The Abdus Salam International Centre for Theoretical Physics

2292-21

School and Conference on Analytical and Computational Astrophysics

14 - 25 November, 2011

Multiscale and Multiphysics Challenge in Modeling of Space Weather - 1

Giovanni Lapenta
Katholic University of Leuven, Centre for Plasma Astrophysics
Belgium

Centrum voor Plasma-Astrofysica

KATHOLIEKE UNIVERSITEIT LEUVEN

Multiscale and Multiphysics Challenge in Modeling of Space Weather

Giovanni Lapenta

Funding from:
BOF & GOA (KU Leuven),
EC (Swiff, Soteria),
NASA (MMS Mission),
Intel Exascience Lab.

SEVENTH FRAMEWORK PROGRAMME

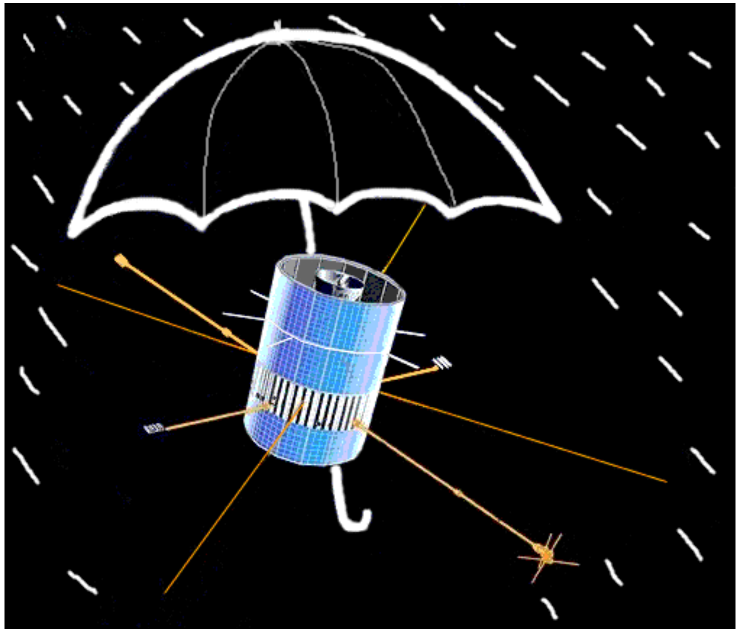
INTEGRATED SPACE-WEATHER FORECASTING FRAMEWORK SWIFF

ExaScience Lab
Intel Labs Europe
EXASCALE COMPUTING

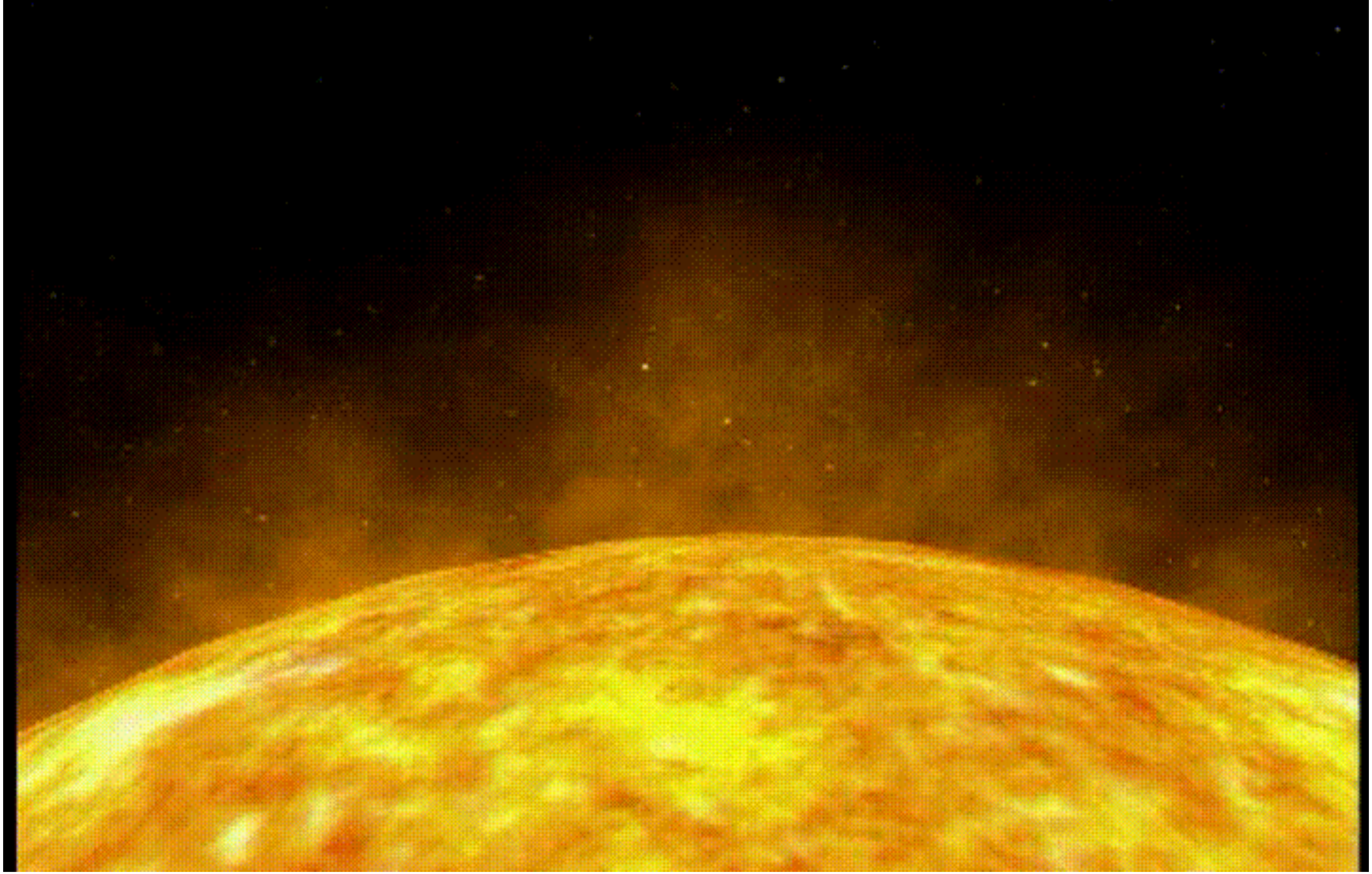
NASA

Space Weather

space weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.



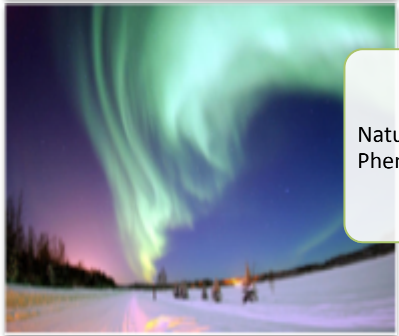
Space Weather Prediction



Importance of Space Weather Simulation

Societal Impact:

Science



Natural Phenomena

Technology in Space

Threats to communication infrastructure, GPS

Humans in Space

Threats to life and missions

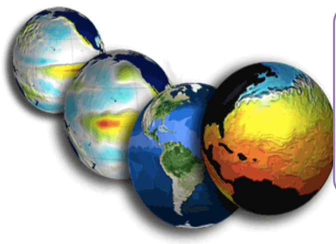
Ground effects

Pipelines

Ground effects

Power grid and communication lines

Impact on Earth Climate



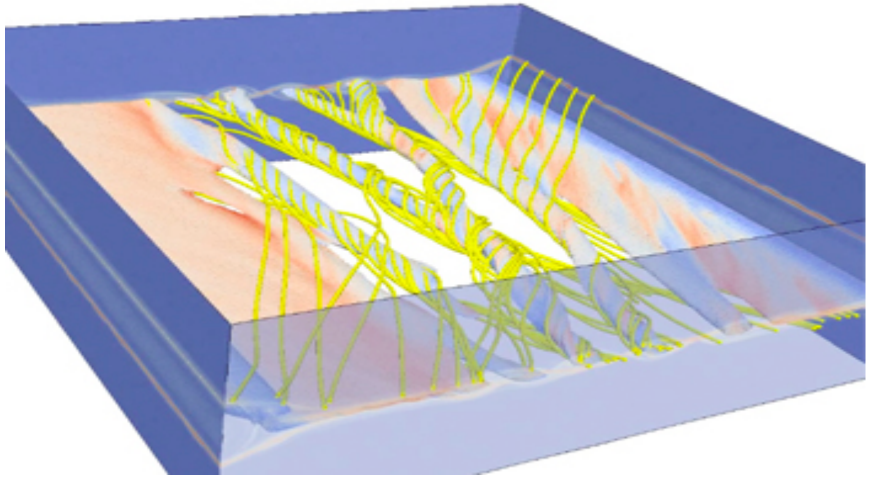
Relative importance of CO_2 and solar drives

Importance of Space Weather Simulation

Paradigm for High performance Computing:

Space weather simulation resembles many grand challenges:

- Fusion energy research (identical)
- Climate research (many common physics modules)
- Engineering applications (many similar algorithms)



VPIC@LANL One of the best performances on petascale (Roadrunner)

Outline

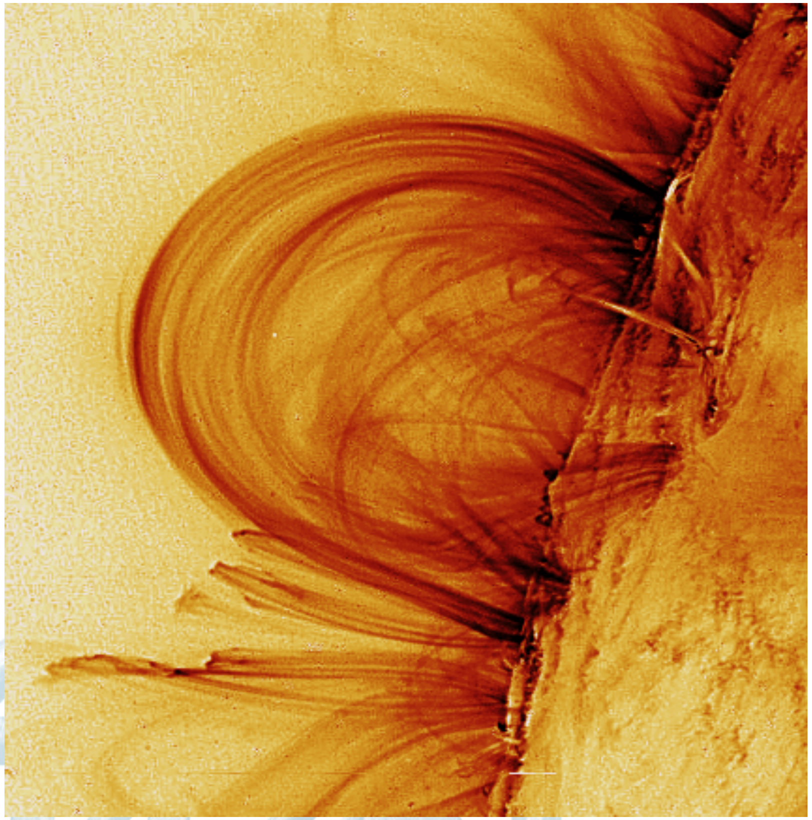
- Challenge1: complex series of events encomassing the whole solar system
- Challenge 2: multiphysics and multiscale
- Research possibilities
- New space missions

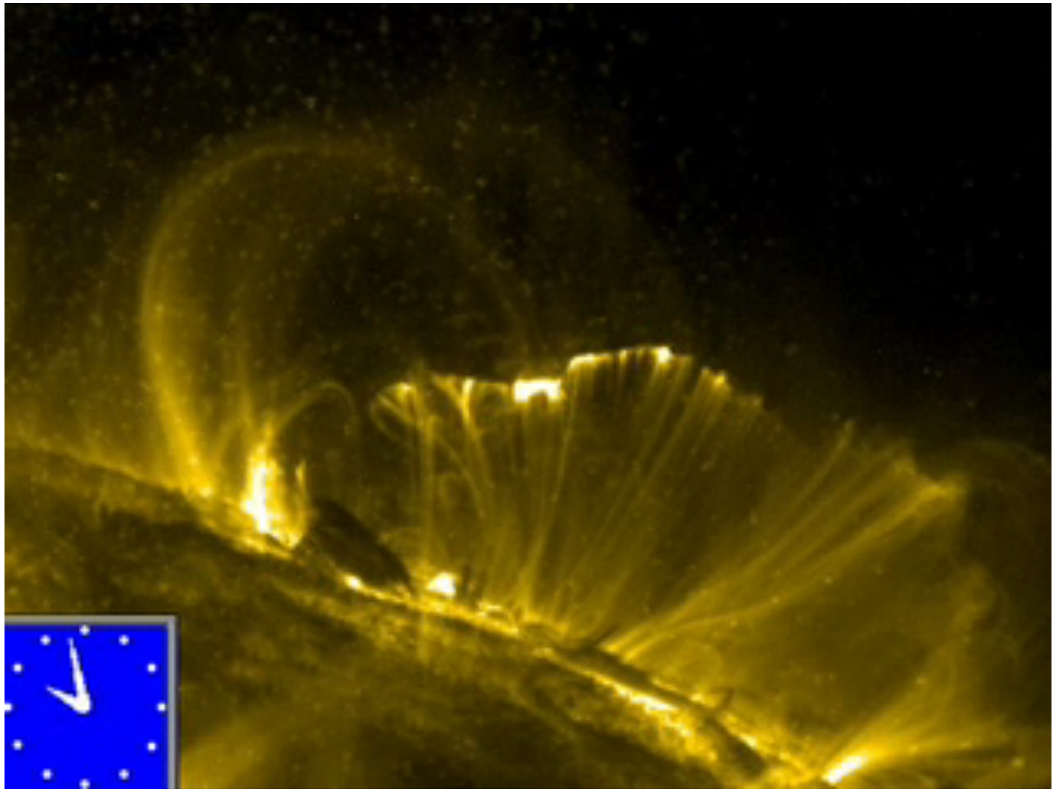
Outline

KATHOLIEKE UNIVERSITEIT LEUVEN

- Challenge1: complex series of events encomassing the whole solar system
- Challenge 2: multiphysics and multiscale
- Research possibilities
- New space missions

