting magnetic structures cannot easily penetrate (frozen-in) => strong changes in CME physical properties:

- geometry and size (deformation, compression)
- propagation direction and orientation (rotation, deflection)
- kinematic properties
- magnetic structure and field (amplification, distortion, reconnection – erosion or flux injection, magnetic tension)
- plasma parameters, thermal properties

Preconditioning and interacting structures (CME-CME, CME-SIR)

Temmer+ 2024 (iSWAT H1+H2 COSPAR Space Weather Roadmap paper)
Impact at Earth – interdisciplinary research

Cascade of reactions happen starting in the magnetosphere (opening of magnetic field, compression, substorms), with consequences for modern life – ionosphere (communication, navigation), thermosphere (satellite drag; e.g., Knipp+ 2004; Bruinsma+2006), GICs (power grids); see e.g., review by Tsurutani+ 2011; also, Dasso+ 2020;

Adapted from Koller+ 2024
**Impact at Earth – interdisciplinary research**

- **Magnetosheath jets** represent a significant coupling effect between SW and the Earth's magnetosphere (e.g. Hietala+2009; Plaschke+2018).
- Recent studies showed significant jet variation with large-scale SW structures SIRs and CMEs (Koller, Temmer+ 2022; Koller, Plaschke, Temmer+2023; Koller+2024).

1st 'Heliophysics in Europe' Workshop
(ESTEC, November 18 – November 22, 2024)

- Lead time: 20 hours (https://swe.ssa.esa.int/).