Space weather and solar-terrestrial relations

Hardi Peter
Kiepenheuer-Institut
für Sonnenphysik
Freiburg

solar eclipse, **11.8.1999**, Wendy Carlos and John Kern

with special thanks to
Bernhard Kliem, AIP, Potsdam

Early note on solar-terrestrial relations

from Richard A. Proctor:
"Other Worlds Than Ours", 1870. Chapter II. What we Learn From the Sun.

[In] 1859, the eminent solar observer, Carrington noticed the apparition of a bright spot upon the Sun's surface.

The light of this spot was so intense that he imagined the screen which shaded the plate employed to receive the solar image had been broken. (...)

Now it was found that the self-registering magnetic instruments of the Kew observatory had been sharply disturbed at the instant when the bright spot was seen. (...)

Telegraphic communication was interrupted, and at a station in Norway the telegraphic apparatus was set on fire;

auroras appeared both in the northern and southern hemispheres during the night which followed.

What is space weather?

Space Weather (definition from a NASA web site)

Space weather happens when a solar storm from the Sun travels through space and impacts the Earth's magnetosphere.

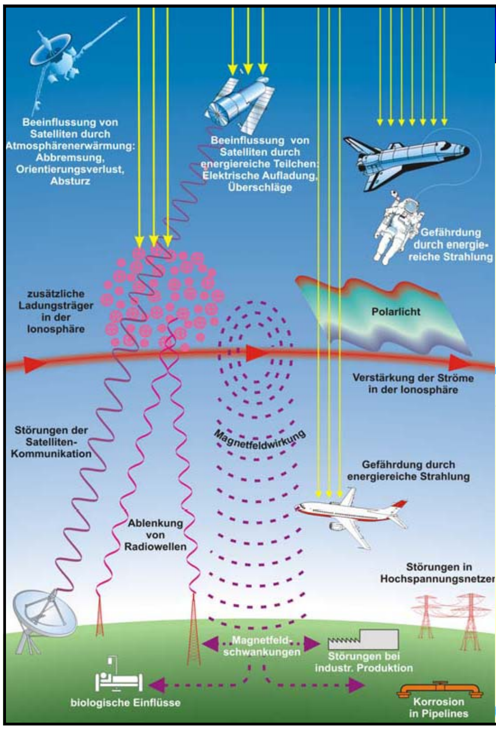
Studying space weather is important to our national economy because solar storms can affect the advanced technology we have become so dependent upon in our everyday lives.

Energy and radiation from solar flares and coronal mass ejections can

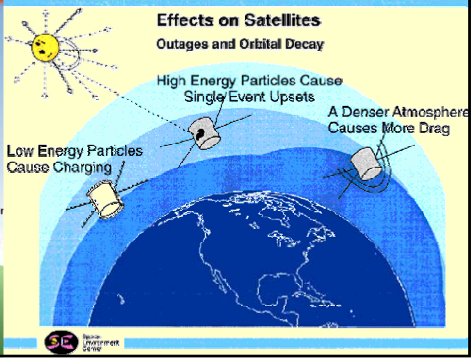
- Harm astronauts in space
- Damage sensitive electronics on orbiting spacecraft…
- Cause colorful auroras, often seen in the higher latitudes…
- Create blackouts on Earth when they cause surges in power grids.

artwork, © Greg Urbanski

Effects of space weather 5



- many things can be affected by the space environment
- and often in many ways…

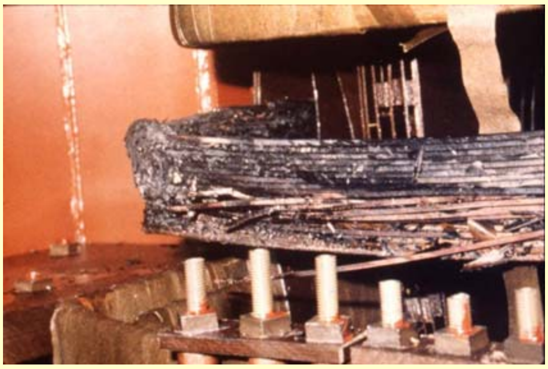


Power transformer and the Sun 6

before

Severe internal damage caused by the space storm of 13 March 1989

after

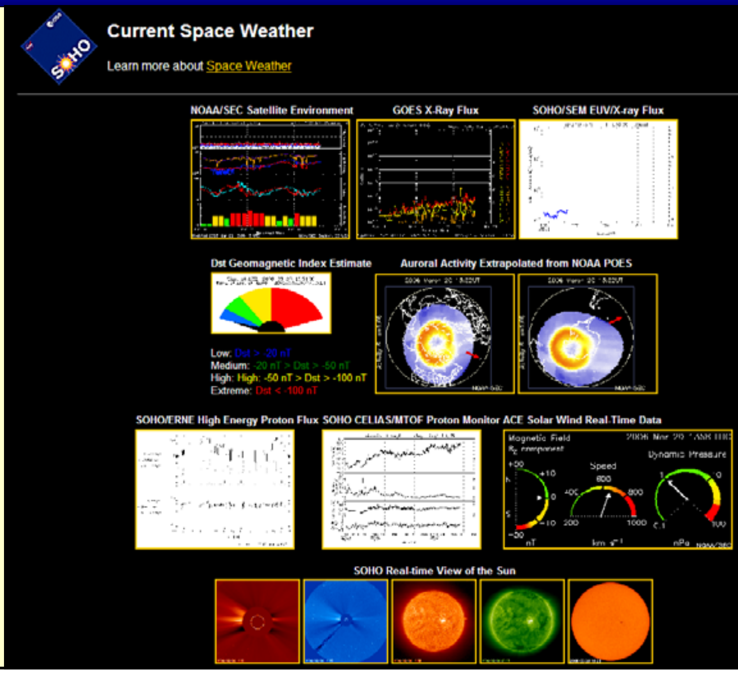


but be careful:
this was the only extreme case we know of…

What is space weather?

7

http://sohowww.nasa.gov/spaceweather/



What questions to ask ?

8

selected physical problems to address:

the driver:

– solar irradiance

– solar (coronal) eruptions

– particle acceleration

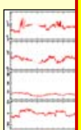
- small & large scale structures: sunspots / faculae
- magnetic instabilities for CMEs and flares
- relativistic description of acceleration process

alternative definition of space weather:

integration of many problems
from the Sun to the Earth
into an **engineering model**
to predict effects on Earth.

