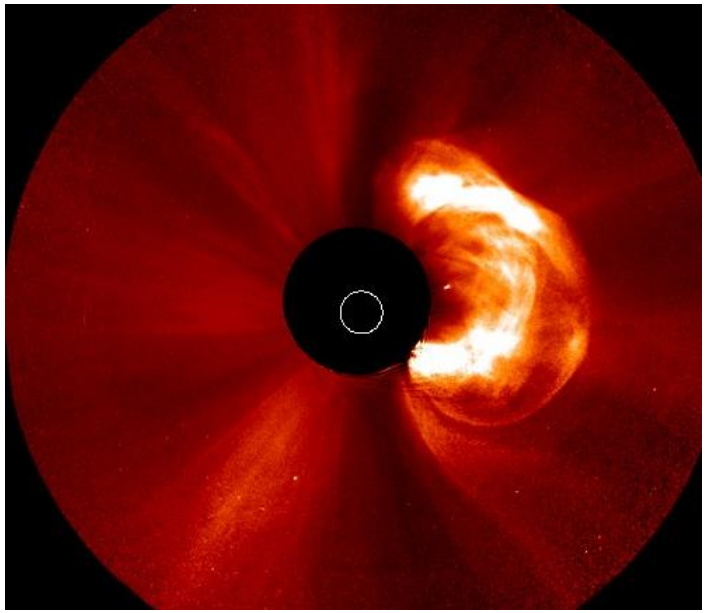
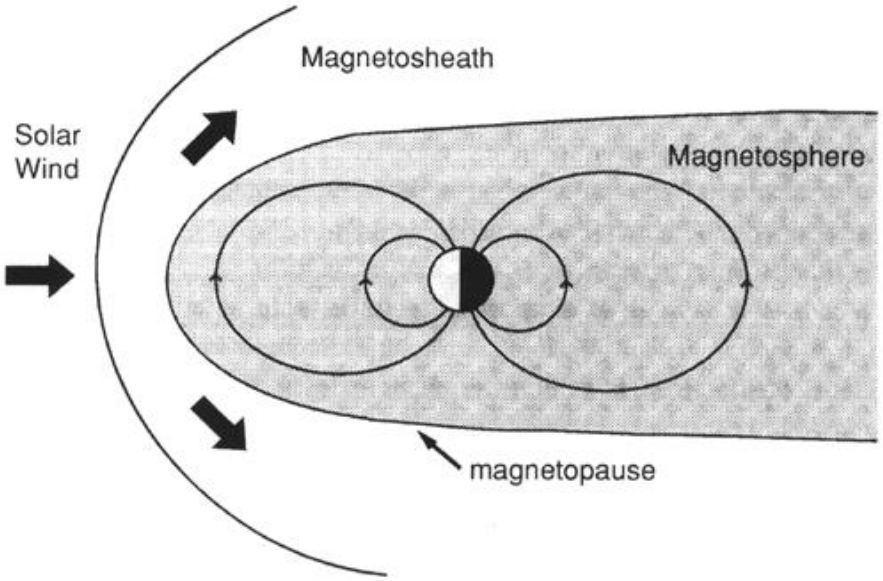
Some Introductory Remarks on Space Weather

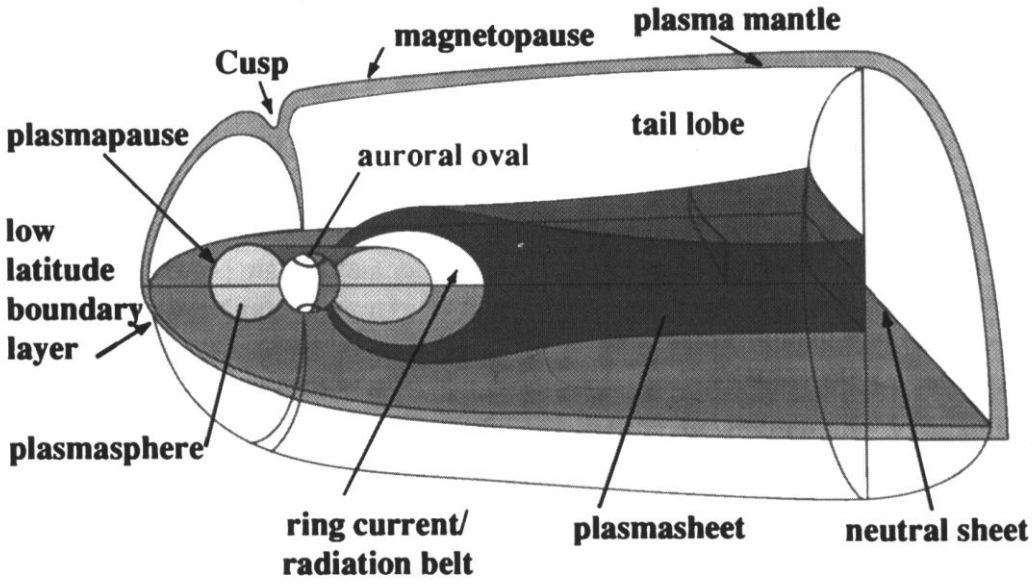
Iver Cairns (University of Sydney)





1. Space Weather

- Conditions in space that may affect human systems & activities on Earth & in space.



2. Qualitative Overview of Space Weather

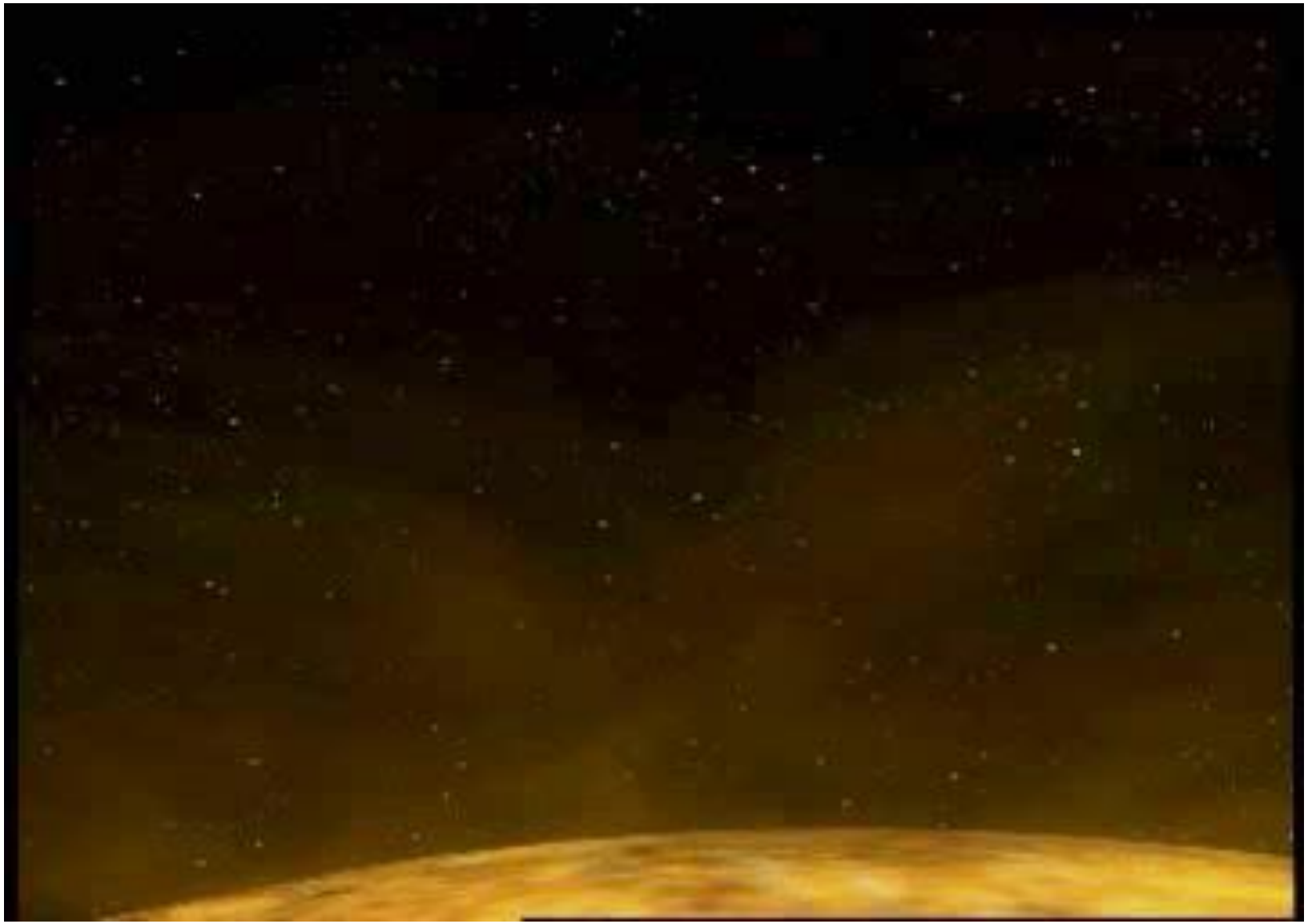
- Refers broadly to conditions in space that may affect human activities on Earth & in space

- These conditions change in response to
  - Solar activity like flares (UV and X-ray)
  - Solar wind phenomena like southwards B_z, P_{ram}. CMEs, & CIRs
  - Changes in coupling between ionosphere, magnetosphere & solar wind.