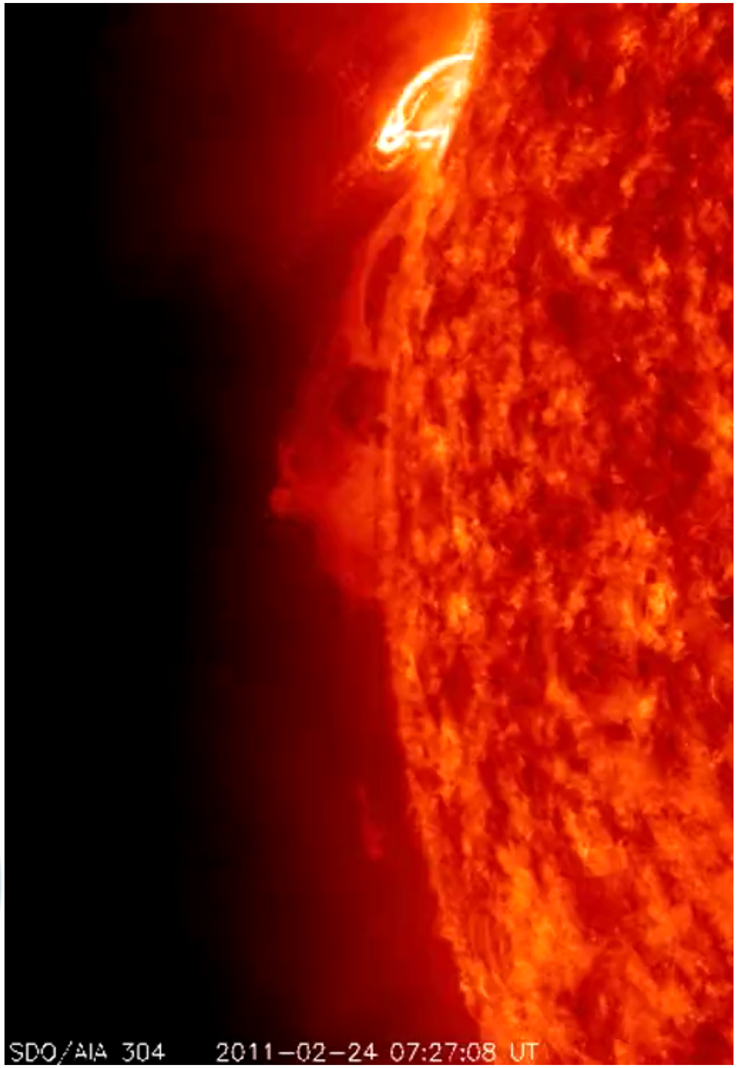
The Sun



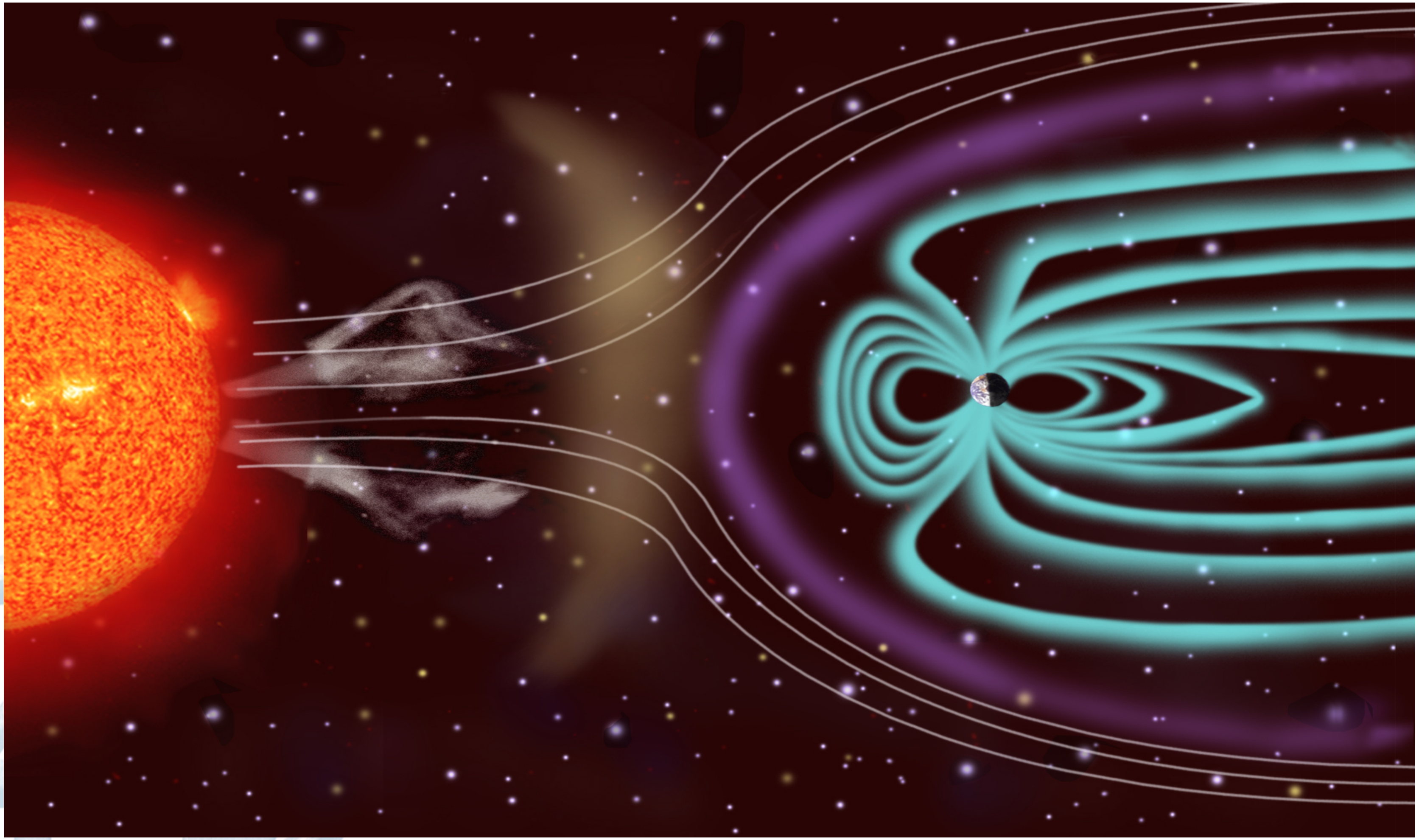


Let us follow the steps of space weather events

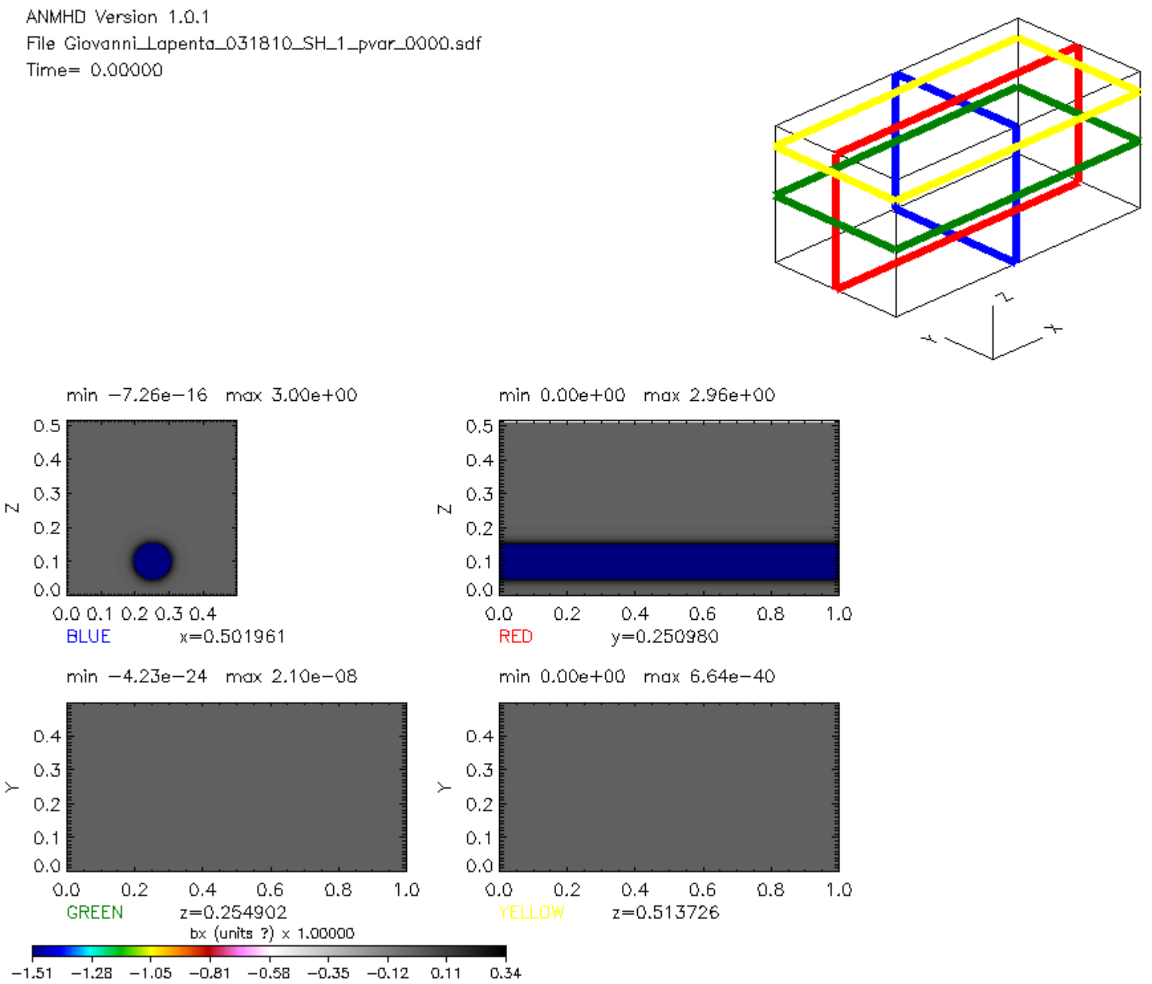
SDO Real Data



The Sun-Earth coupling

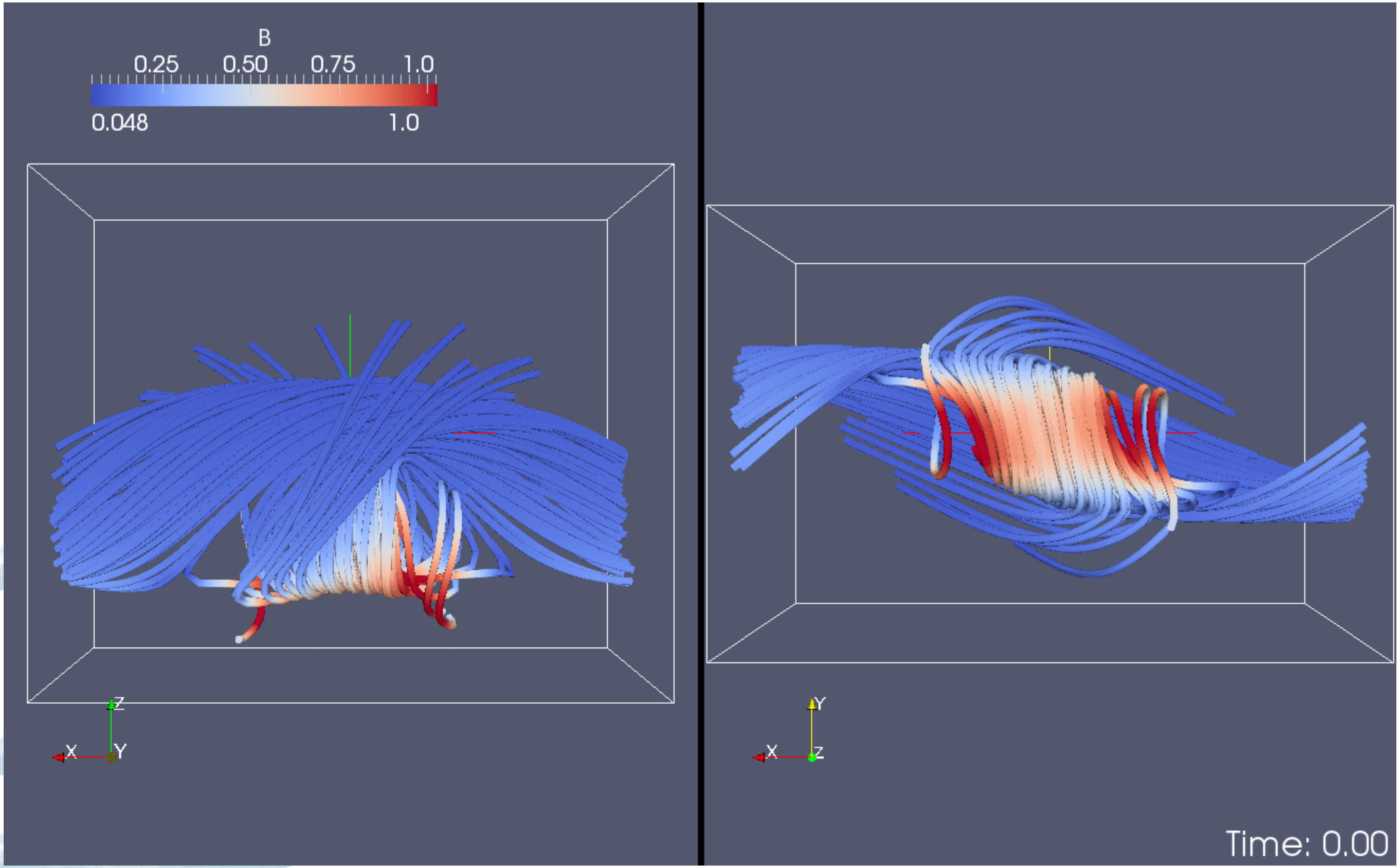


Flux emergence
(Lapenta, ANMHD at CCMC-NASA)

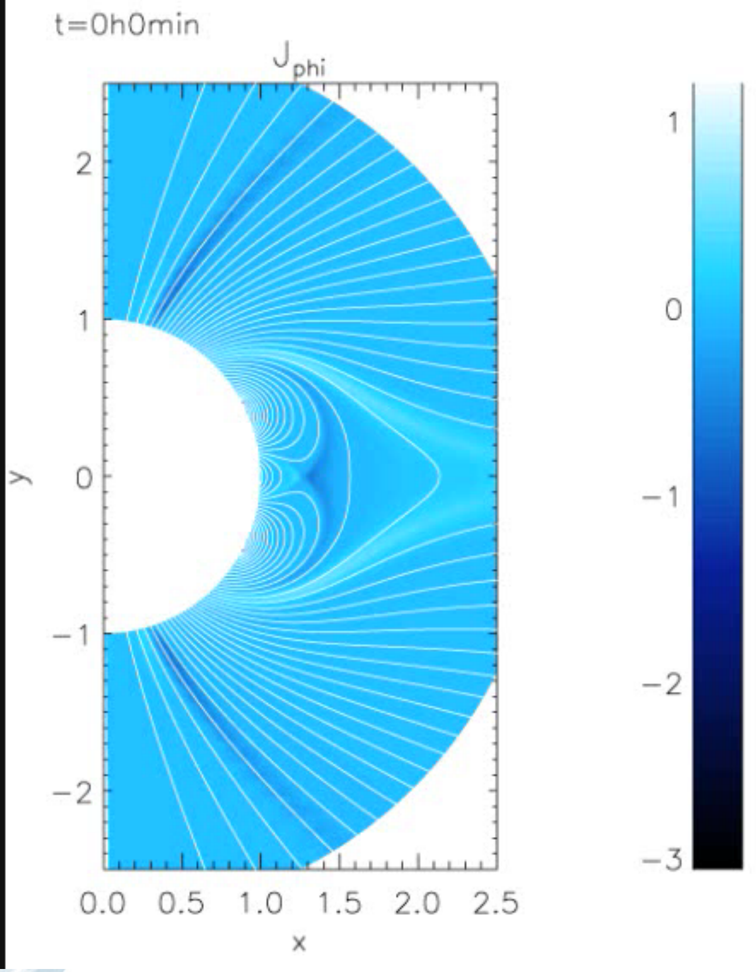


CME initiation challenge

(Lapenta and Bettarini, FLIP-MHD at KU Leuven)



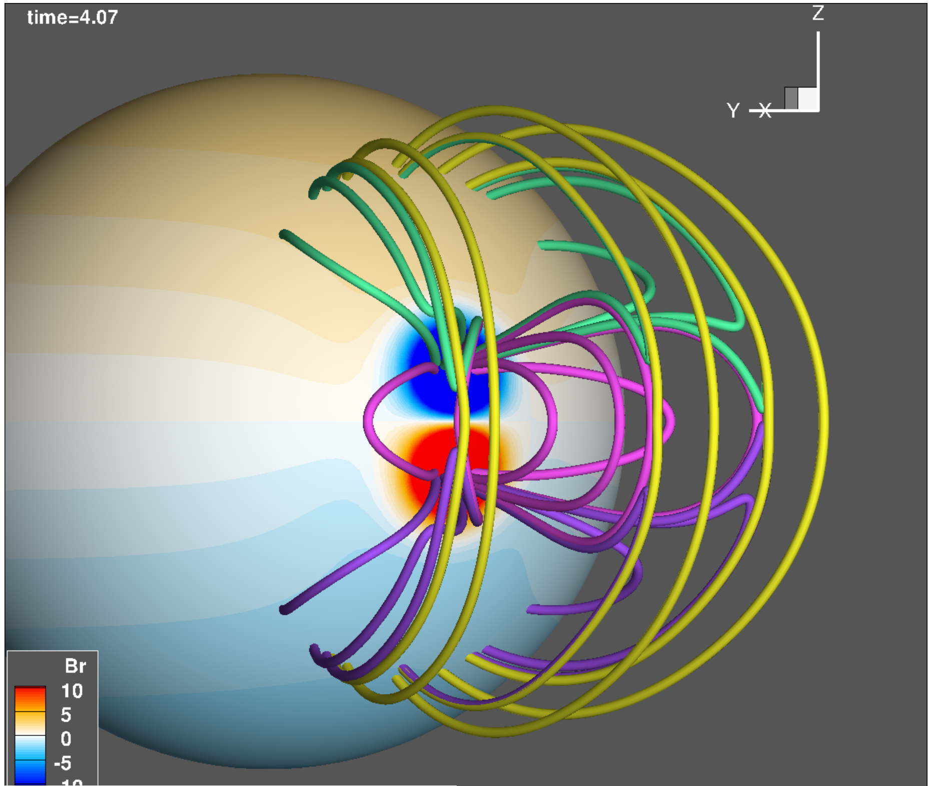
Coronal Mass Ejection Simulation
(Zuccarello, Poedts, VAC at KU Leuven)

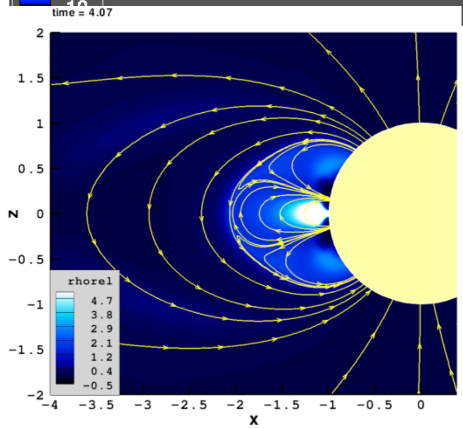


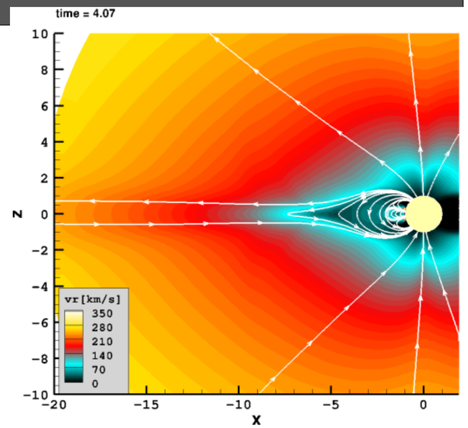
CME modeling (3D)
(Jacobs, Poedts, VAC at KU Leuven)

After t = 5 hrs:

- As the magnetic field strength increases in the bipolar active region, the central arcade (pink) expands, pushing against the overlying field (yellow)