COMPLICATION:
we have not yet understood
most of the relevant individual problems…

propa



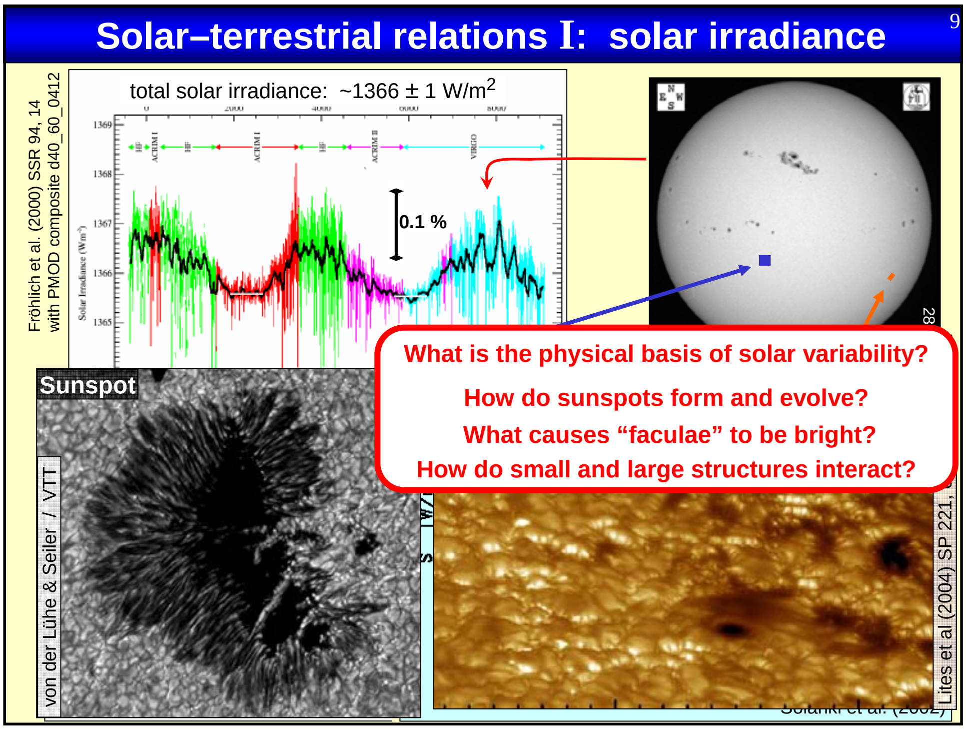
- wave-particle interaction
- kinetic description of transport phenomena
- interaction of large scale solar wind/CME structures

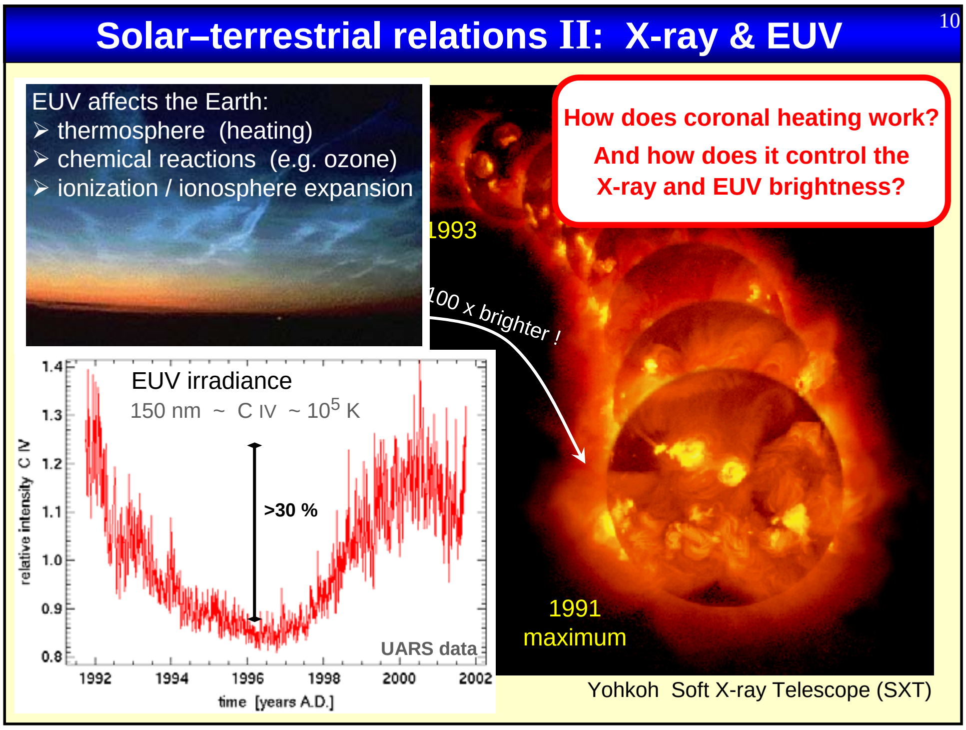
effects

– energetic radiation and life

– advanced technology

- interaction of solar wind with Earth's magnetosphere
- intrusion of particles into Earth's magnetosphere
- reconnection and acceleration in magnetosphere

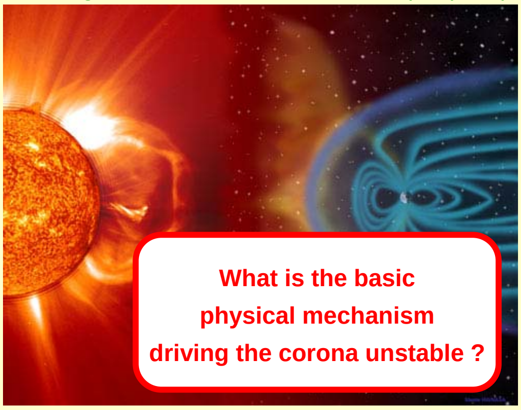

Solar–terrestrial relations I: solar irradiance
9
total solar irradiance: ~1366 ± 1 W/m2
0.1 %
Fröhlich et al. (2000) SSR 94, 14
with PMOD composite d40_60_0412
What is the physical basis of solar variability?
How do sunspots form and evolve?
What causes “faculae” to be bright?
How do small and large structures interact?
Sunspot
von der Lühe & Seiler / VTT
Lites et al (2004) SP 221,


Solar–terrestrial relations II: X-ray & EUV
10
EUV affects the Earth:
➢ thermosphere (heating)
➢ chemical reactions (e.g. ozone)
➢ ionization / ionosphere expansion
How does coronal heating work?
And how does it control the
X-ray and EUV brightness?
1993
100 x brighter !
EUV irradiance
150 nm ~ C IV ~ 10^5 K
>30 %
relative intensity C IV
time [years A.D.]
UARS data
1991
maximum
Yohkoh Soft X-ray Telescope (SXT)

Solar–terrestrial relations III: mass ejections

11

- Large magnetic structures become unstable
  - coronal mass ejections (CME)
  - flares → high-energy particles
- interaction with Earth's magnetosphere
- danger to instrumentation and life (in space)



What is the basic physical mechanism driving the corona unstable ?