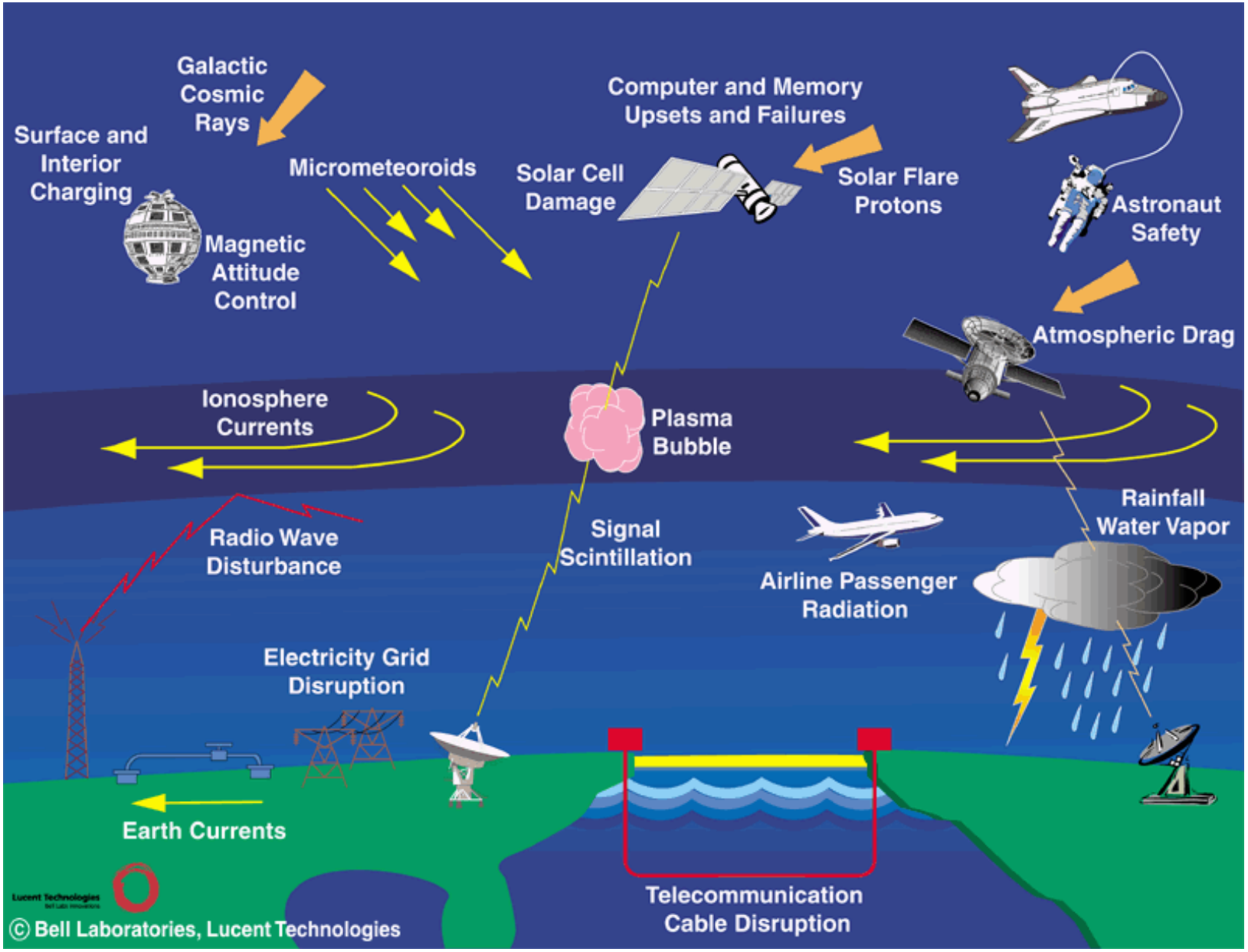
- The magnetosphere is a dynamic, time-varying system which responds in complex, not always understood ways to changes in the solar wind.

Space weather at Earth mostly due to CMEs & southward Bz

….. due to ``magnetic reconnection''



Overview of Space Weather at Earth



Terrestrial space weather events due to

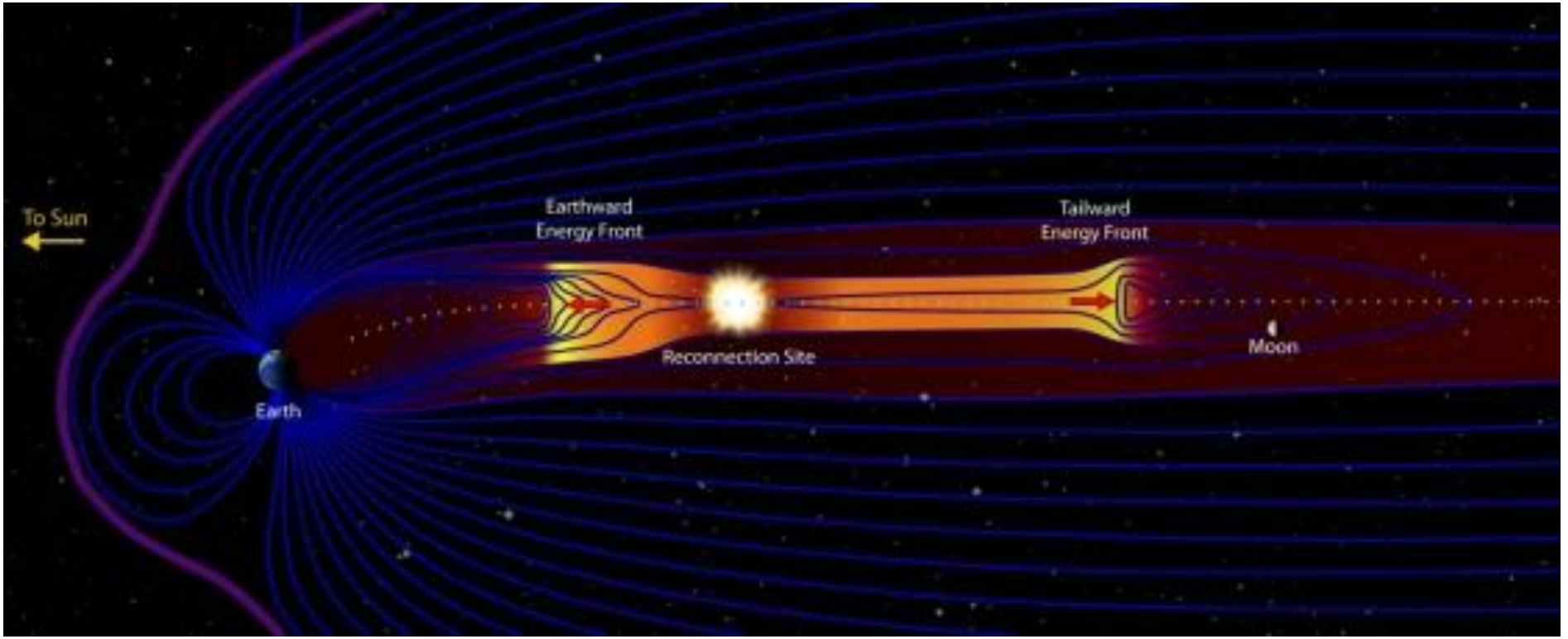
- Changes in the ionosphere assoc. with
  - Auroral activity
  - Particle precipitation
  - Different coupling to the magnetosphere
  - Changing radio propagation conditions
- Enhanced transport into magnetosphere of
  - Solar wind plasma
  - Energetic particles
  - Reconnected magnetic field lines
- Magnetic substorms and assoc. changes in **B**, **J**, & **E** in the
  - Magnetosphere
  - Ionosphere
  - At Earth's surface

