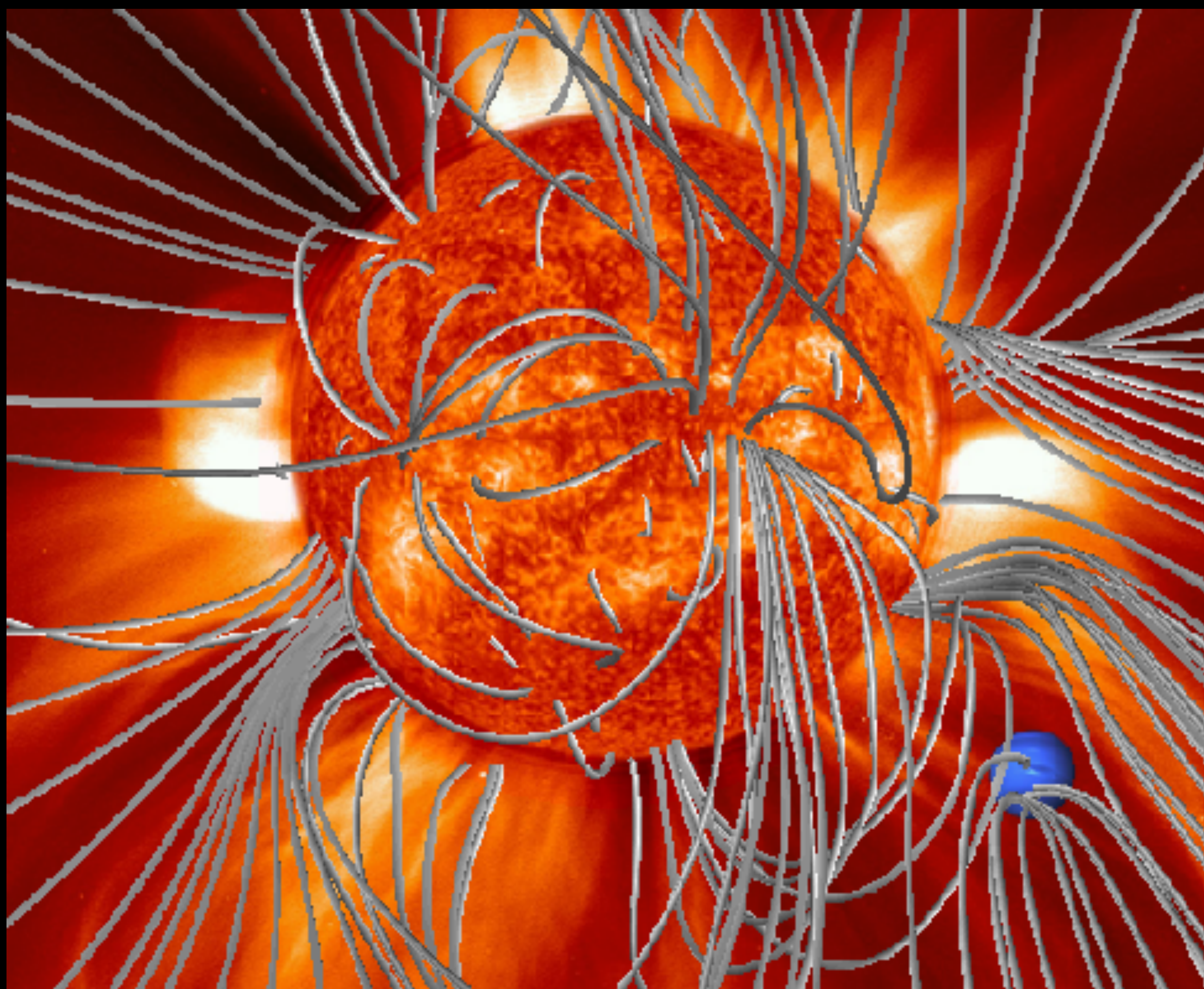
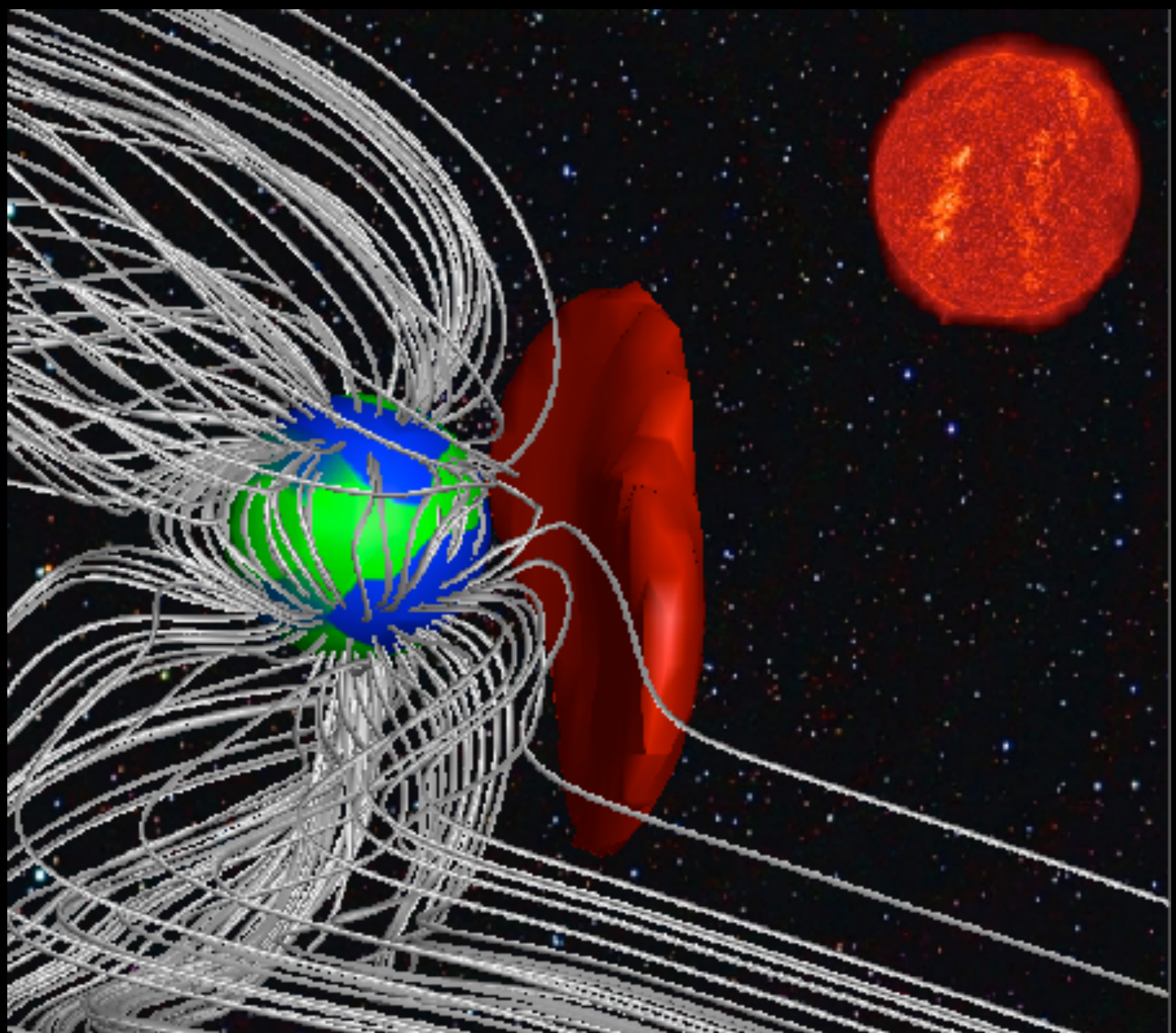
Computational Plasma Physics in the Solar System and Beyond