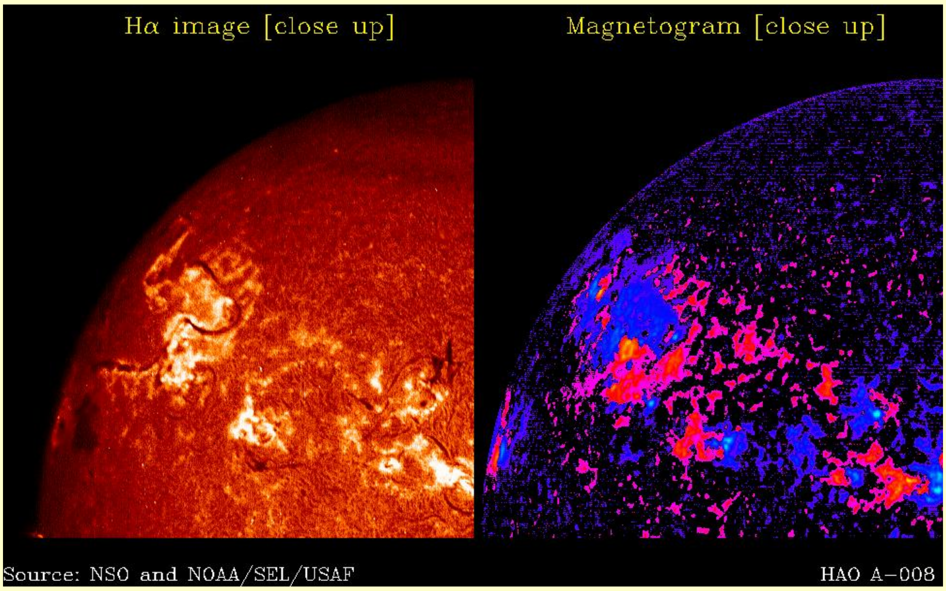
observations: EIT / Lasco /SOHO

sketch: Earth's magnetosphere

Prominences and magnetic field

12

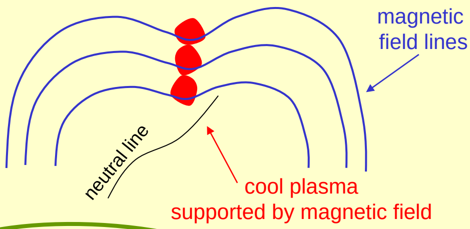
prominences are found above magnetic neutral lines



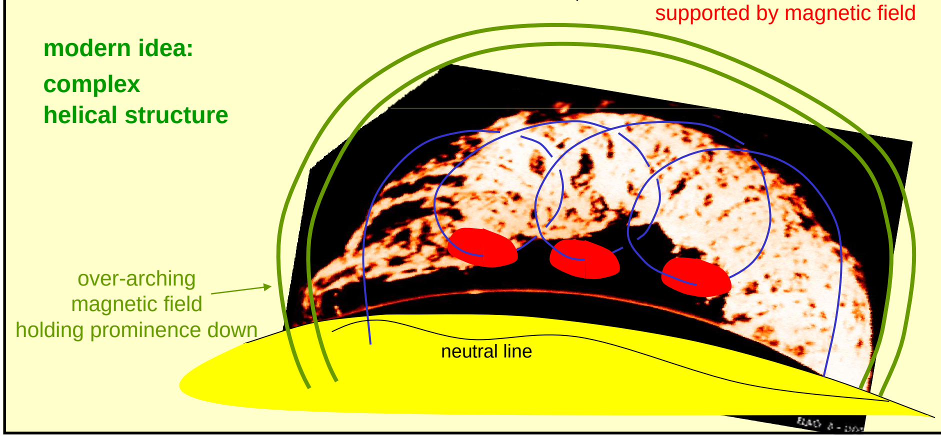
What is a prominence ?

the „hammock“
of Kippenhahn & Schlüter (1957):

- cool dense plasma (~10^4 K) in a hot surrounding (~10^6 K)
- enough (cool) plasma for significant absorption of photospheric emission



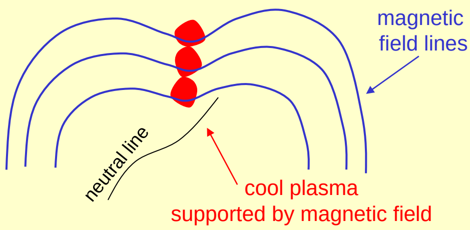
modern idea:
complex helical structure



Prominence vs. coronal loop

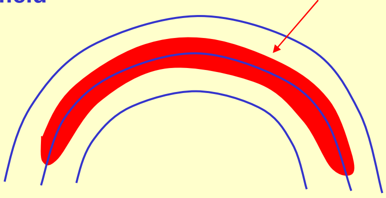
the „hammock“
of Kippenhahn & Schlüter (1957):

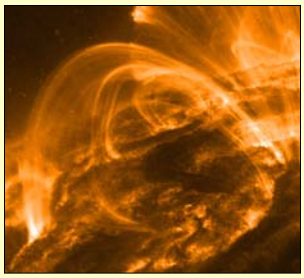
- **cool dense plasma** (~10^4 K) in a hot surrounding (~10^6 K)
- enough (cool) plasma for significant absorption of photospheric emission