Causes for particular human concern

- Radio, GPS, and navigation difficulties due to ionospheric scintillations & changed radio propagation
- Magnetic field changes → induced EMFs and currents → power, communication, & pipeline failures and difficulties with high-tech industry & prospecting.
- Radiation damage, dielectric charging & breakdown of space systems like satellites
- Increased ionospheric drag etc. for satellites
- Radiation damage to humans (airlines, astronauts)

3. Magnetic Reconnection & Space Weather

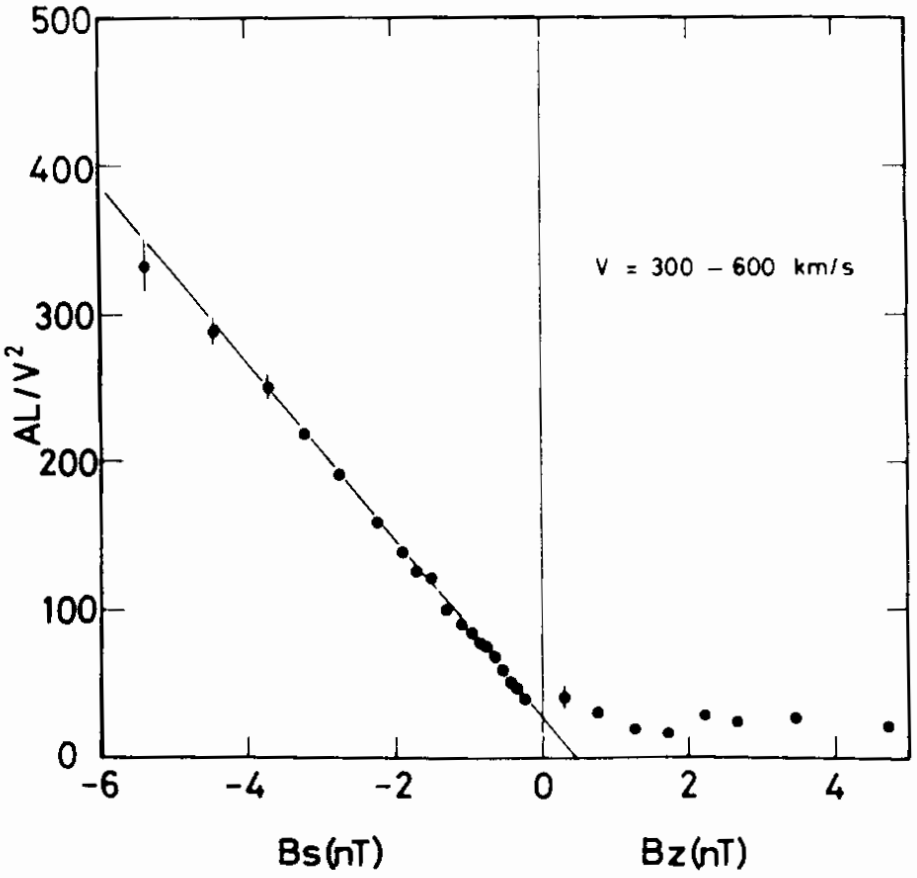
- 90% of large space weather events at Earth due to CMEs with southwards B_z & associated magnetic reconnection (B energy ➔ heating & flows)



Space weather at Earth ⇔ CMEs and southwards B_z

- 90% of large substorms at Earth due to CMEs

[I.Richardson et al., 2006]

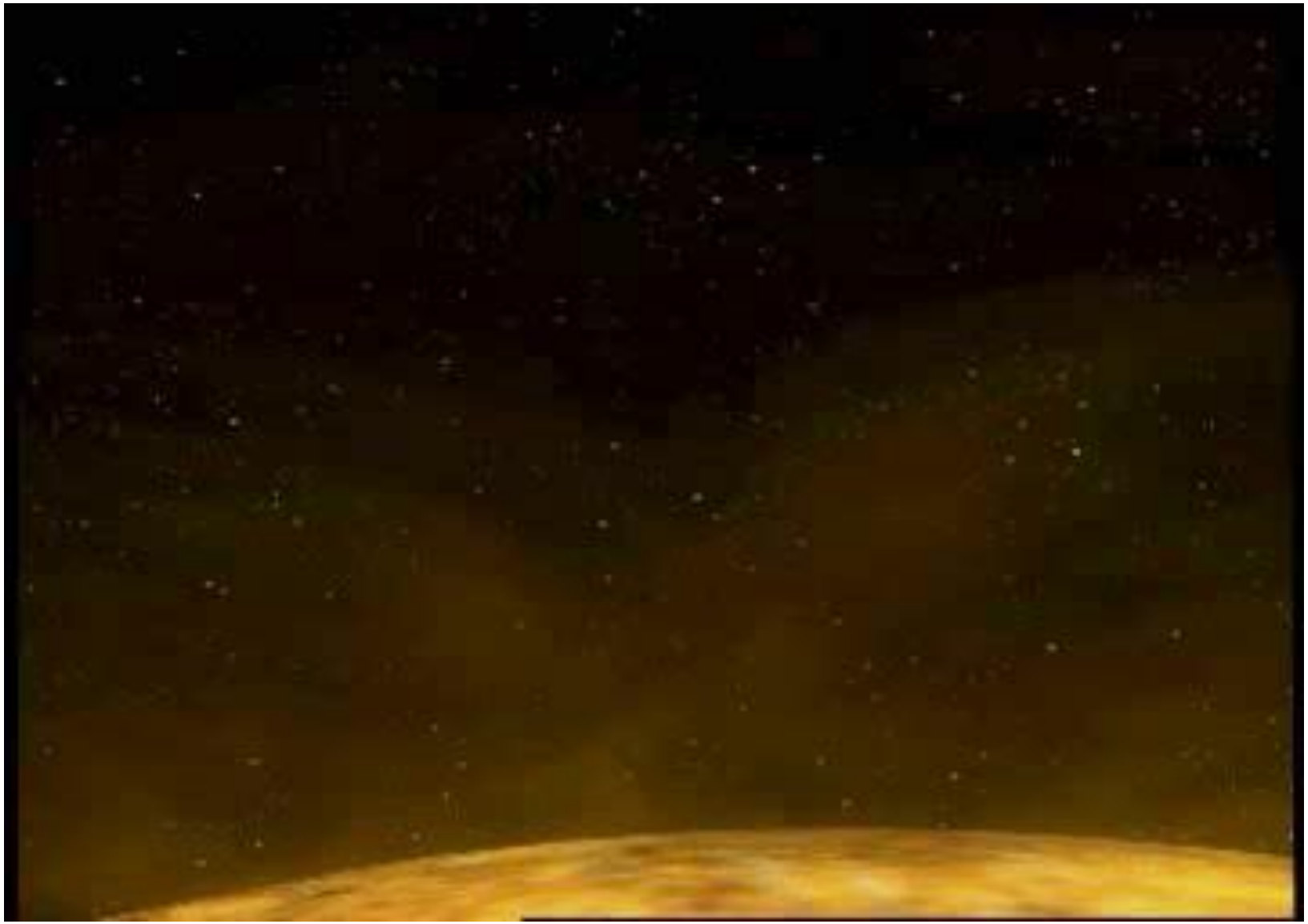


- Index AL / v_{sw}^2
- ➔ substorms assoc. with long duration and large values of southward B_z
- ➔ reconnection vital.