- At the null line, reconnection between the central arcade and the overlying field causes flux transfer from the central system to the side arcades (green and purple).



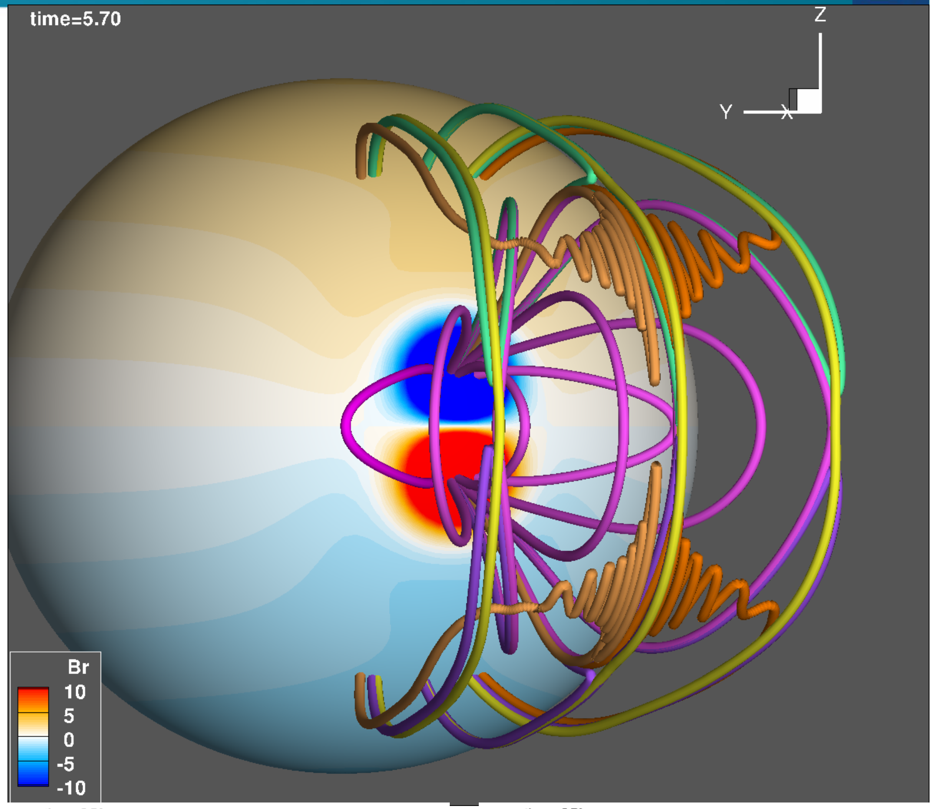


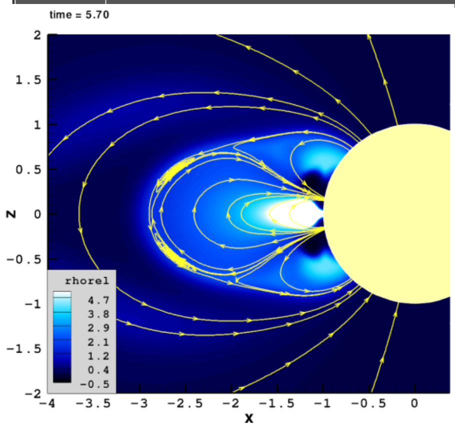


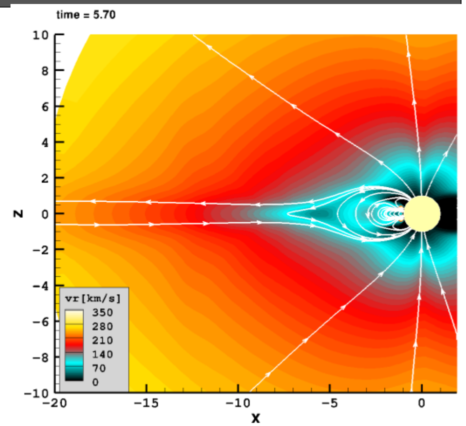
CME modeling (3D)
(Jacobs, Poedts, VAC at KU Leuven)

After t = 7 hrs:

- The expansion of the central arcade causes the tips of the side arcades to stretch and finally squeeze together and reconnect
- Since the emerging field is not purely poloidal, a squeezed magnetic field line of the side arcades does not reconnect on itself, but with a neighbouring field line, creating the spring-like structures (orange).