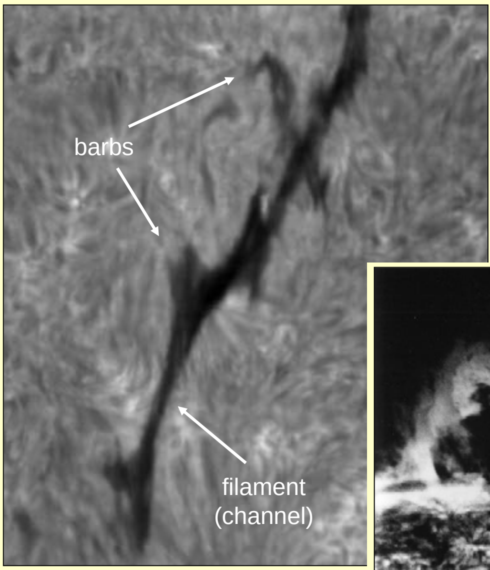
What is a coronal loop ?

emission of **hot plasma** (~10^6 K) with enhanced density as compared to the background corona **along the magnetic field**



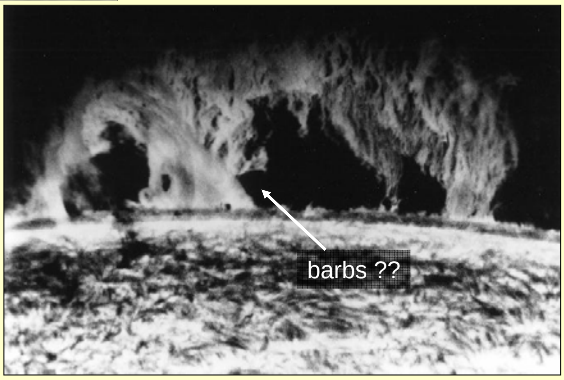


Filaments and prominences

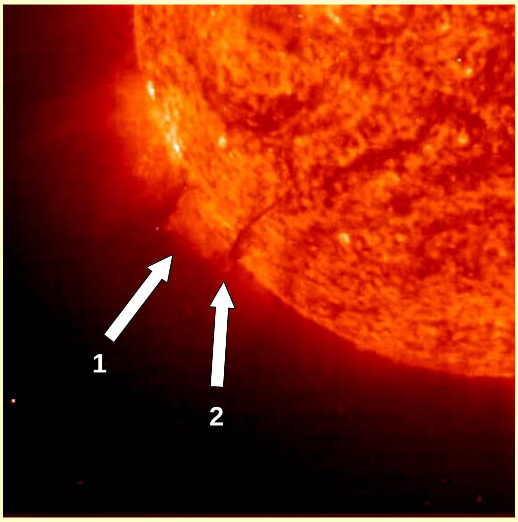


filament: cool plasma held
by magnetic field
absorbs photospheric light

prominence: cool plasma
seen in emission



Filament / prominence eruption

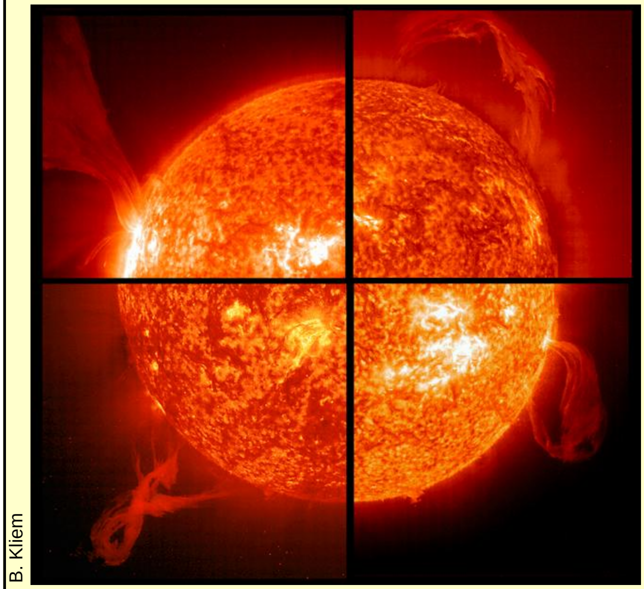


EIT / SOHO – He II 304 Å – ~60.000 K – 10.10.2002

1. first one prominence behind the limb seen in emission erupts

2 then the prominence in the front seen in absorption takes of…

Eruptive Prominences: many flavors



almost always:

– single magnetic flux rope
– topology preserved

mostly:

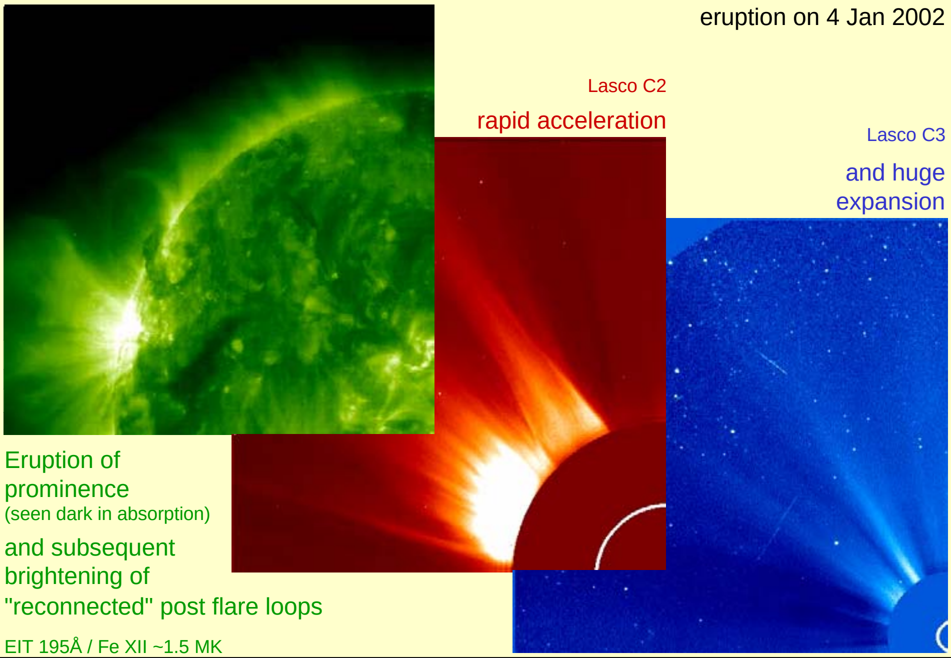
– helical shape
– signature of twist

often:

– ejection (CME)
– high speeds ($\sim v_A$)