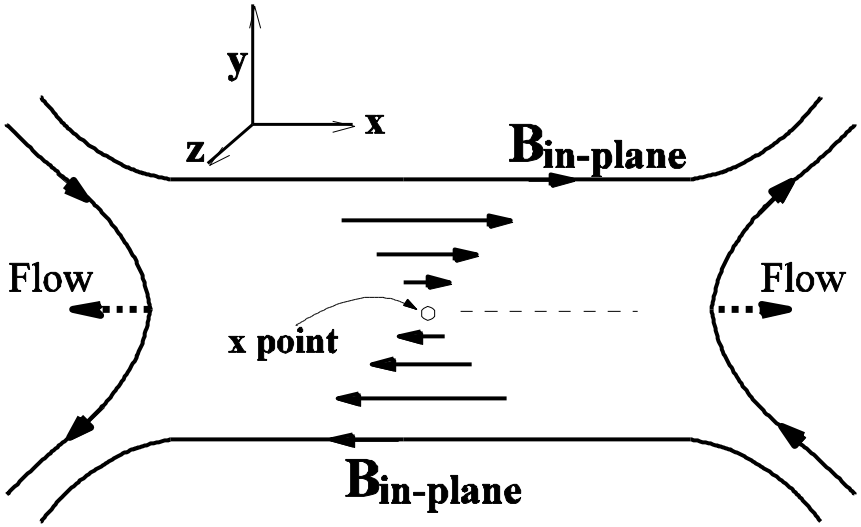
[Muruyama et al., 1980]

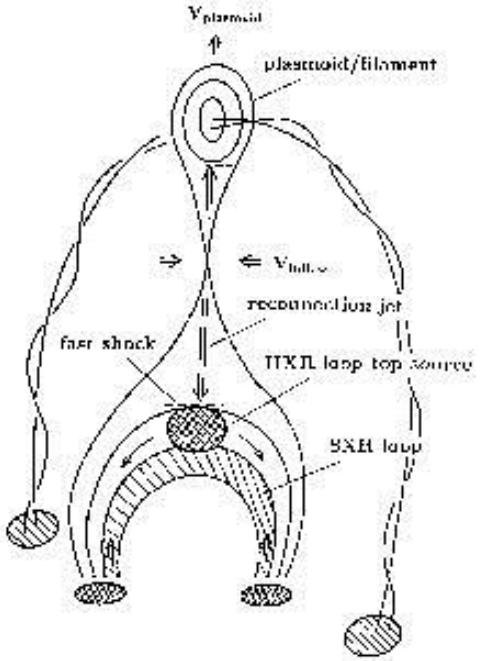
Space weather at Earth mostly due to CMEs & southward Bz

….. due to ``magnetic reconnection''



Basics of Magnetic Reconnection

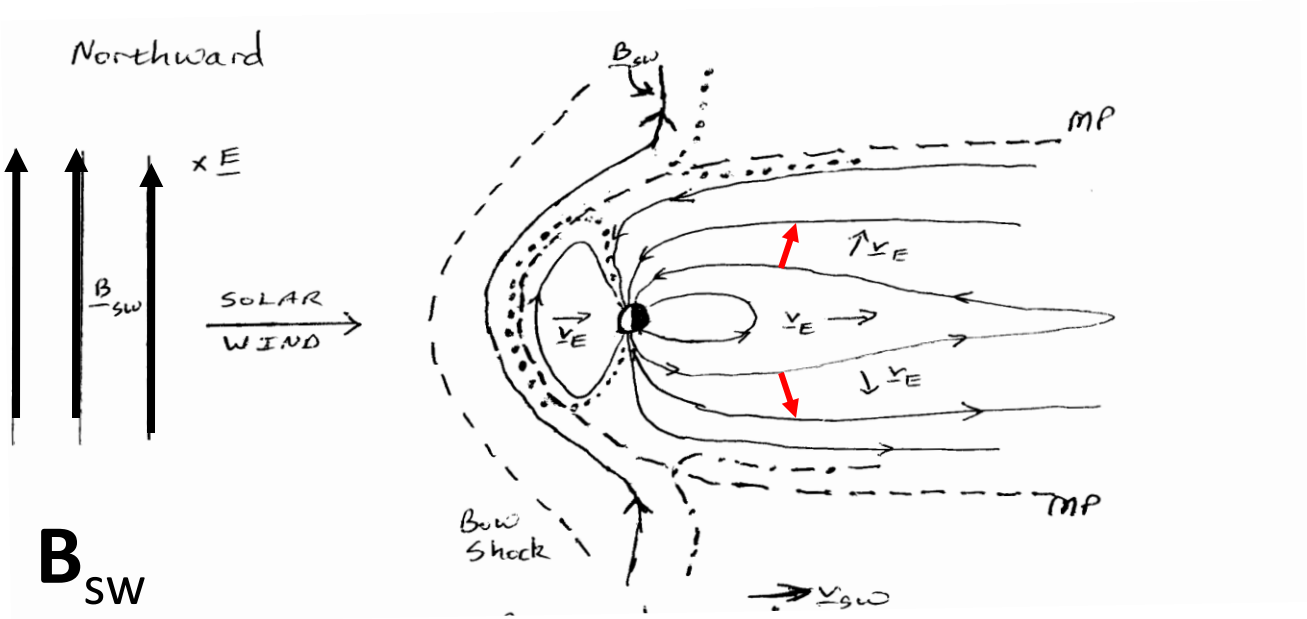




- Anti-parallel magnetic components brought together by plasma flow ➔ **B** annihilation.
- Where does magnetic energy $B^2/2\mu_0$ go when **B** + (-**B**) = 0 ?
- Some to transverse outflow at Alfven speed V_A.
- Most ➔ plasma heating and energetic particle acceleration (?)