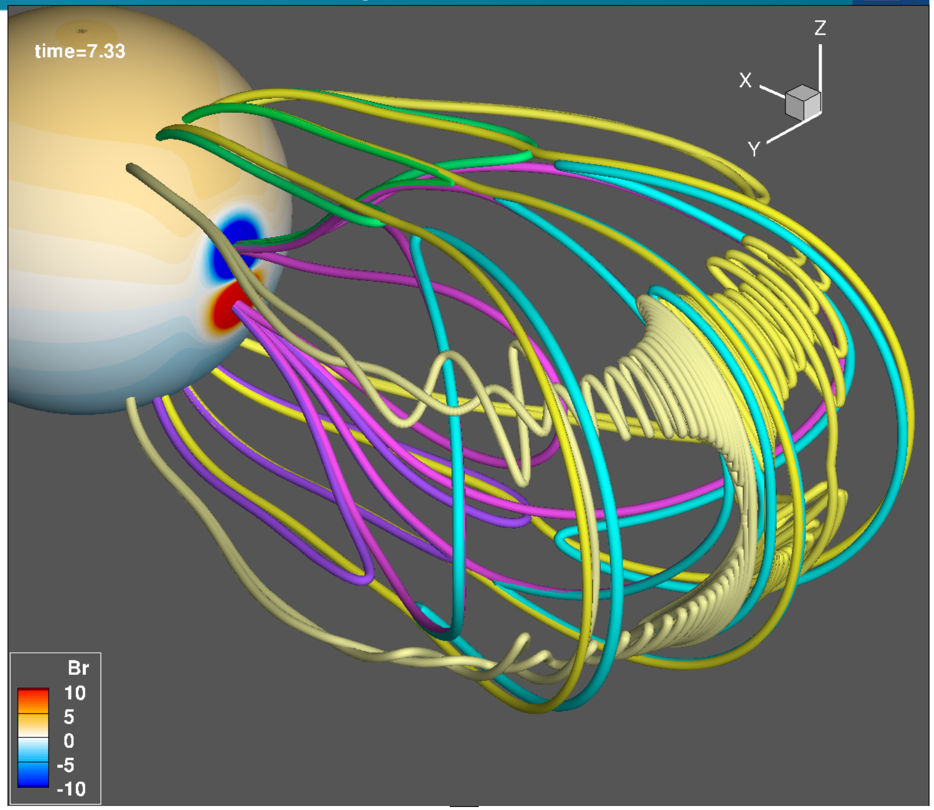


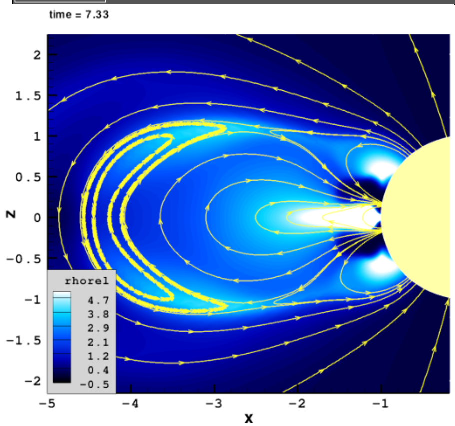
CME modeling (3D)
(Jacobs, Poedts, VAC at KU Leuven)

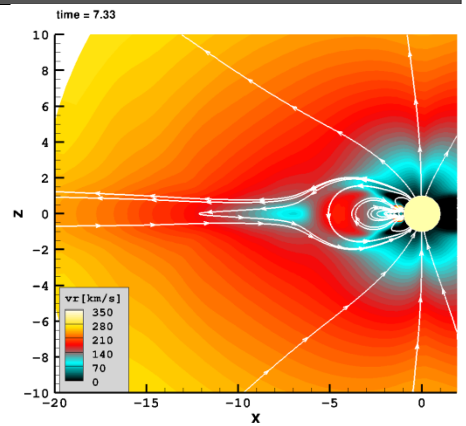
KATHOLIEKE UNIVERSITEIT LEUVEN

After t = 9 hrs:

- Eventually, the tips of the side arcades are removed, and the expanding arcade will reconnect with the overlying field at its side flanks, creating closed magnetic field structures overlying the central arcade system (light blue)
- These structures are squeezed together by the expanding central arcade, and highly twisted magnetic field lines, connecting both hemispheres, are created.



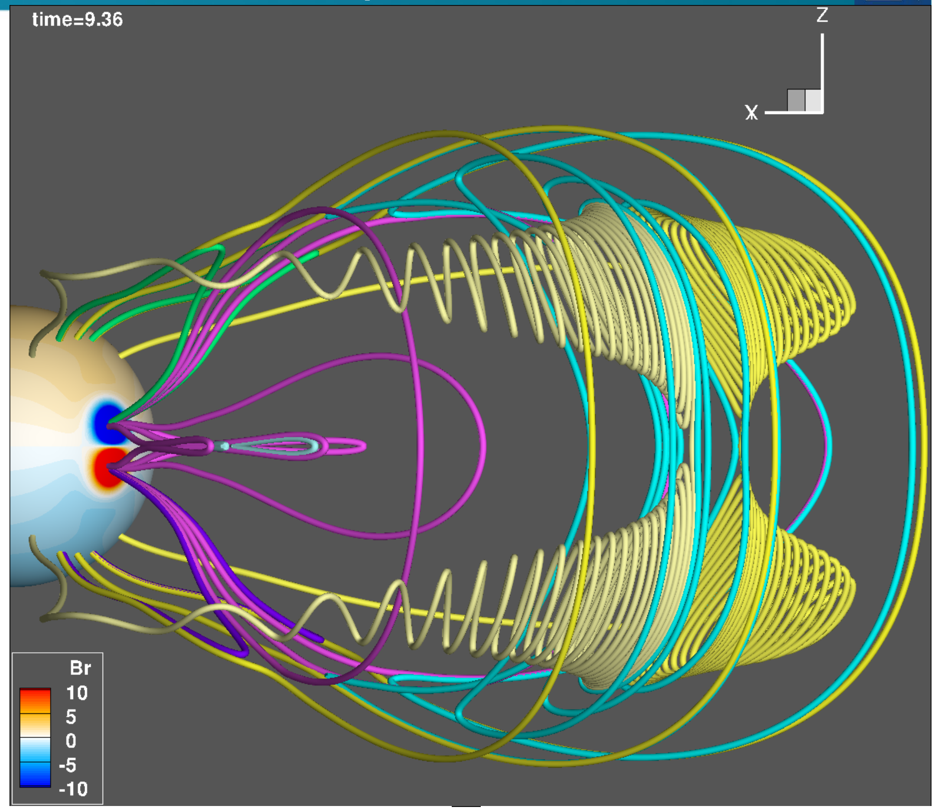


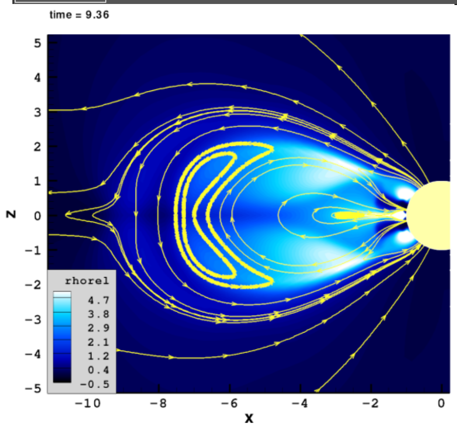


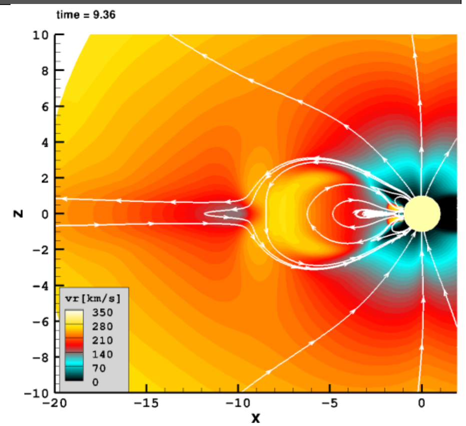
CME modeling (3D)
(Jacobs, Poedts, VAC at KU Leuven)

After t = 10.5 hrs:

- Finally, a current sheet forms below the expanding arcade, and reconnection detaches the top of the central arcade
- Eventually, the system evolves to a new stationary state.