Coronal mass ejections

eruption on 4 Jan 2002



Lasco C2

rapid acceleration

Lasco C3

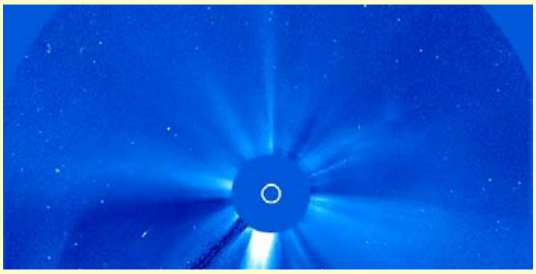
and huge expansion

Eruption of prominence
(seen dark in absorption)

and subsequent brightening of "reconnected" post flare loops

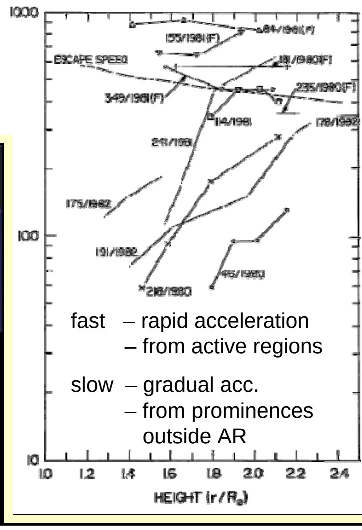
EIT 195Å / Fe XII ~1.5 MK

CME properties



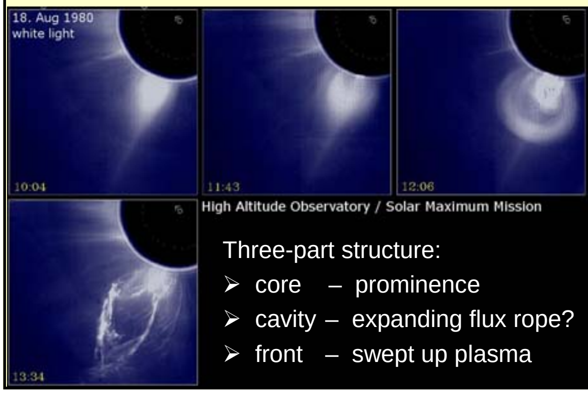
huge expansion > 10^3
huge solid angle > $\pi/2$
often twisted flux ropes

two CME classes: fast & slow



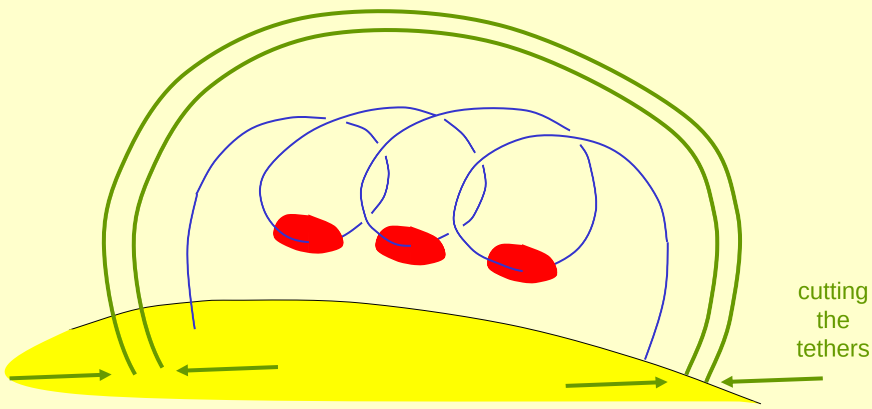
fast – rapid acceleration
– from active regions

slow – gradual acc.
– from prominences outside AR

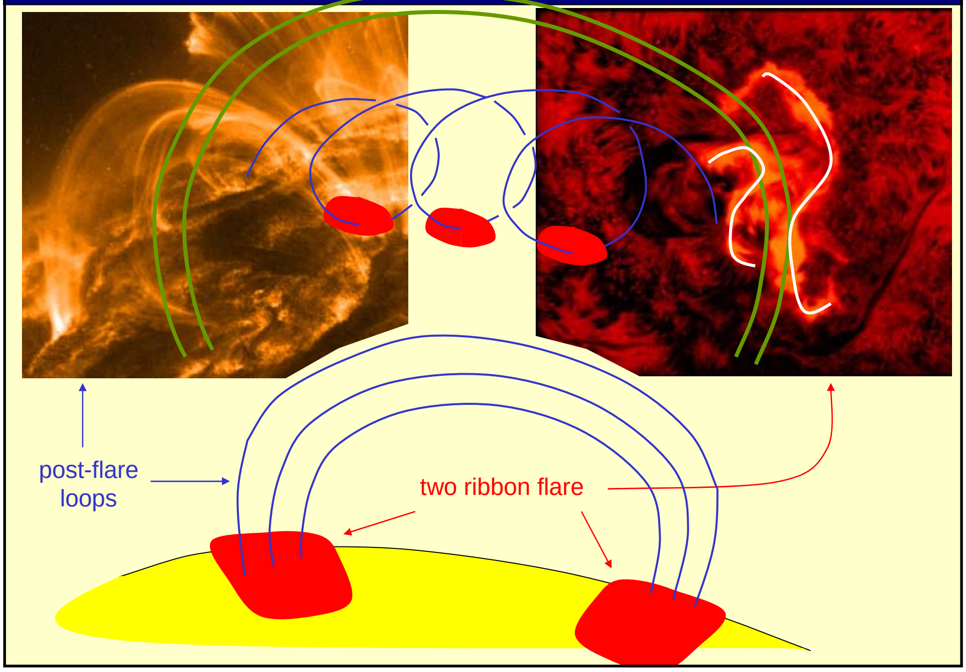


Three-part structure:
- core – prominence
- cavity – expanding flux rope?
- front – swept up plasma