Reconnection: Northward IMF & dusk-to-dawn $\mathbf{E}_{sw}$

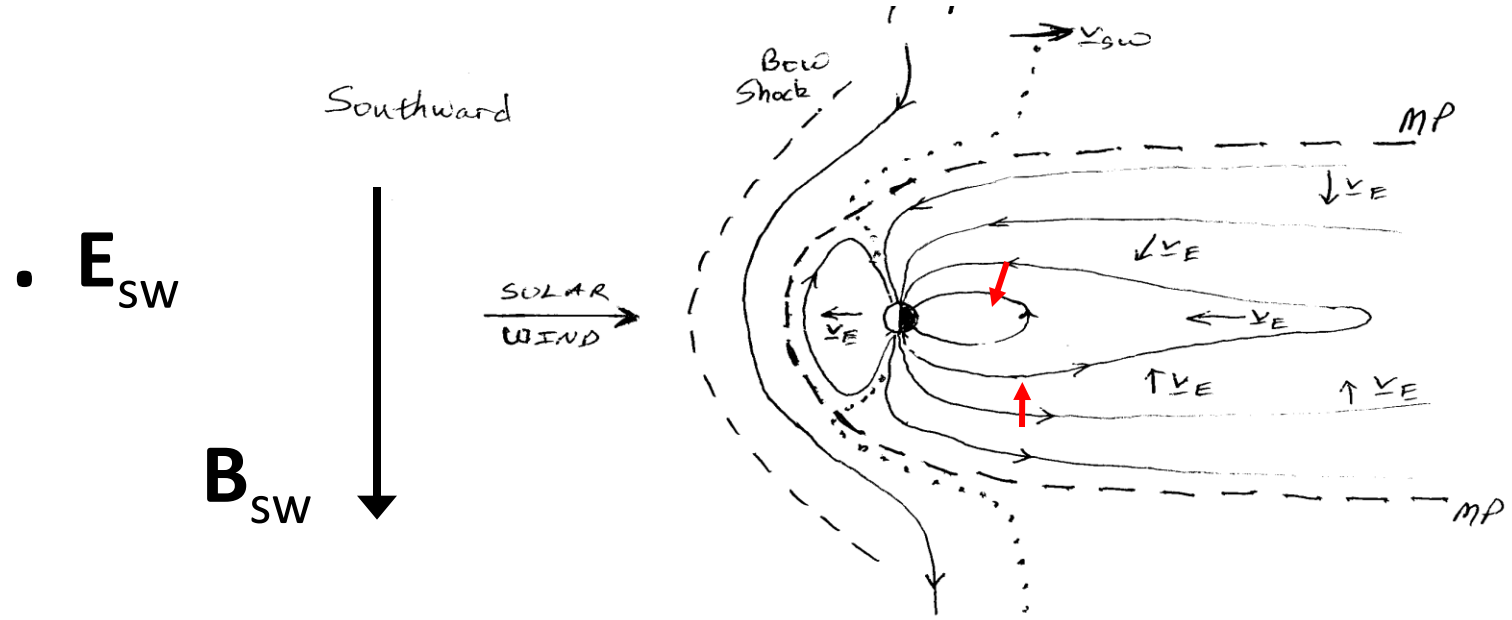
x $\mathbf{E}_{sw}$



$\mathbf{B}_{sw}$

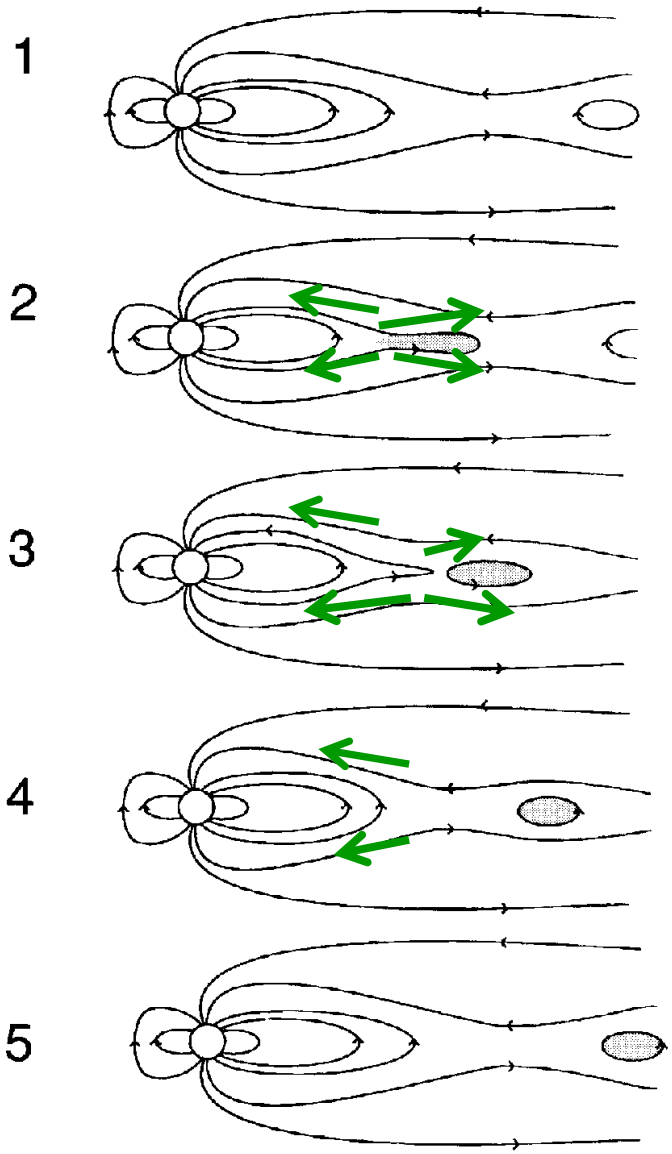
- High latitude magnetic reconnection only
- Load **B** into dayside & lose tail field
- ExB ➔ plasma leaves dayside + lost from tail
- (Stronger mantle, diffuse plasmasheet)

Southward IMF & dawn-to-dusk $\mathbf{E}_{sw}$ ➔ instability & space weather



- Dayside magnetic reconnection & in tail
- Strip **B** from dayside & build tail field
- ExB ➔ plasma & **B** moves toward neutral sheet
- ➔ new reconnection in tail ➔ hot fast plasma to ring current + auroral region & B dipolarizes
- plasmoid leaves magnetotail

Reconnection & Plasmoid Ejection

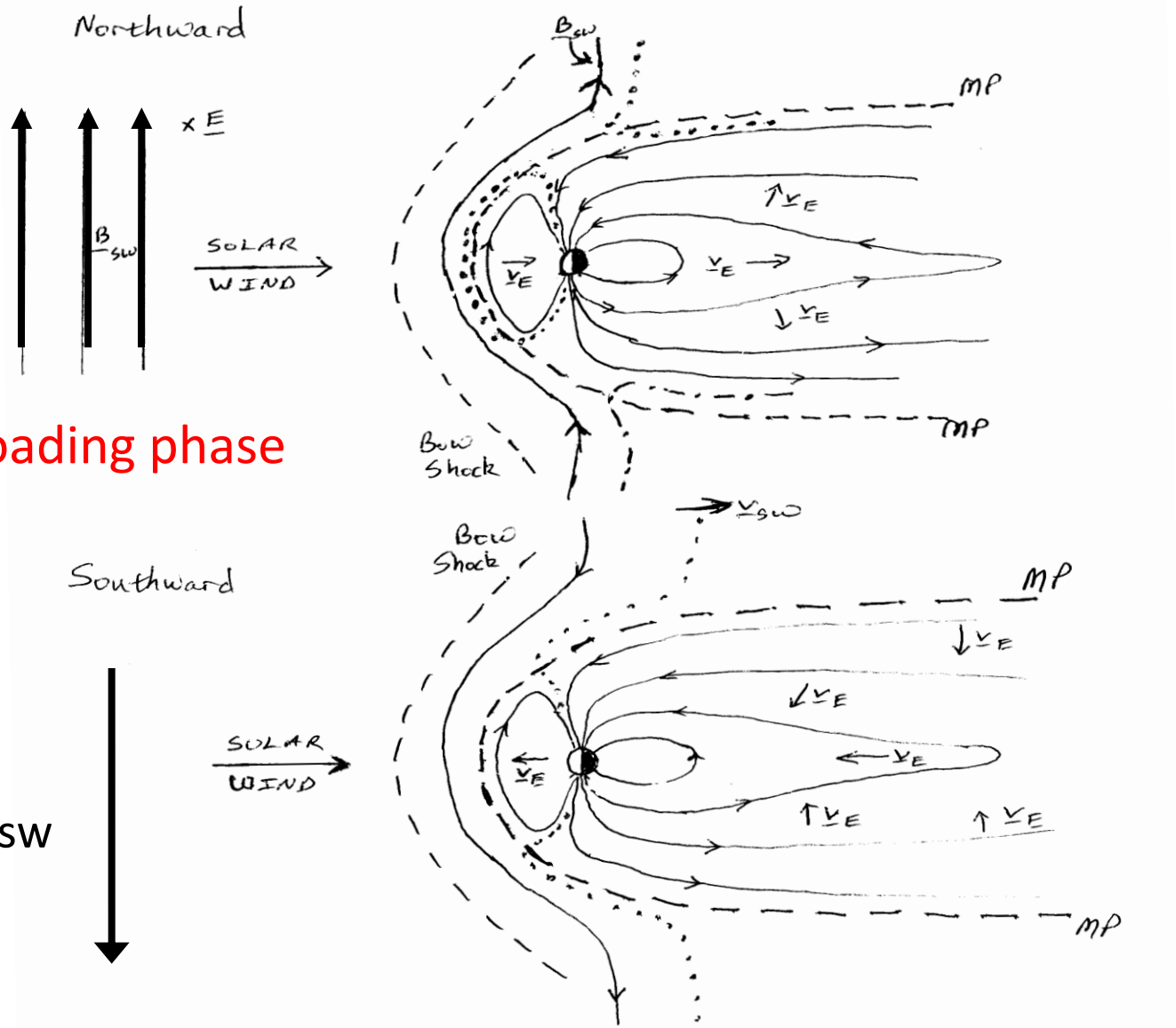


[Hones, 1984]

→ Reconnection outflow of hot, fast plasma & energetic particles

➔ Enhanced ring current, aurora, increased B variability, power line issues, increased ionospheric ionization