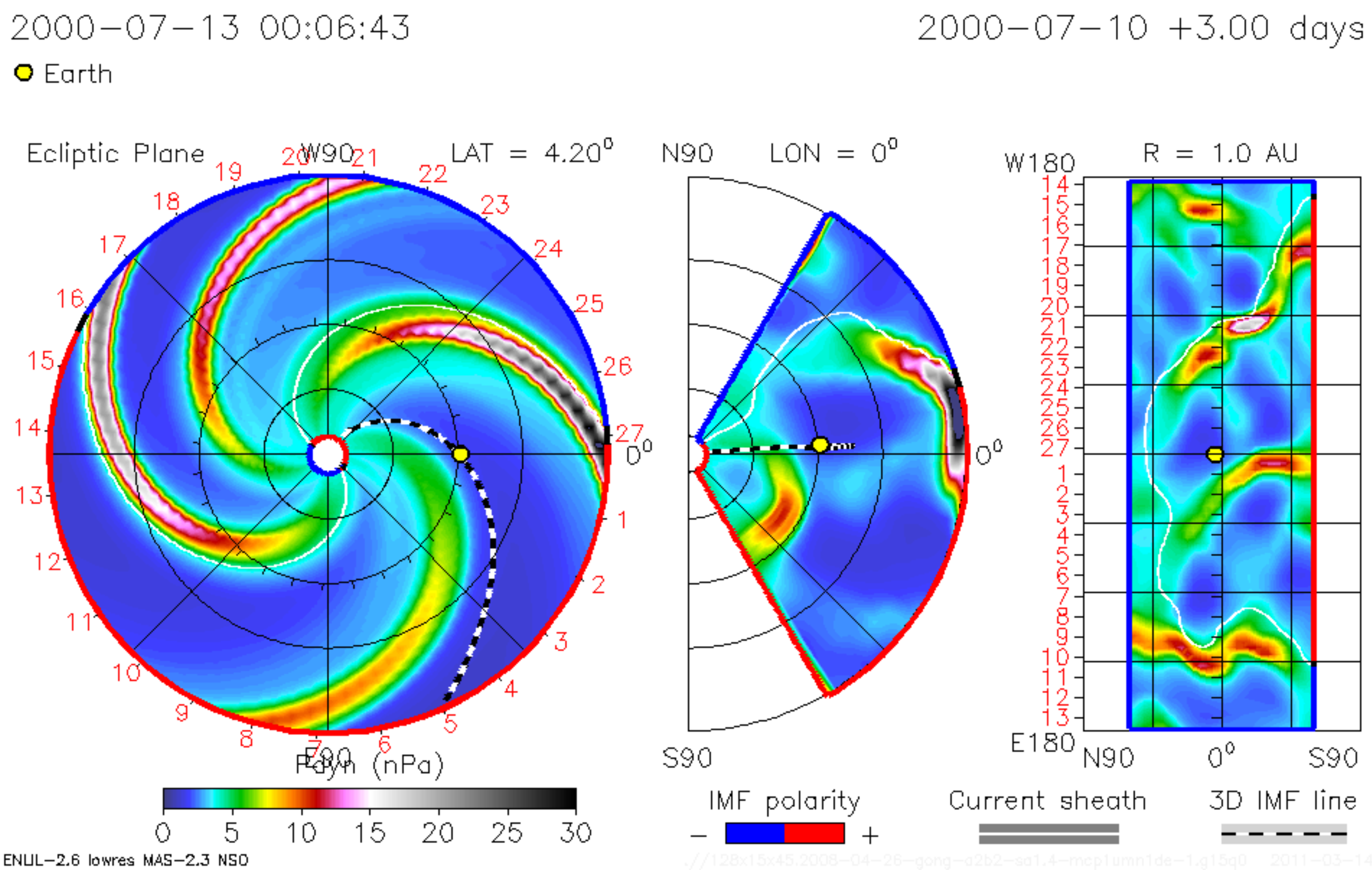






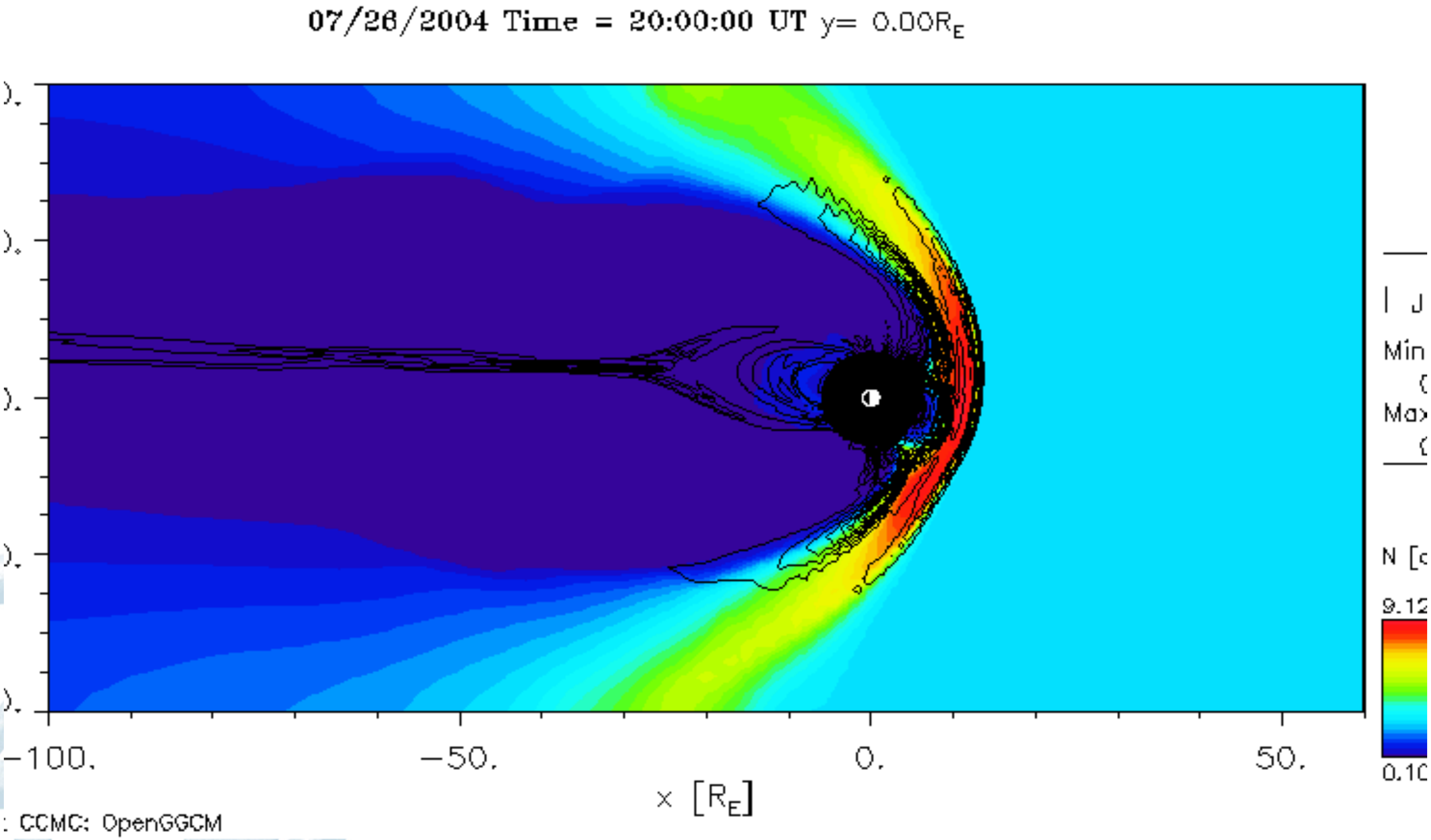
Heliospheric simulation

Lapenta using ENLIL at CCMC (NASA)

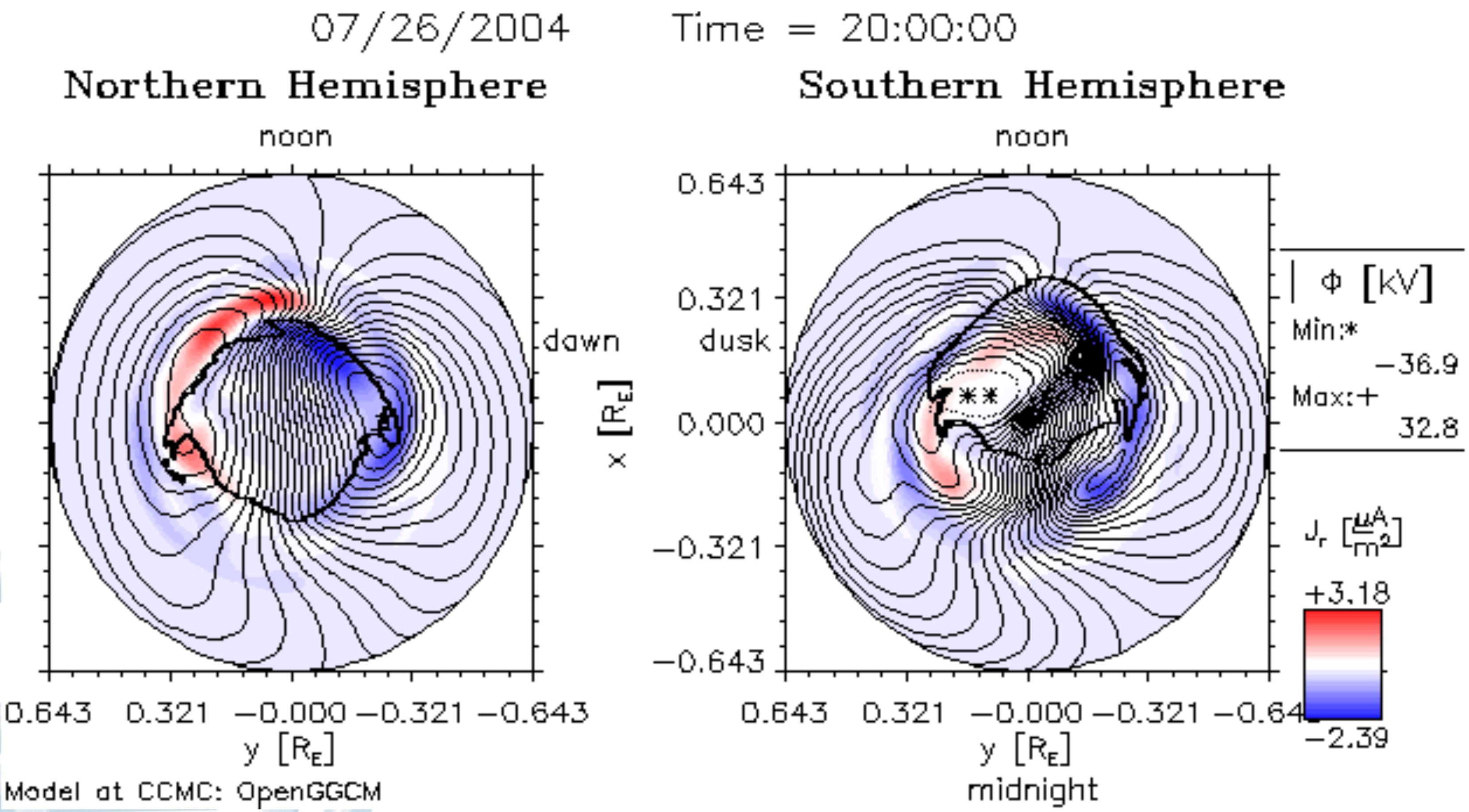


Interaction with the Earth

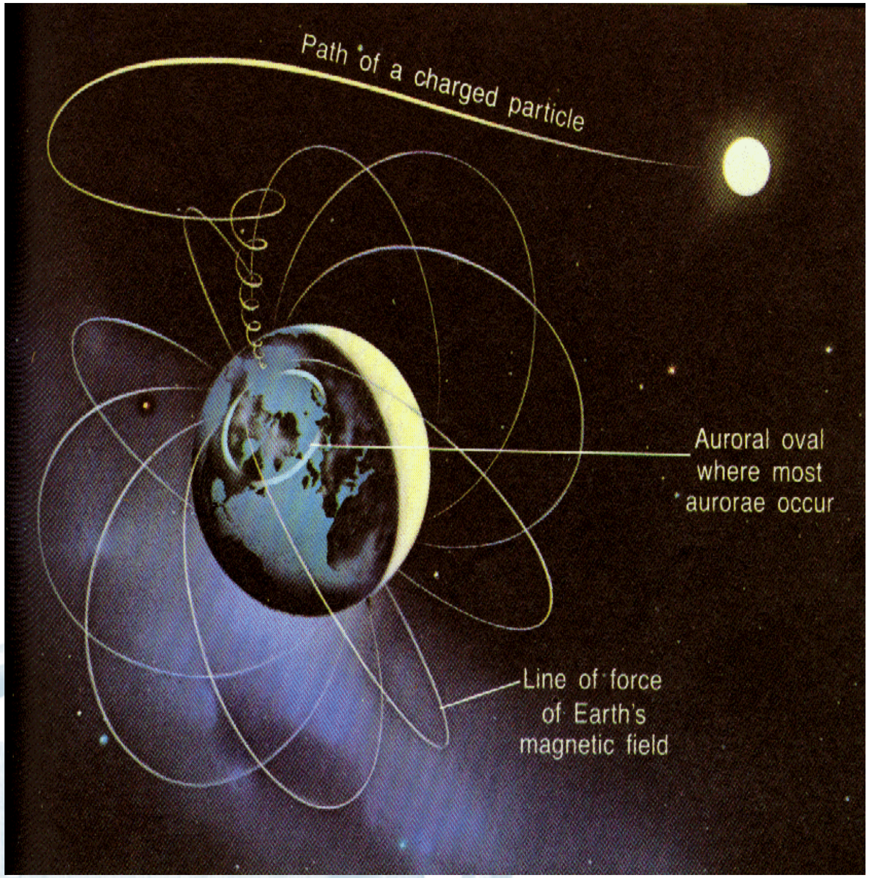
Soteria project - OpenGGCM at CCMC (NASA)



Ionospheric Simulations
Soteria project - OpenGGCM at CCMC (NASA)



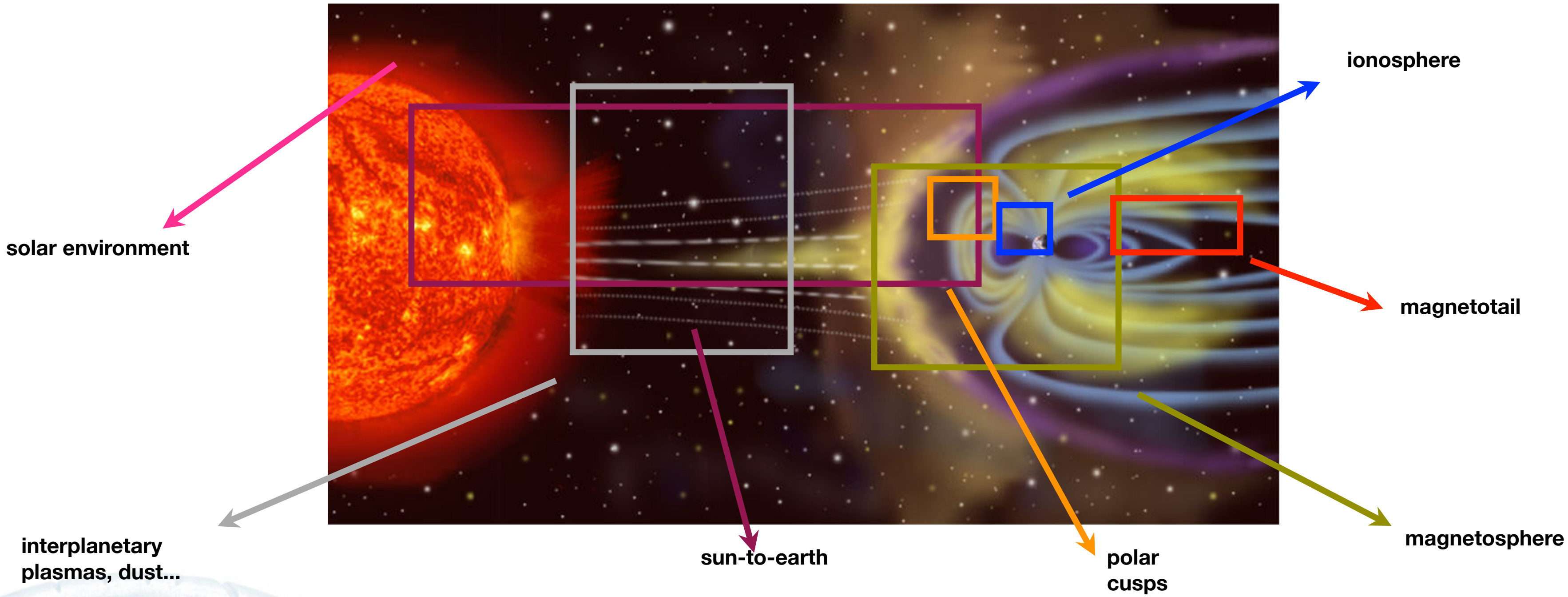
Aurora: Night lights

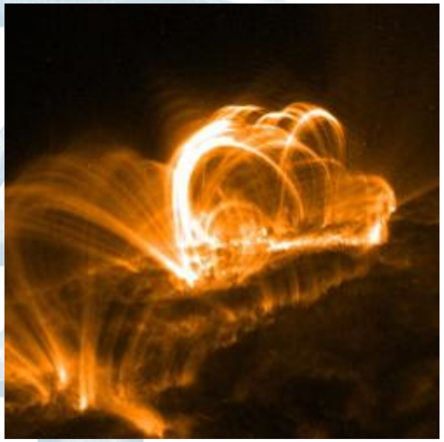


First space weather effect discovered, as documented by:

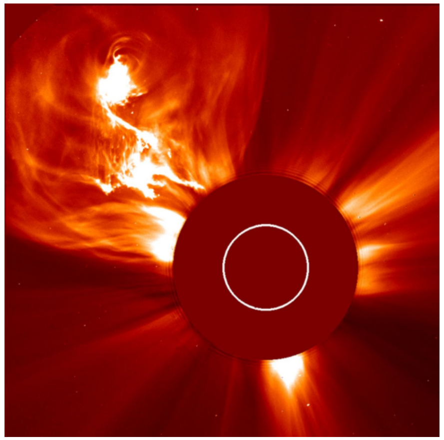
- 40,000 BC in a Cro-Magnon (first homo sapiens to live at high latitude) cave-painting
- 2,600 BC in a Chinese inscription

CHALLENGES IN MODELING SPACE WEATHER: MULTIPLE PHYSICS





TRACE September 2005



LASCO September 2002

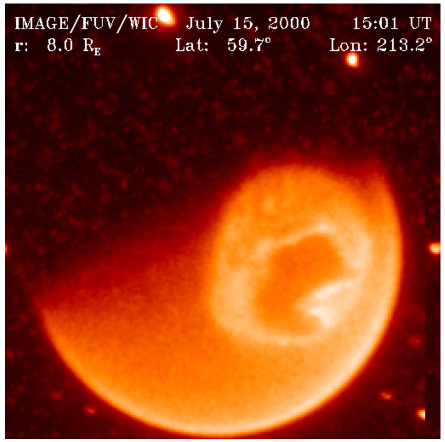
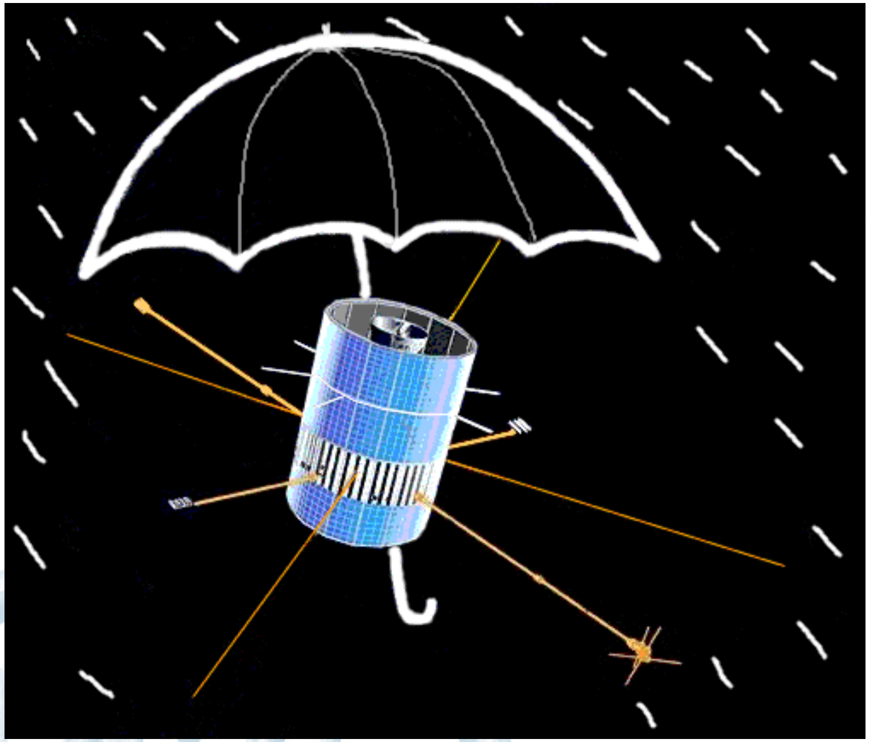


IMAGE July 2000

Outline

- Challenge1: complex series of events encomassing the whole solar system
- Challenge 2: multiphysics and multiscale
- Research possibilities
- New space missions

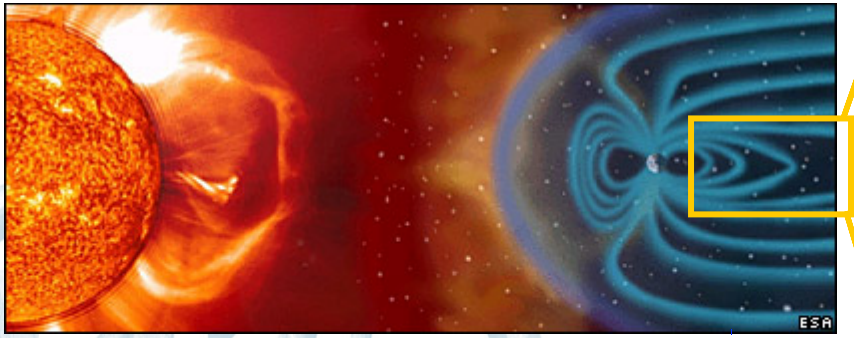
Space weather physics

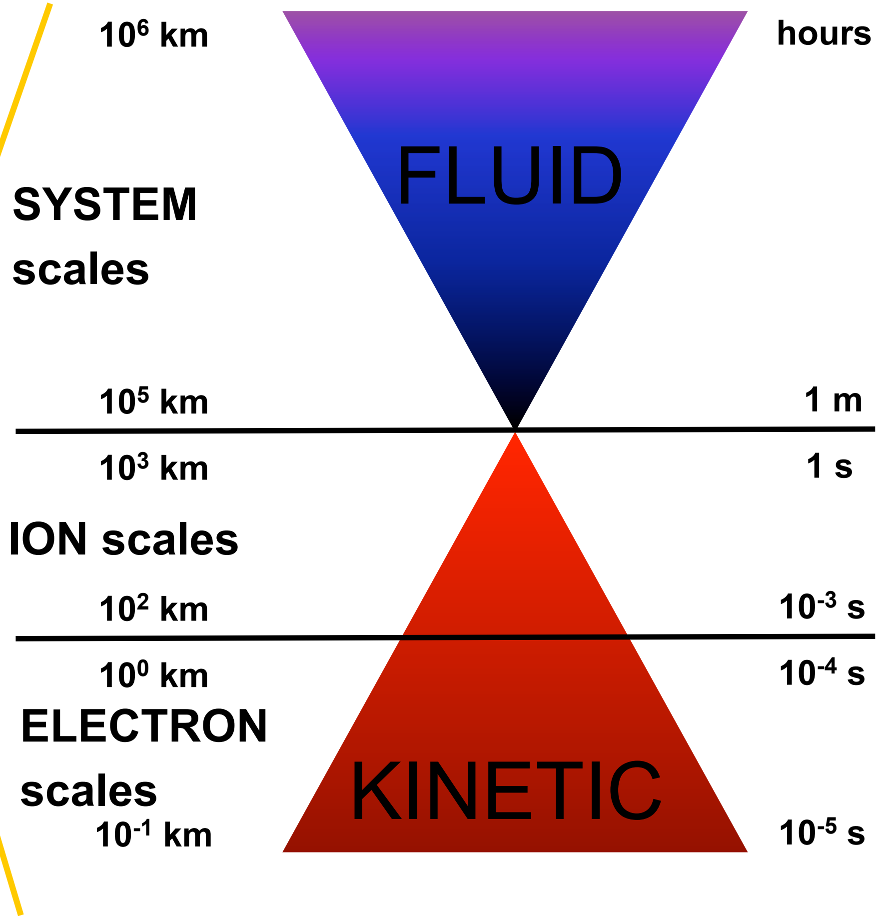


- The Solar System is an active region filled with a low density but energetic plasma.
- A plasma is a ionized gas composed of electrons and ions, interacting via force fields
- The plasma in the solar system is called solar wind and the magnetized plasma environment around a planet is called: magnetosphere
- The Sun, the solar wind and the magnetospheres are very active regions with enormous energies being continuously exchanged

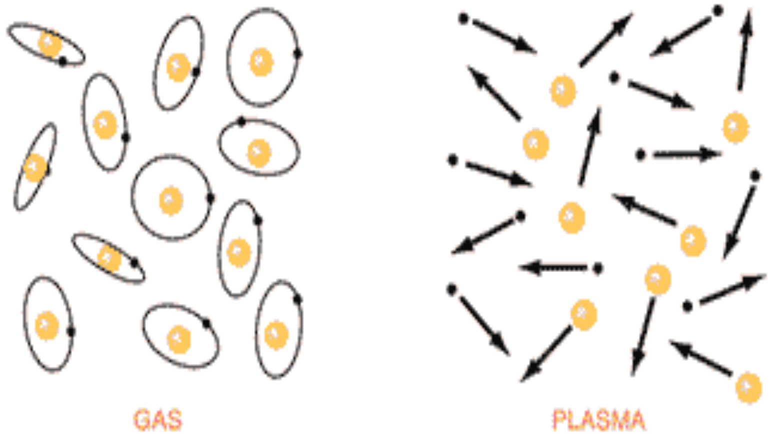
Overview of the scales involved

- Overall event duration: hours to days
- AU = 150 million Km (1.49 10^8 km)
- Solar Radius = 6.9 10^5 km
- Earth Radius = 6.4 10^3 km





A plasma and its models



Motion of charged particles without magnetic field.

Motion of charged particles with magnetic field.

- Single particle level: tracing every single particle and their interactions:

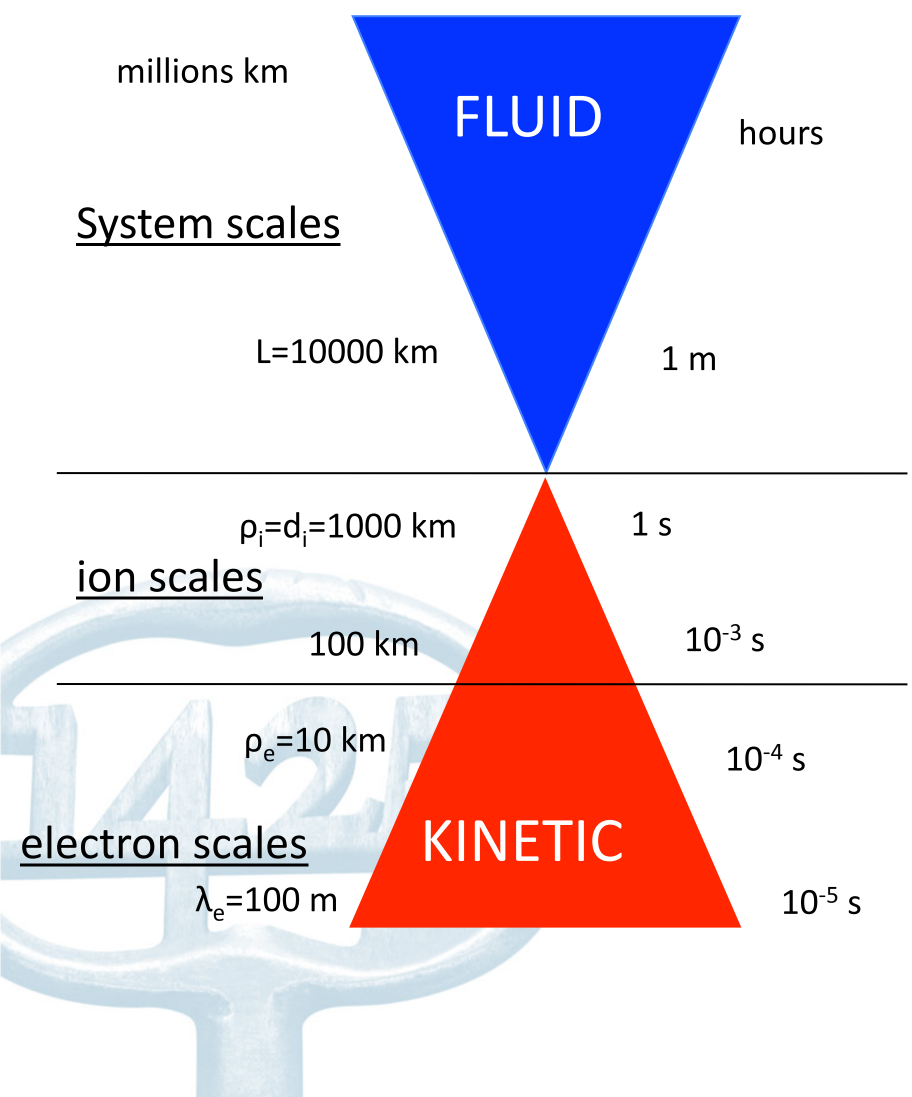
$$\{x_p, v_p\}$$

- Kinetic approach: study the distribution function (probability of finding a particle with a given velocity in a given point at a given time): $f(\mathbf{x}, \mathbf{v}, t)$