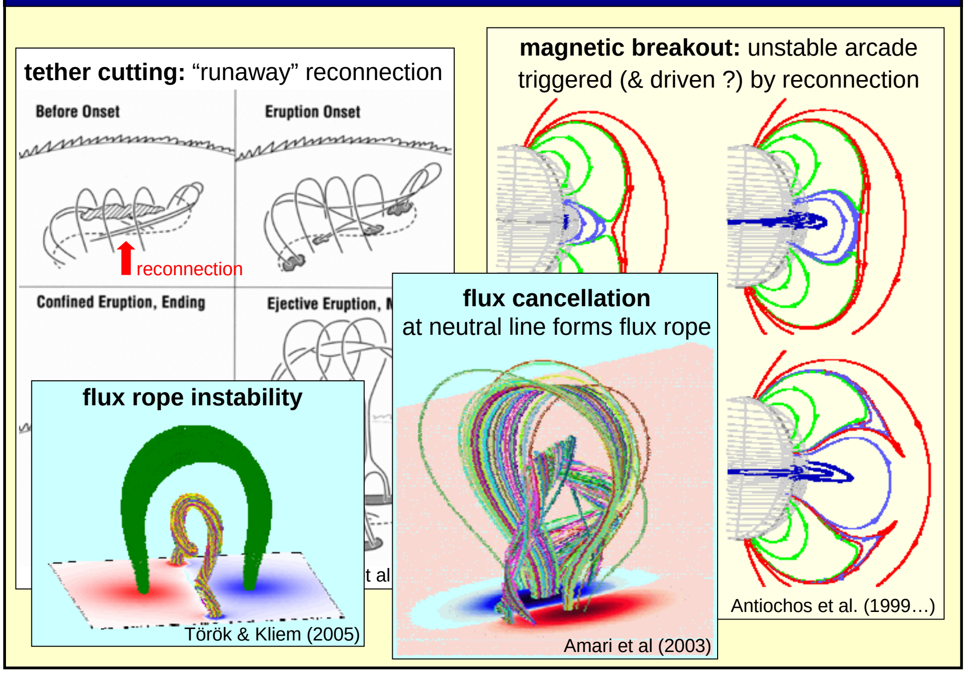
A very simplified scenario for a CME



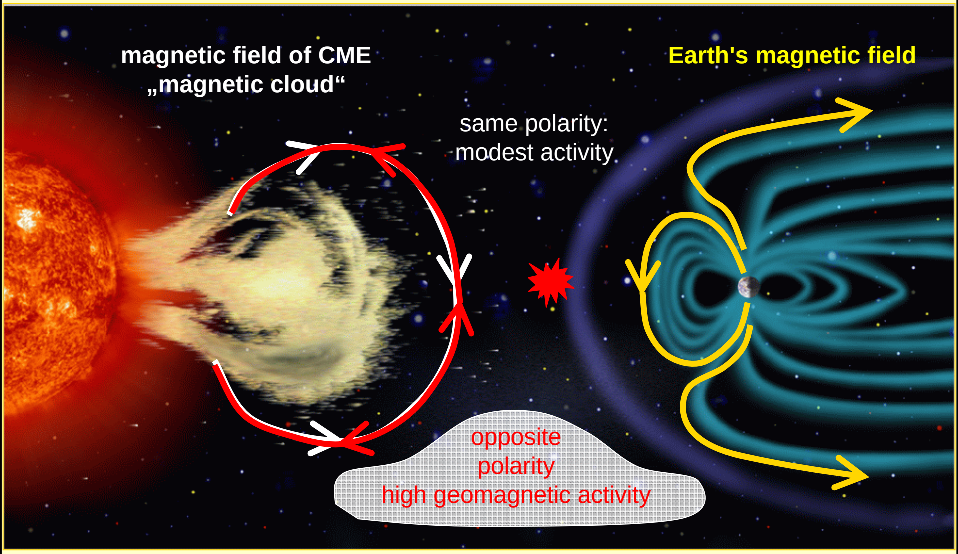
A very simplified scenario for a CME



Modern CME scenarios / models

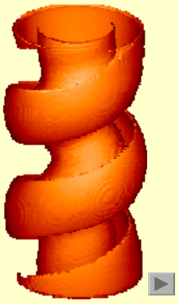


Traveling to Earth…

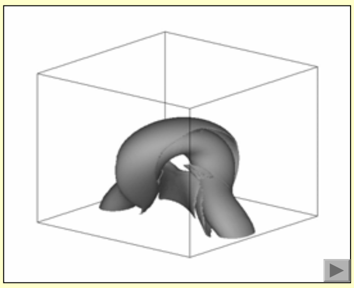


to understand the interaction with the Earth:
first understand the origin of the magnertic cloud, namely the CME ejection

The kink instability



Helical
kink
(m=1)



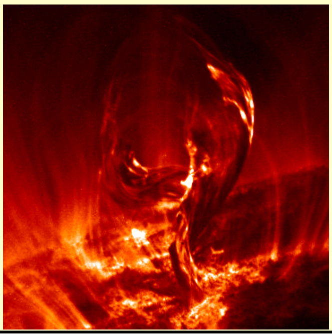
Gerrard et al. (2001)
A&A 373, 1089

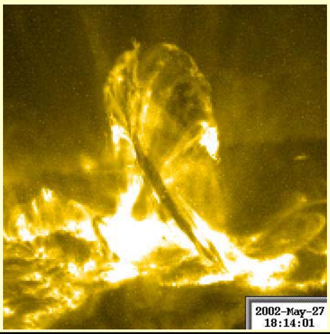
Török et al. (2004) A&A 413, L27

- kink is an ideal MHD instability ➡ twisting a flexible tube
  if twist is above threshold:
  ➡ twist "transformed" into **writhe**
- conserved: helicity ~ twist + writhe
- twist threshold: $\Phi = 2\pi N$ with $N \approx 1\ldots2$

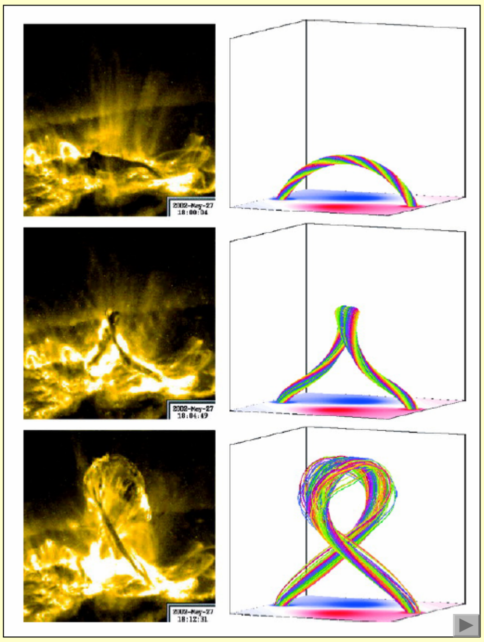
Kink instability in solar eruptions

- many erupting filaments / prominences:
  - – suggest twisted field
  - – develop helical shape
- Sakurai (1976) suggested
  kink instability as driver of prominence eruptions
- *recent years:*
  kink instability as explanation only for confined events
- *very recently:*
  kink instability triggers also ejective events (CMEs)
  (Török & Kliem 2005, Fan 2005)