x E_{sw}



North Bz ➔ loading phase

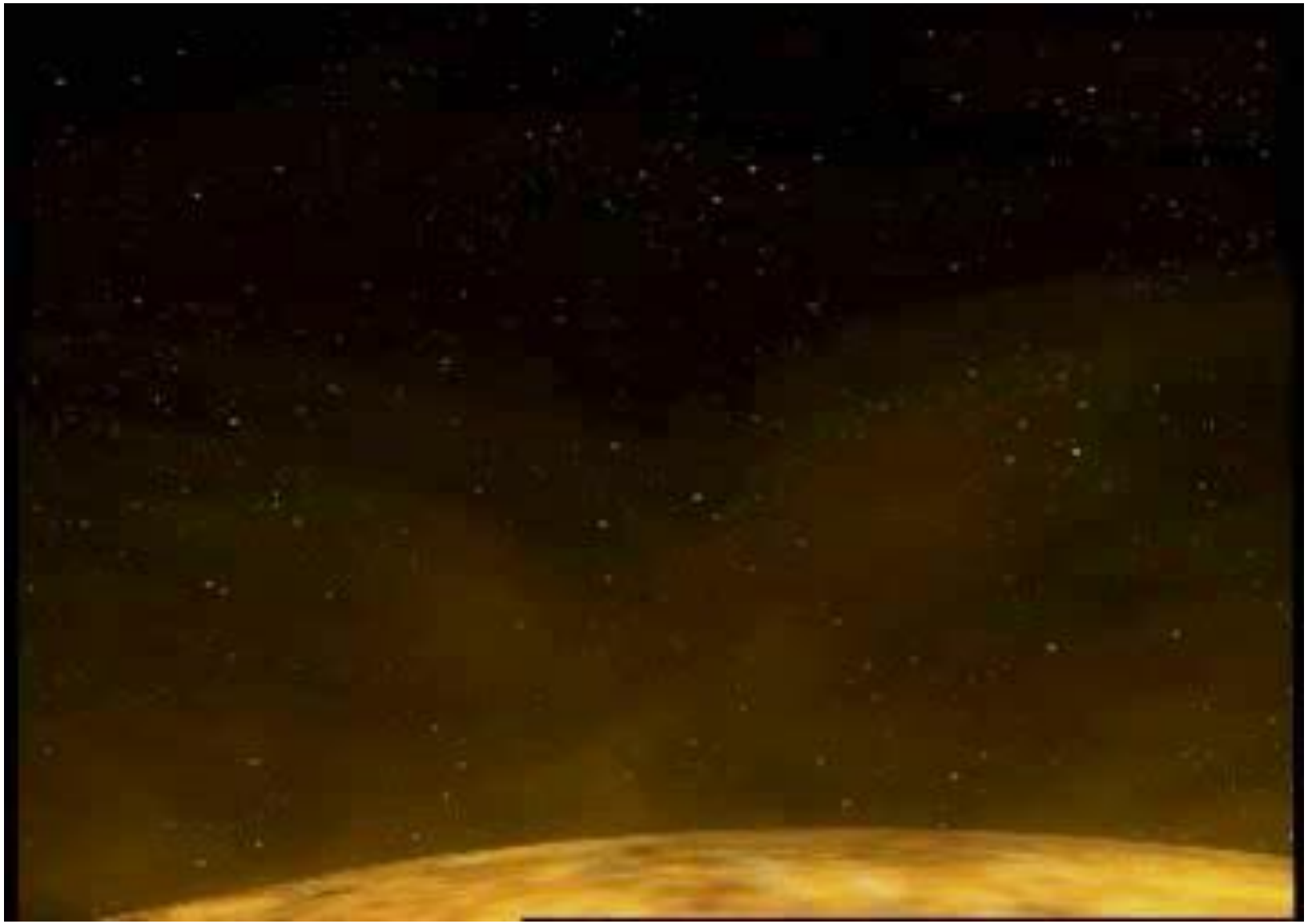
. E_{sw}

B_{sw}

South Bz ➔ instability / unloading with Space Weather events

Space weather at Earth mostly due to CMEs & southward Bz

….. due to ``magnetic reconnection''

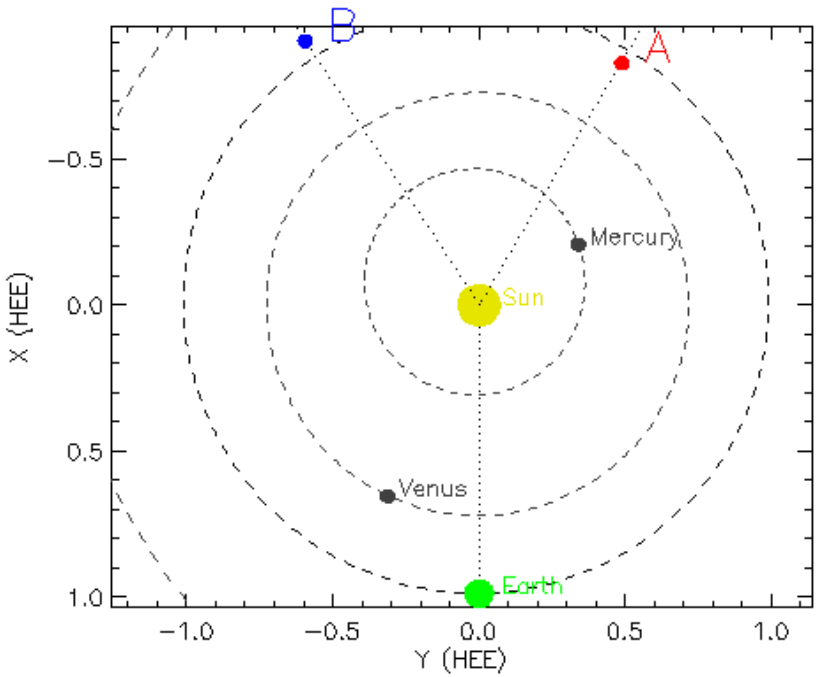


4. Prediction of Space Weather

- Need to:
  - Predict motion and properties of CMEs from Sun to Earth.
  - Predict timing and properties of CIRs
  - Predict resulting magnetic reconnection and changes in Earth's magnetosphere and ionosphere, and so the space weather events.

- Next ?

5. Sun to Earth: STEREO's 1st in situ Interplanetary Type II Burst

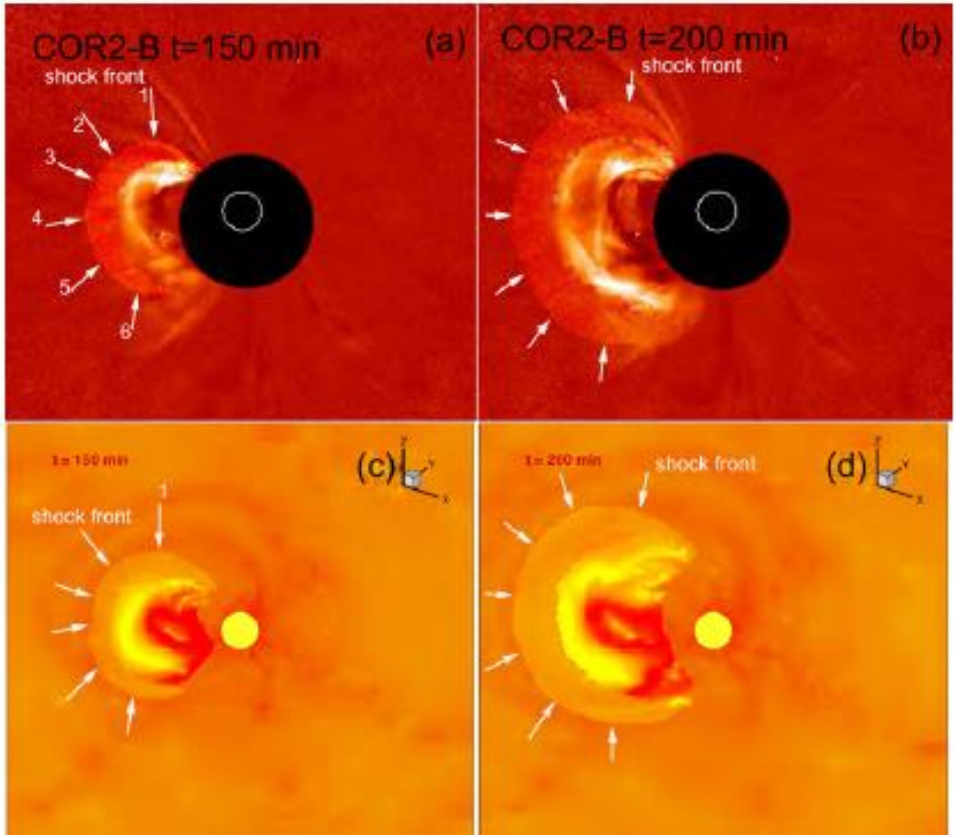


- 29 Nov – 1 Dec 2013
- STEREO A and B (double test since $\Delta r \approx 1$ AU):
  - CME,
  - remote radio,
  - shock crossing at STEREO A only (Langmuir waves, electrons, local radio)
- Excellent agreement from high corona to 1 AU
- B_z prediction .... ➔ space weather prediction

[Schmidt & Cairns, JGR, 2016; Cairns and Schmidt, 2015 ; Schmidt et al., JGR, 2016]