- Fluid approach: study local averages (density, average speed, temperature,….)

$$n(\mathbf{x}, t), \mathbf{U}(\mathbf{x}, t), T(\mathbf{x}, t)$$

Scales and models: Standard view

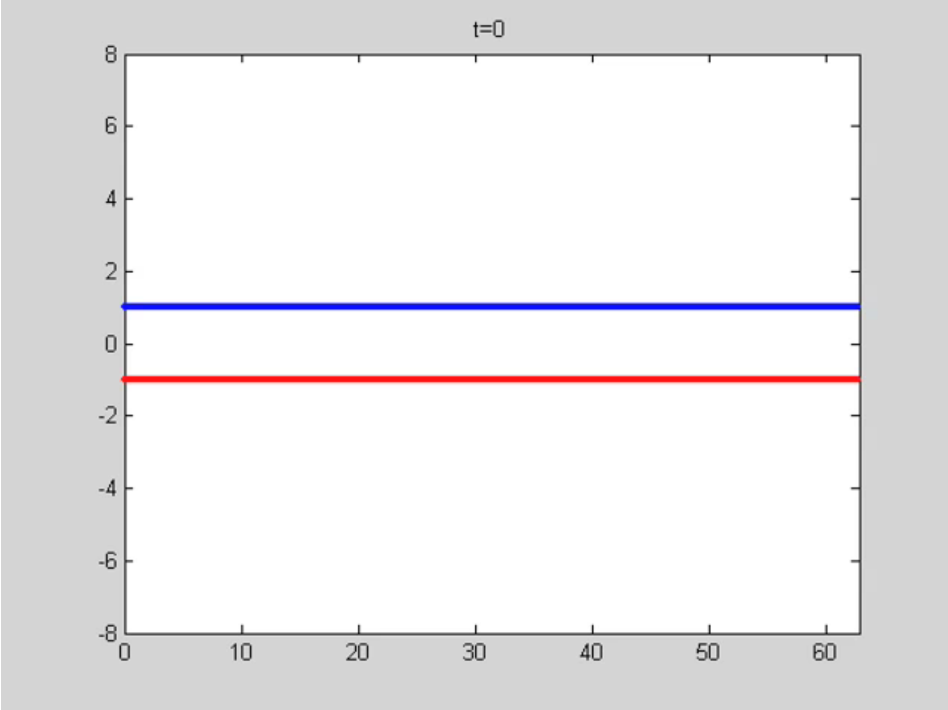


- Fluid models
  - economically viable at large scales
  - miss the small scale physics
  - need for advanced fluid models that reintroduce what is missing
  - One can include only what one understands
- Kinetic models
  - include all physics, in particular what we do not yet understand
  - surprisingly simple to conceive and implement in computers
  - not economical at large scales
- Why not economical?

Kinetic model

- Kinetic theory
- Phase space: probability density in 6D space of position and velocity
- Example of a string plasma: particles move on a string (in both directions)
- Phase space is 2D: (X, P)
- Initially beams evolve and form complicated patterns
- But at near equilibrium the structures become manageable via the moments

$$M_n(x,t) = \int f(x,v,t) v^n dv$$



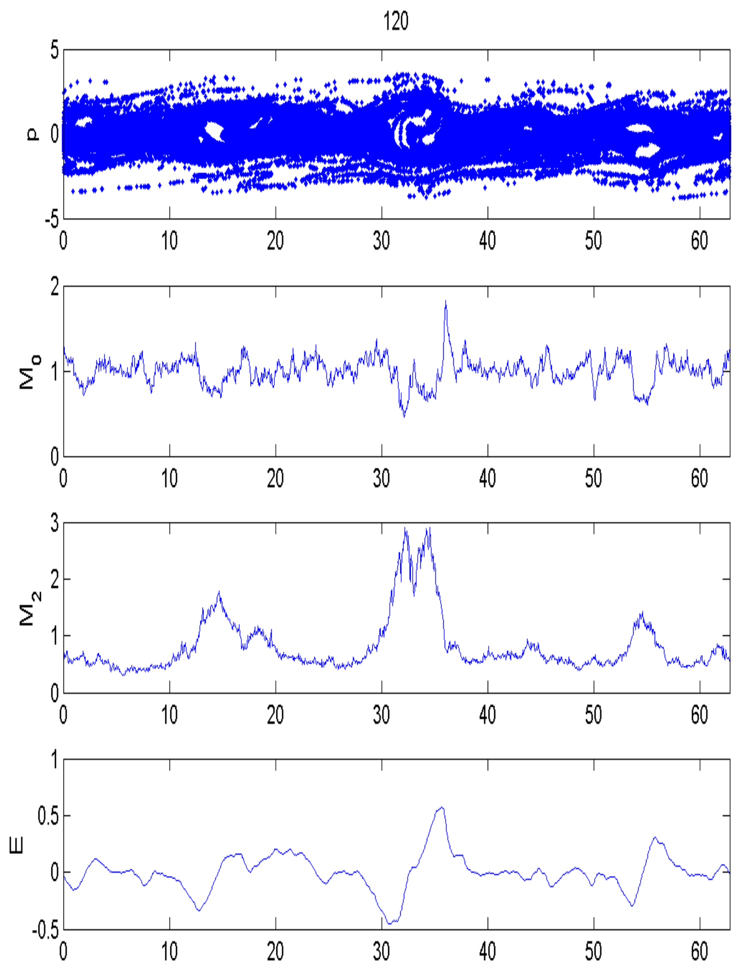
Simulation conducted with Parsek (Lapenta et al. ApJ 666 949 doi: 10.1086/520326, 2007).

Fluid model

- The fluid model is based on using a finite number of moments:

$$M_n(x,t) = \int f(x,v,t) v^n dv$$

- Near thermodynamic equilibrium it is an accurate description
- Cannot capture complex features in phase space



Outline

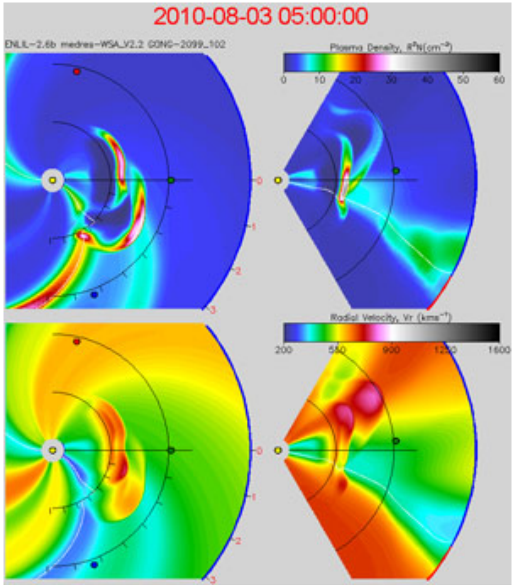
- Challenge1: complex series of events encomassing the whole solar system
- Challenge 2: multiphysics and multiscale
- Research possibilities
- New space missions

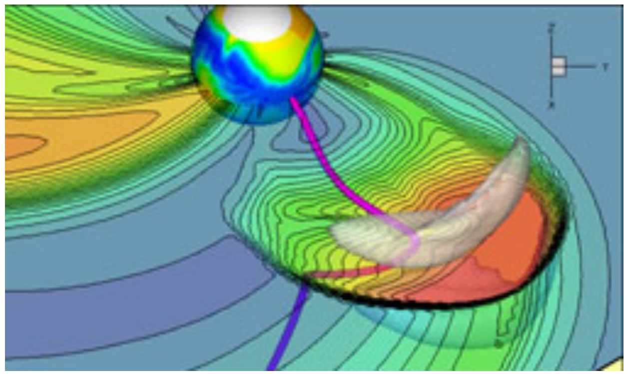
KATHOLIEKE UNIVERSITEIT LEUVEN

Space Weather Research - USA

- NOAA: Space Weather prediction center in Boulder
- Military: similar center in Colorado also
- Modeling activity:
  - CISM (Boston, multicenter)
  - SWMF (Michigan)
  - CCMC
- Modeling becoming operational

- Research funded by
- NASA
- NSF
- DoD (Navy, Air Force)



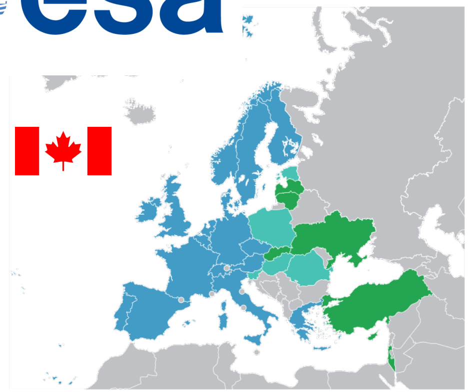


Space Weather Research - Europe

FWO VLAANDEREN

Belgian Science Policy Office
belspo

esa



Space Weather in Europe

European Commission

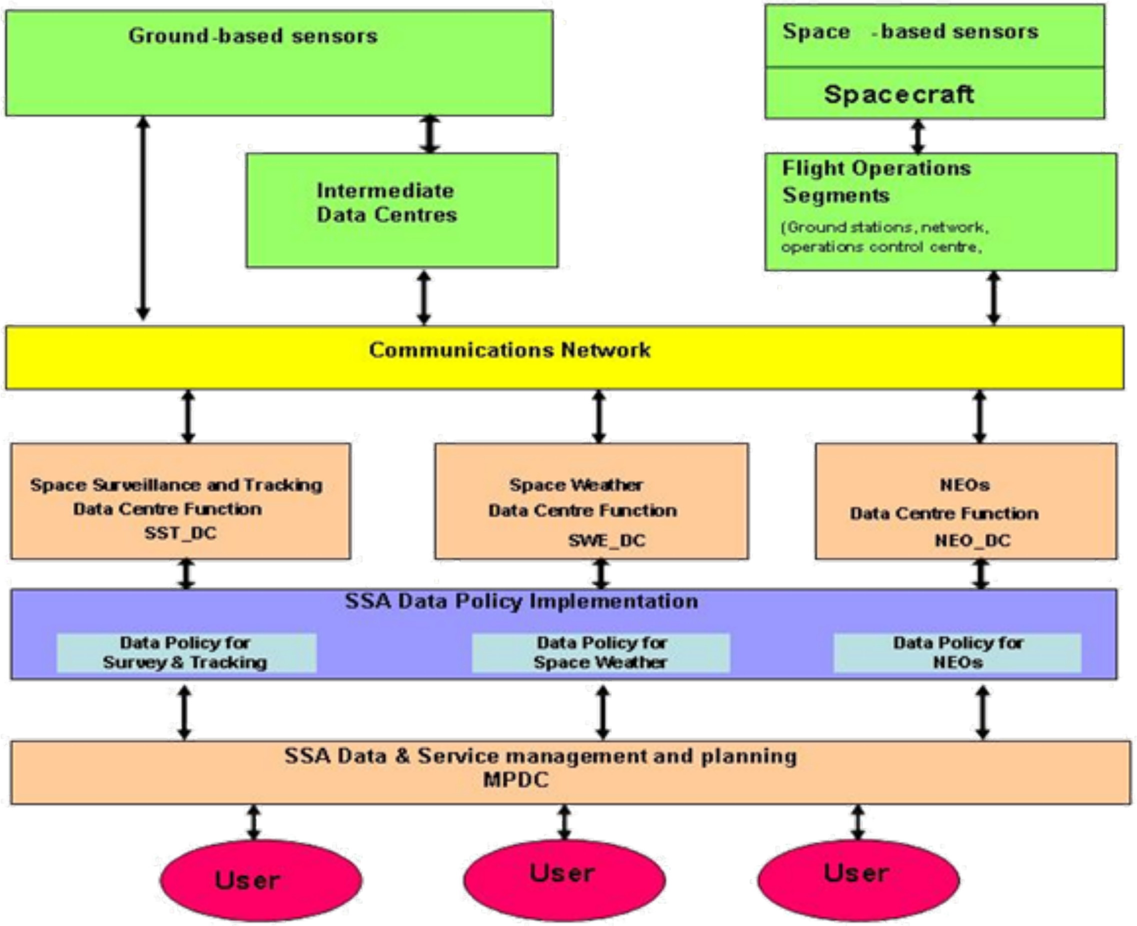
Framework Program 8

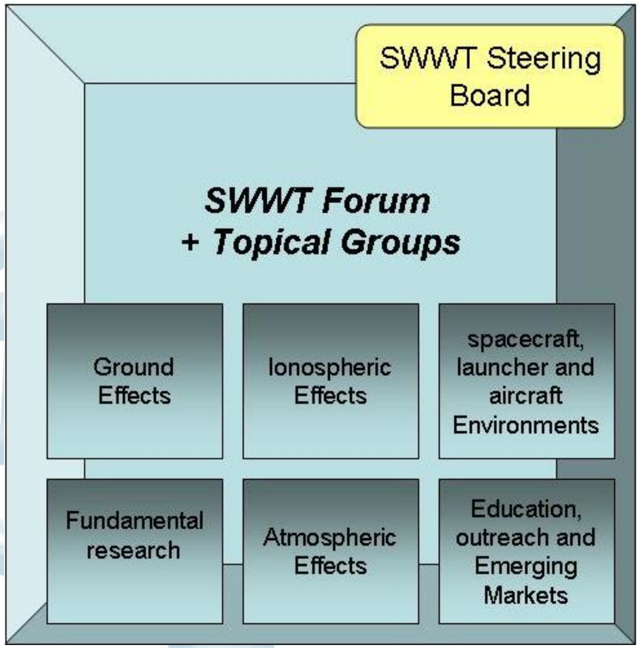
- Framework Program 7
  - Basic Space Science (Soteria, eHeroes)
  - Infrastructure (Cassis,Helio, Europlanet)
  - Space Weather (Swiff, Spacecast, Comesep, Affects, SepServer,…)
  - ITN (e.g. Solaire)

Namur, Belgium

Nov 28 – Dec 2

Space Situational Awareness (SSA)





Support at KU Leuven

KATHOLIEKE UNIVERSITEIT LEUVEN

Soteria

- First ever EC funded project on space weather
- Involving 16 centers in 13 countries
- Focus on space weather and Earth impact
- Observation (some simulation)

Swiff

- Multiphysics modelling of space science applied to space weather
- Focus on simulation and theory
- To run till 2014
- Involving 7 centers in 5 countries

eHeroes

- Being negotiated.
- Scheduled to start in march 2012
- Continuation of Soteria with emphasis on space exploration instead of Earth impact.
- Possibility of interaction with Boulder Lunar Science.