A confined filament eruption



Török & Kliem (2005) ApJ 630, L97

- one possible driver is rotational motion of foot points
  - ➡ energy stored in twist of magnetic field
- helical kink instability triggers event

HERE:

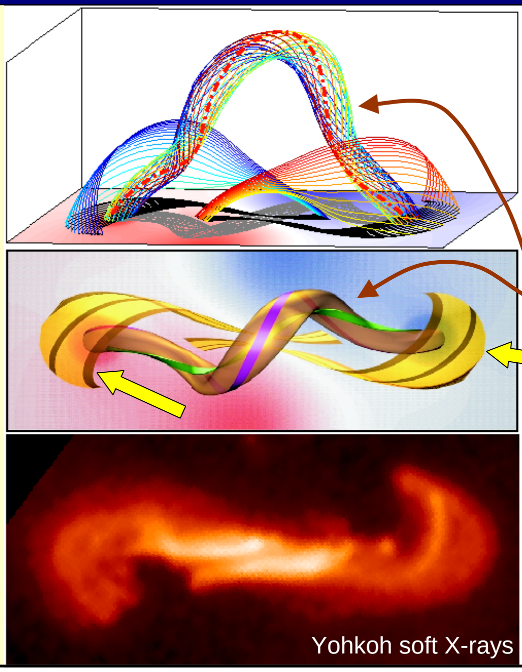
- filament eruption is confined
  - ➡ no outbreak / CME

investigate models with different
- – flux rope twist
- – overlying field

➡ strong overlying magnetic field can prevent eruption

X-ray sigmoids and flux eruption

Kliem, Titov & Török 2004, A&A 413, L23



ideal MHD simulation of flux rope eruption through kink instability

assumption:
heating concentrated in current sheets

➡ current sheets outline expected hot X-ray emission

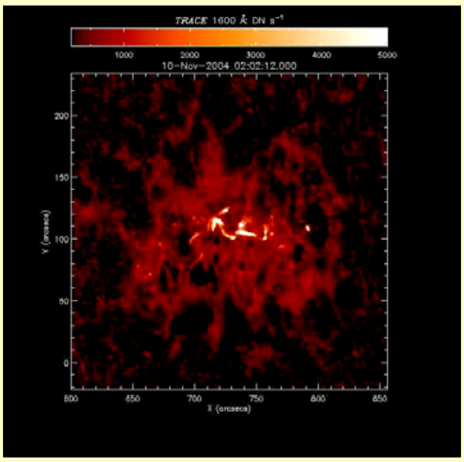
➡ very good qualitative match to observations

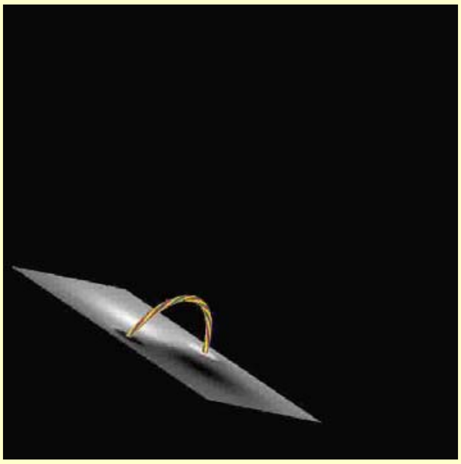
Ejective filament eruption

TRACE 1600 Å – cool ejected material
chromospheric temperatures + C IV (10^5 K)

flux rope kink instability
small overlying *B* allows ejection

Williams et al (2005) ApJ 626, L163





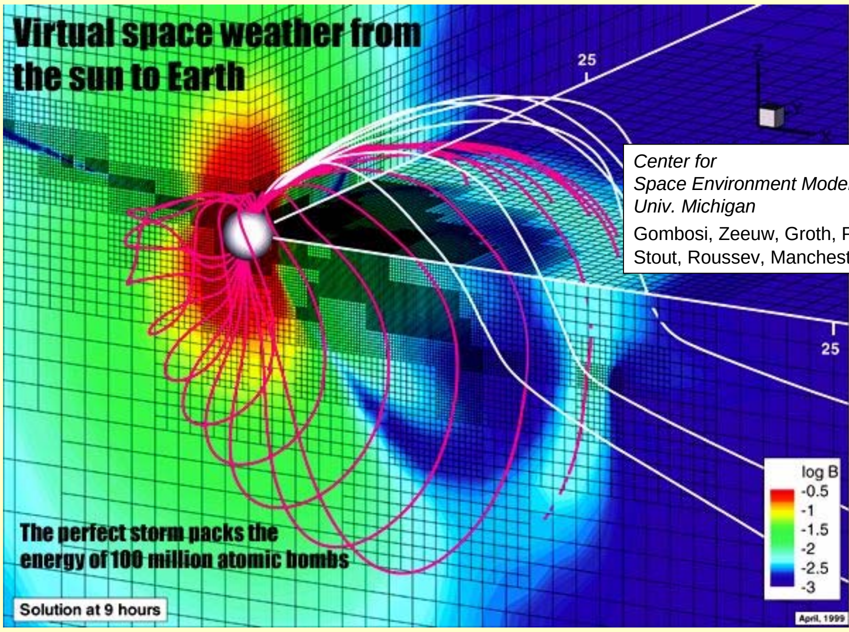
(some) open questions for kink instability-based models

- huge expansions of CMEs by > 10^3
- eruptions with little or no apparent helical shape

} ➡ Torus instability ?

Finally: a complete "space weather" model

29



Center for
Space Environment Modeling
Univ. Michigan
Gombosi, Zeeuw, Groth, Powell, Stout, Roussev, Manchester, Toth…

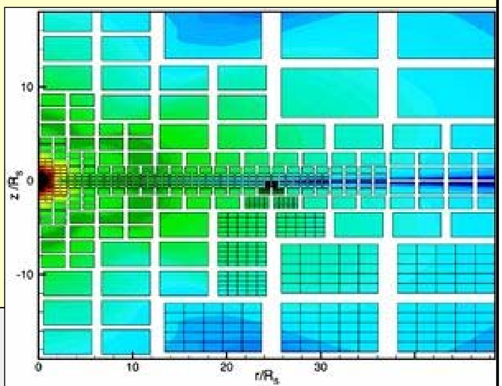
Simulating space weather: numerical challenge

30

needed for these global models:

advanced codes for many different physical problems:

- adaptive mesh refinement (AMR) to resolve large and small scales
- MHD codes
- particle codes
- ….