5.1 White light predictions from simulations

Data

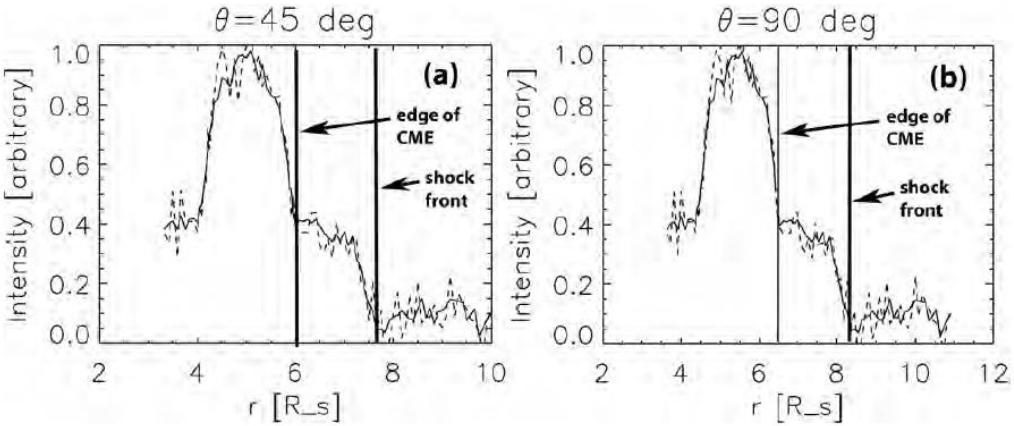


29 Nov 2013
CME near 20 UT

Prediction with BATS-R-US

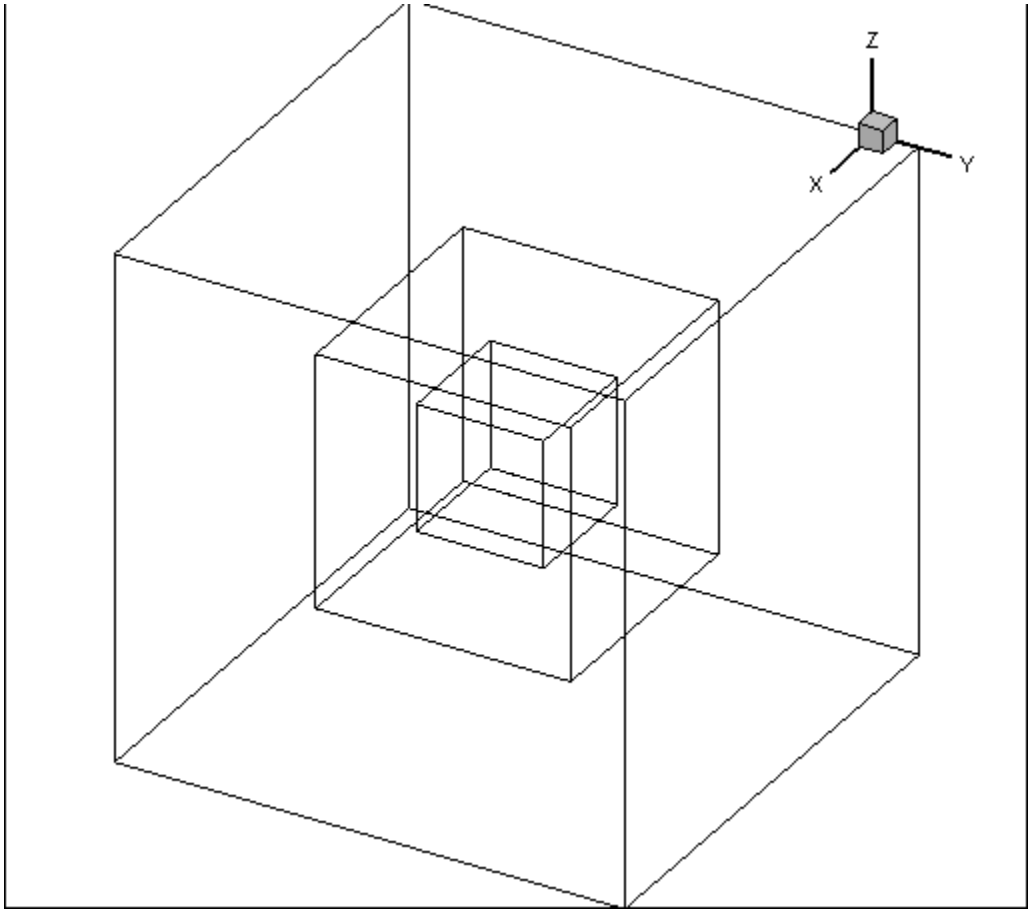
- Predict observable shock
- White light observations &
- predictions agree well.

Intensity along rays
➔ Clearly abrupt shocks

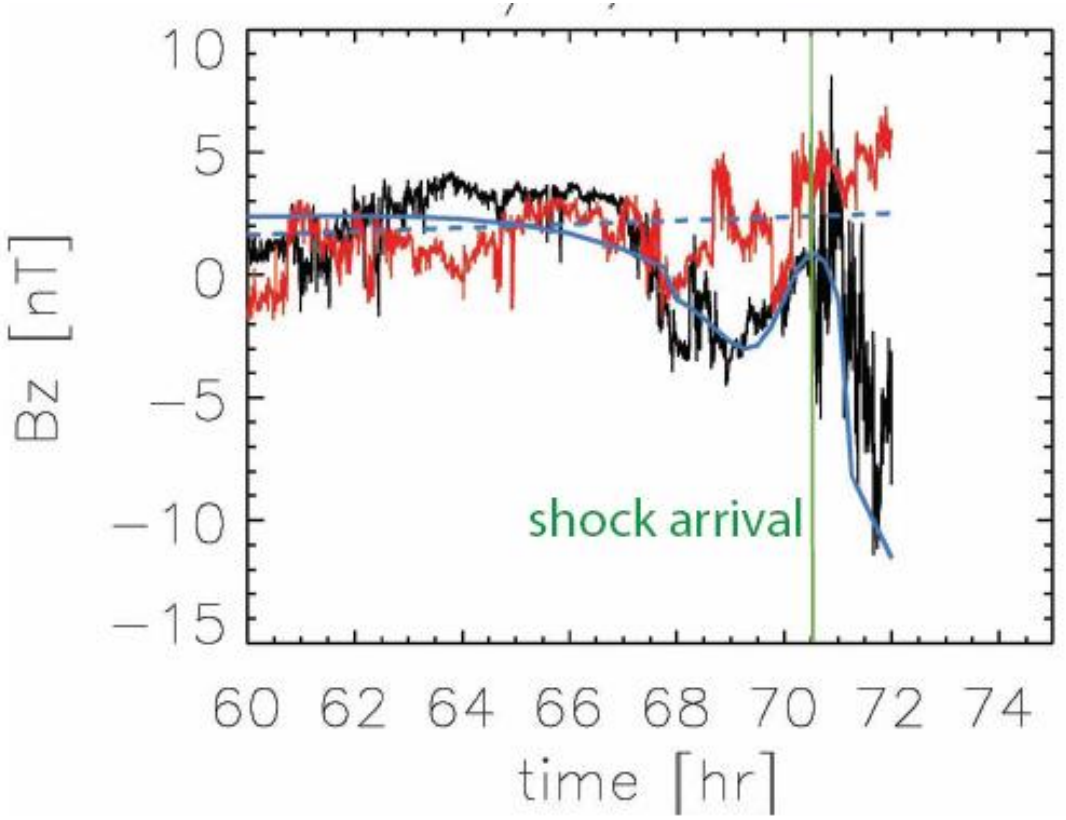


[Schmidt et al., JGR, 2016]

CME evolution from Sun to STEREO A (29 Nov – 1 Dec 2013)