DEEP

Intel-based hybrid architectures

ExaScience Lab
Intel Labs Europe
EXASCALE COMPUTING

Co-Design of space simulation on exascale

SOTERIA EC to continue as **eHeroes** funded by the EC/FP7- Space

SEVENTH FRAMEWORK PROGRAMME

www.soteria-space.eu

Coordinator: G. Lapenta

Data (ground & space) and simulation on:

- **Space Weather**
- **Solar sources and their evolution**
- **Terrestrial Impact**
- **Space Activities**

Participant Number	Participant short name	Participant organisation name	Country
1 (coordinator)	KU Leuven	Katholieke Universiteit Leuven	Belgium
2	UNIGRAZ	Universitaet Graz	Austria
3	PMOD-WRC	Pyhsikalisch-Meteoroligisches Observatorium Davos and World Radiation Center	Switzerland
4	KO	Konkoly Observatory	Hungary
5	CNRS LPCE & LP	Centre National de la Recherche Scientifique	France
6	ROB/SIDC	Koninklijke Sterrenwacht van Belgie	Belgium
7	OBSPARIS	Observatoire de Paris	France
8	SRC-PAS	Space Research Centre, Polish Academy of Sciences	Poland
9	MTA-KFKI-RMKI	MTA-KFKI-RMKI Research Institute for Particle and Nuclear Physics	Hungary
10	DTU	Technical University of Denmark	Denmark
11	UOulu	University of Oulu	Finland
12	UGOE	Georg-August-Universität Göttingen Stiftung Öffentlichen Rechts	Germany
13	HVAR	Hvar Observatory, Faculty of Geodesy, University of Zagreb	Croatia
14	NOVELTIS	Noveltis Sas	France
15	FIAN	P.N. Lebedev Physical Institute	Russia
16	IEEA	Informatique Electromagnetisme Electronique Analyse numérique	France

Soteria

- Focus on data dissemination

eHeroes

- adds emphasis to space exploration (specifically manned missions to the Moon and Mars)

SWIFF: Space Weather Integrated Modelling Framework

KATHOLIEKE UNIVERSITEIT LEUVEN

Space Weather Integrated Forecasting Framework

Coordinator: Giovanni Lapenta

Katholieke Universiteit Leuven

Collaborative Project

FP7- Space

- Create a mathematical-physical framework to integrate multiple-physics (fluid with kinetic)
- Focus on method and software development, rather than reuse of existing codes
- Physics-based forecasting
- Focus on coupling small-large scales
- Based on implicit methods and AMR

Science Lead	Participant organisation name	Country
Coordinator: G. Lapenta	Katholieke Universiteit Leuven	Belgium
V. Pierrard	Belgian Institute for Space Aeronomy	Belgium
F. Califano	Università di Pisa	Italy
A. Nordlund	Københavns Universitet	Denmark
A. Bemporad	Astronomical Observatory Turin - Istituto Nazionale di Astrofisica	Italy
P. Travnicek	Astronomical Institute, Academy of Sciences of the Czech Republic	Czech Republic
C. Parnell	University of St Andrews	UK

Outline

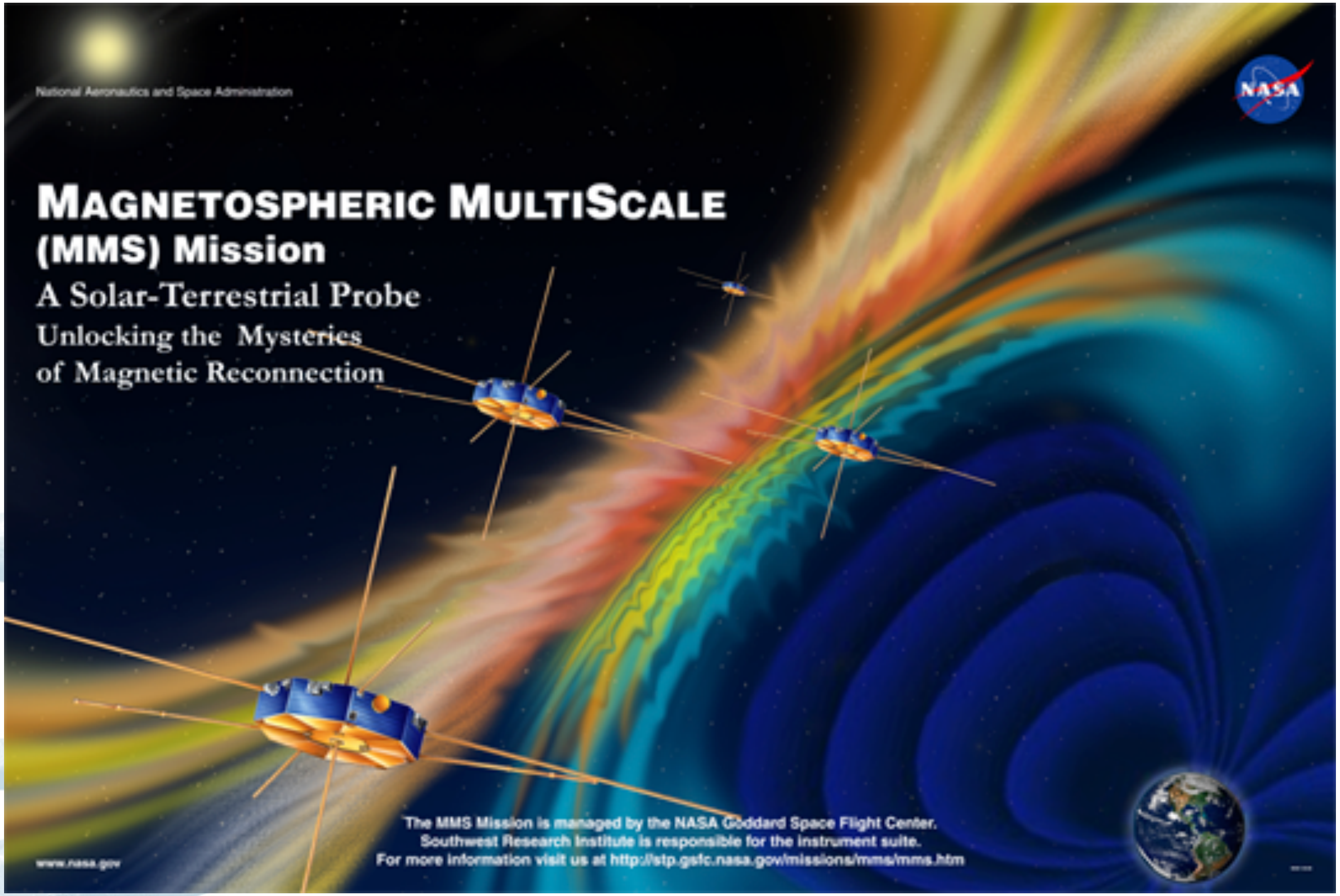
Challenge1: complex series of events encomassing the whole solar system

Challenge 2: multiphysics and multiscale

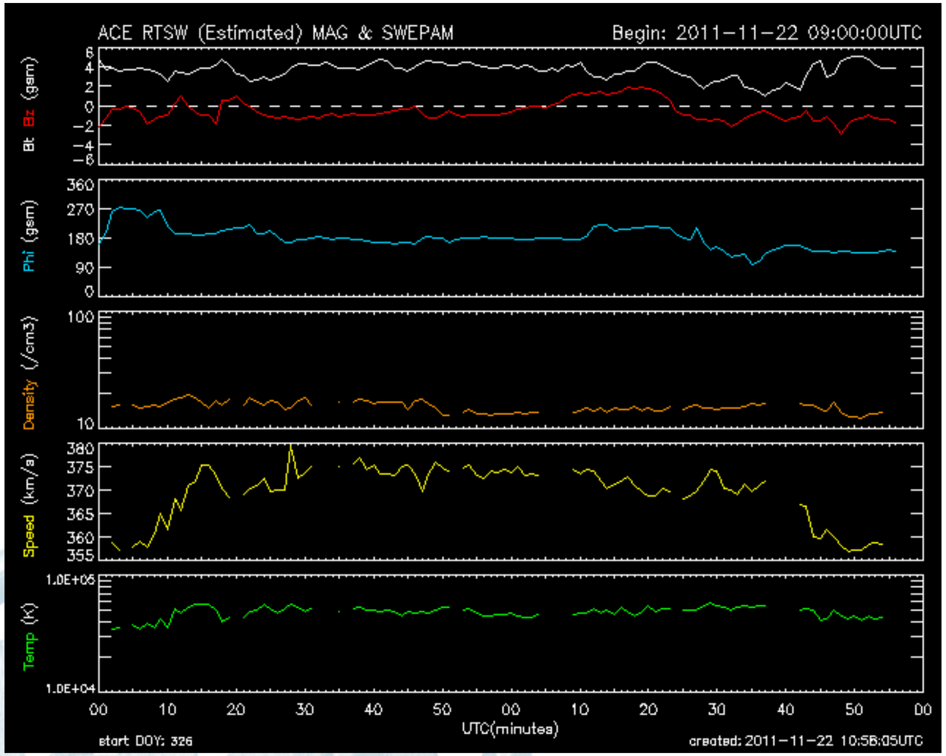
Research possibilities

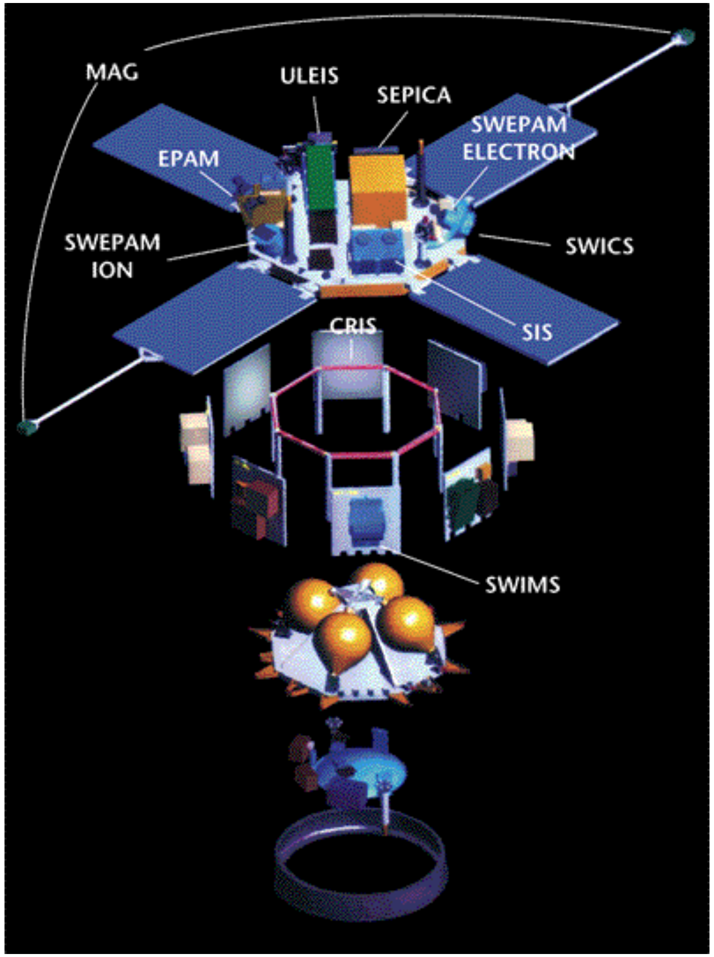
New space missions

MMS Mission
Theory Team at U Colorado



ACE: our aging workhorse





Solar Orbiter