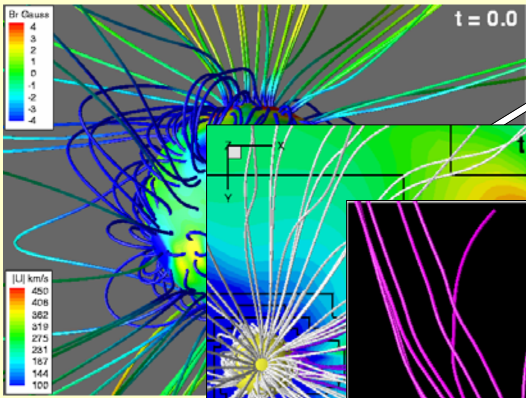
Bats'r'us: snapshot of grid (AMR) for CME model

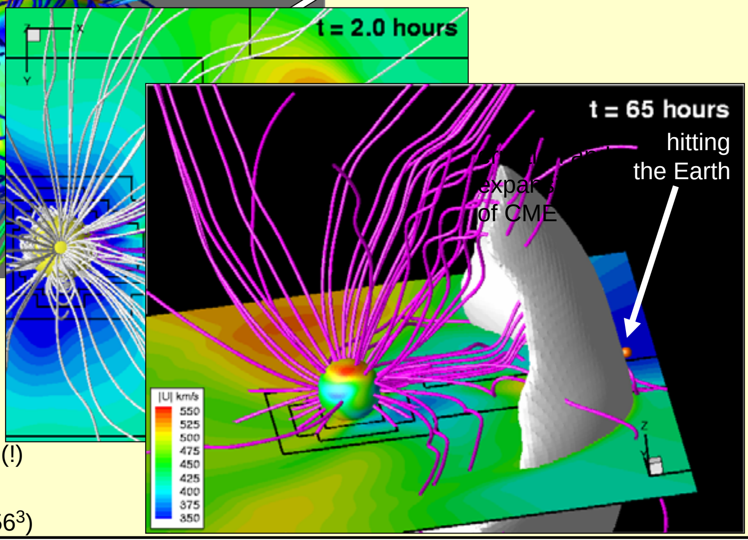
Physics Domain	Models / Codes
Solar Corona	BATSRUS
Eruptive Event Generator	BATSRUS
Inner Heliosphere	BATSRUS
Solar Energetic Particles	Kóta's SEP model
Global Magnetosphere	BATSRUS
Inner Magnetosphere	Rice Convection Model
Ionosphere Electrodynamics	Ridley's potential solver
Upper Atmosphere	General Ionosphere-Thermosphere Model (GITM)

modules of the space weather code of Center for Space Environment Modeling, University of Michigan

CME eruption and propagation to Earth

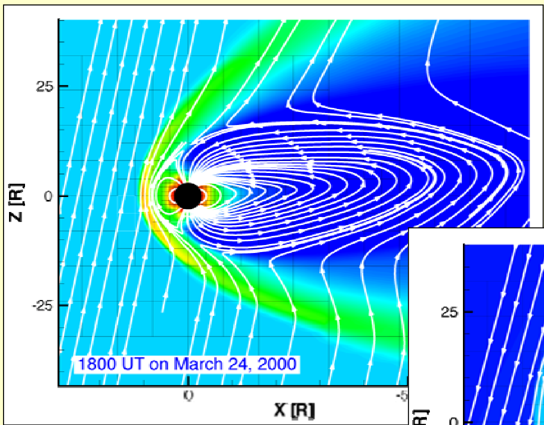
initial state:
observed *B* in photosphere
➡ field extrapolation
➡ add flux rope in AR (white)



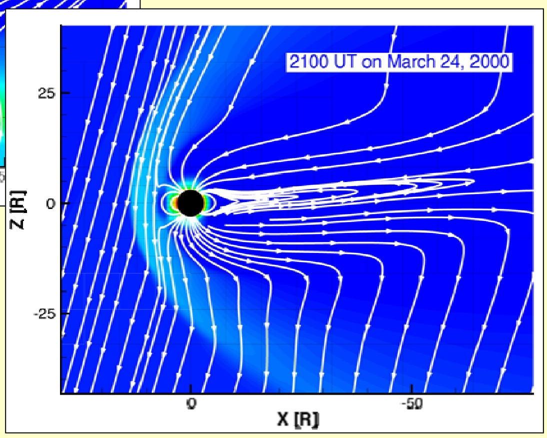


spatial resolution of simulation in corona and heliosphere:
1/32 $R_\odot$ = 21 Mm (!)
to 4 $R_\odot$
≈ 14·10^6 cells (~256^3)

Interaction with Earth



just before the CME hits the Earth



Earth's magnetosphere after the interaction

Limitations of this approach

33

The global space weather model puts together many modules:
good "engineering model" of physical phenomena

- a general problem: **not yet in real time**
  - ➡ many weeks to simulate an event which last for only some days…
- there are important physics pieces still missing!

  for the coronal parts:
  - solar wind heating and acceleration
  - problem of CME initiation
  - reconnection processes
- spatial resolution in corona:
  - currently AMR with smallest cells 1/32 $R_{\odot}$ = 21 Mm (!)
  - this resolution certainly cannot catch the relevant physics
    - ➡ for comparison: coronal box models: computational domain ~ 60x60x40 Mm

However: if one is interested in an engineering approach
i.e. only predict when, where and how a CME hits the Earth
this might be an appropriate approach

Summary / lessons learnt

34

- there are many ways in which the Sun affects the Earth
  - Luminosity: bolometric, X-rays, VUV etc.
  - particle radiation: CMEs, energetic particles
  - magnetic field: cosmic rays
- the most relevant phenomenon concerning corona: CME
  - different scenarios for CME initiation
  - instabilities, tether cutting, breakout…
  - all scenarios are (in the end) driven by photospheric shuffling of magnetic field
- global models of CME initiation to Earth interaction needed for "space weather"
  - global models currently in an "engineering state"
  - detailed physics CME and/or interaction with Earth are not really included