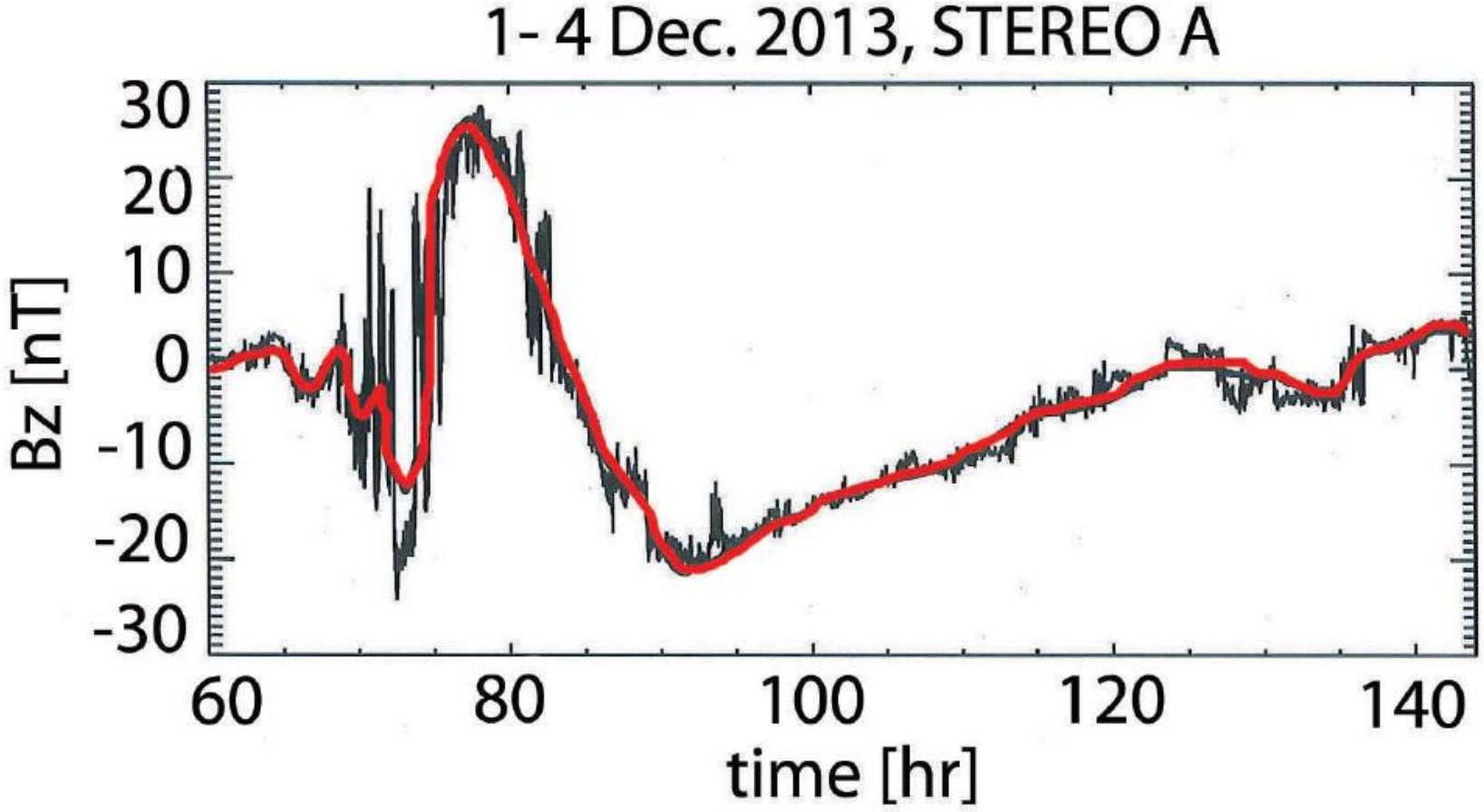


5.2 Good B_z and CME predictions at STEREO A



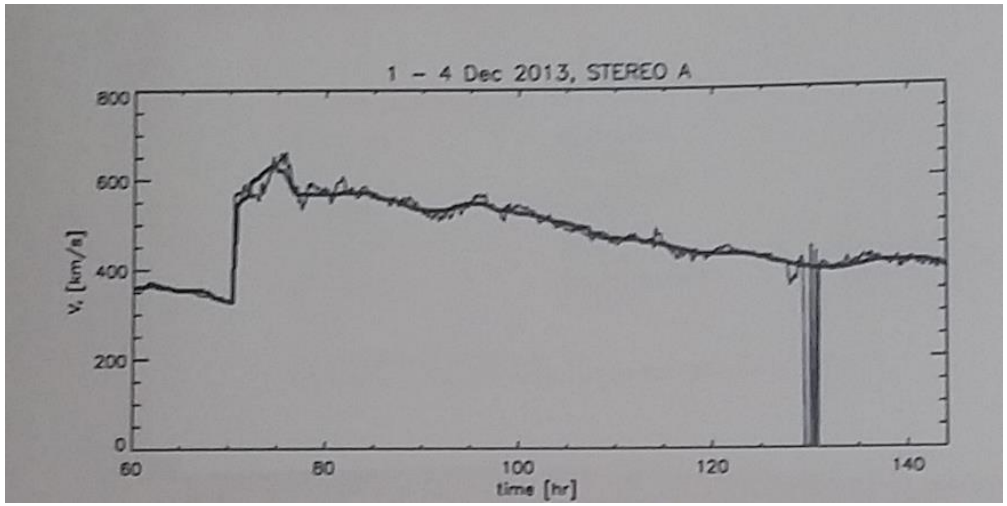
[Cairns and Schmidt, 2015]

- STEREO A data (black) and prediction (blue solid curve)
- ➔ good prediction of B_z and shock / CME arrival
- ➔ vision intact to predict space weather using type IIs ...
- STEREO B less good: data (red) and prediction (- - -)

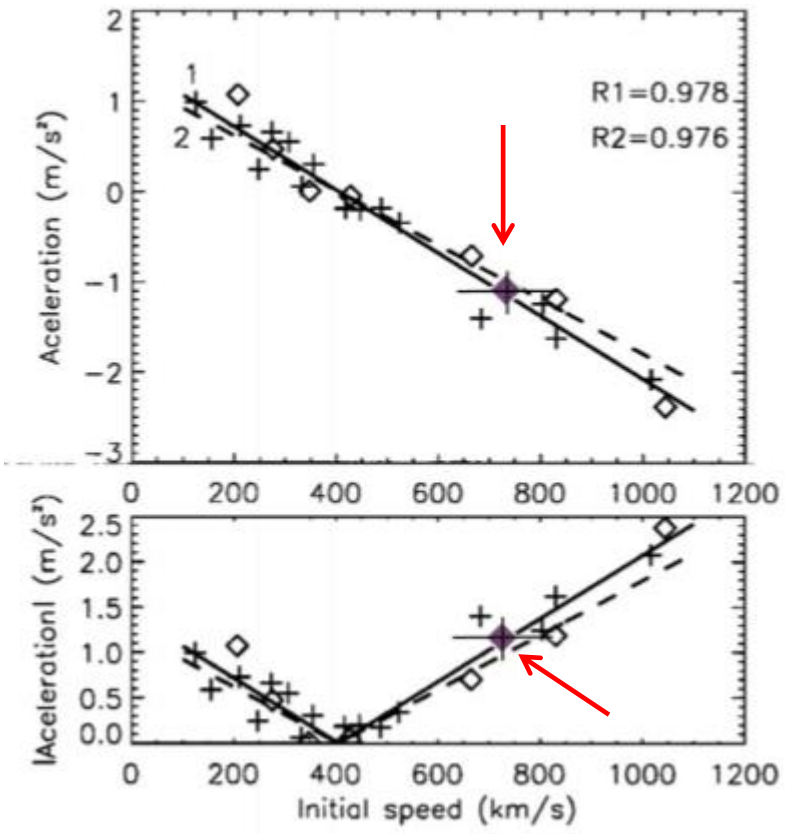


- STEREO A data (black) and prediction (red)
- → very good prediction of B_z before shock → into CME

Shock - CME motion & arrival predicted well



- STEREO A data (thin black) and prediction (thick black)



[M. Astore,2016]

- V_x and shock arrival predicted very well.
- Simulated shock decelerates as predicted by Gopalswamy et al. [2000] data & model for CMEs

6. Conclusions

- Most large space weather events at Earth are due to CMEs with southwards B_z & associated magnetic reconnection .
- Arguably close to accurately simulating CMEs from the Sun to Earth, based on Schmidt, Cairns, et al. case studies
  - White light images can be accurately predicted (CME and shock).
  - CME plasma & field variables can be predicted well, including B_z.
  - CME arrival, speed & deceleration can agree well with data.

- Agreement ➔ strong support that SWMF / BATS-R-US code (3D MHD) can accurately model 3D corona/wind & CME.

- Vision & space weather relevance: ➔ use type II burst (not shown) & white light data-theory iterations to confidently predict in transit CME arrival and B_z.