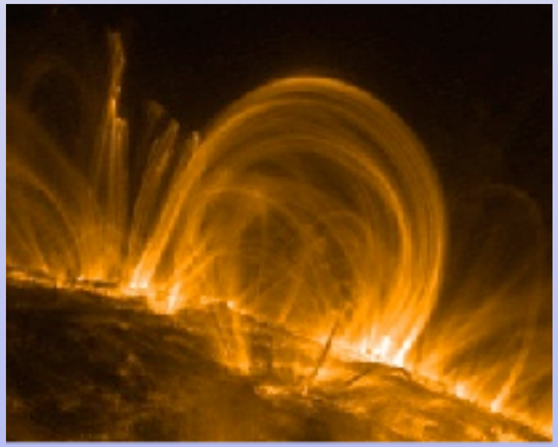


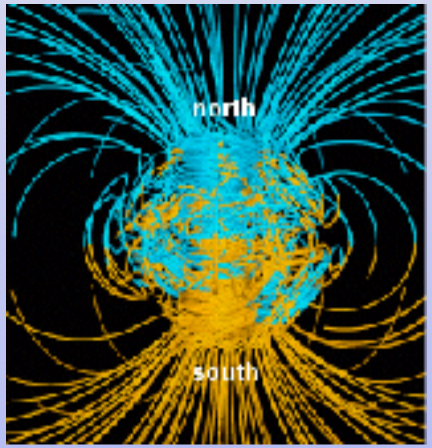


Ofer Cohen

HPC Day 2017 at UMass Dartmouth

Plasma physics (not medical!!!) - studying the interaction between charged particles and electromagnetic fields.

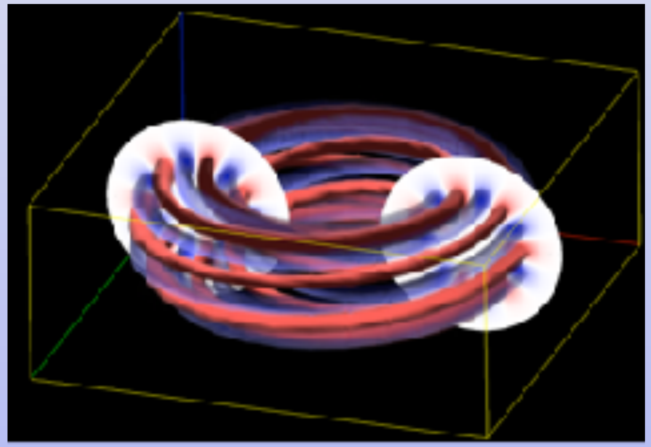

NASA/TRACE



NASA


NASA/Chandra


NOAA


alice.loria.fr

In most space physics problems - the plasma $\beta = P_{magnetic}/P_{thermal} << 1$
Magnetic fields dictate the plasma dynamics.

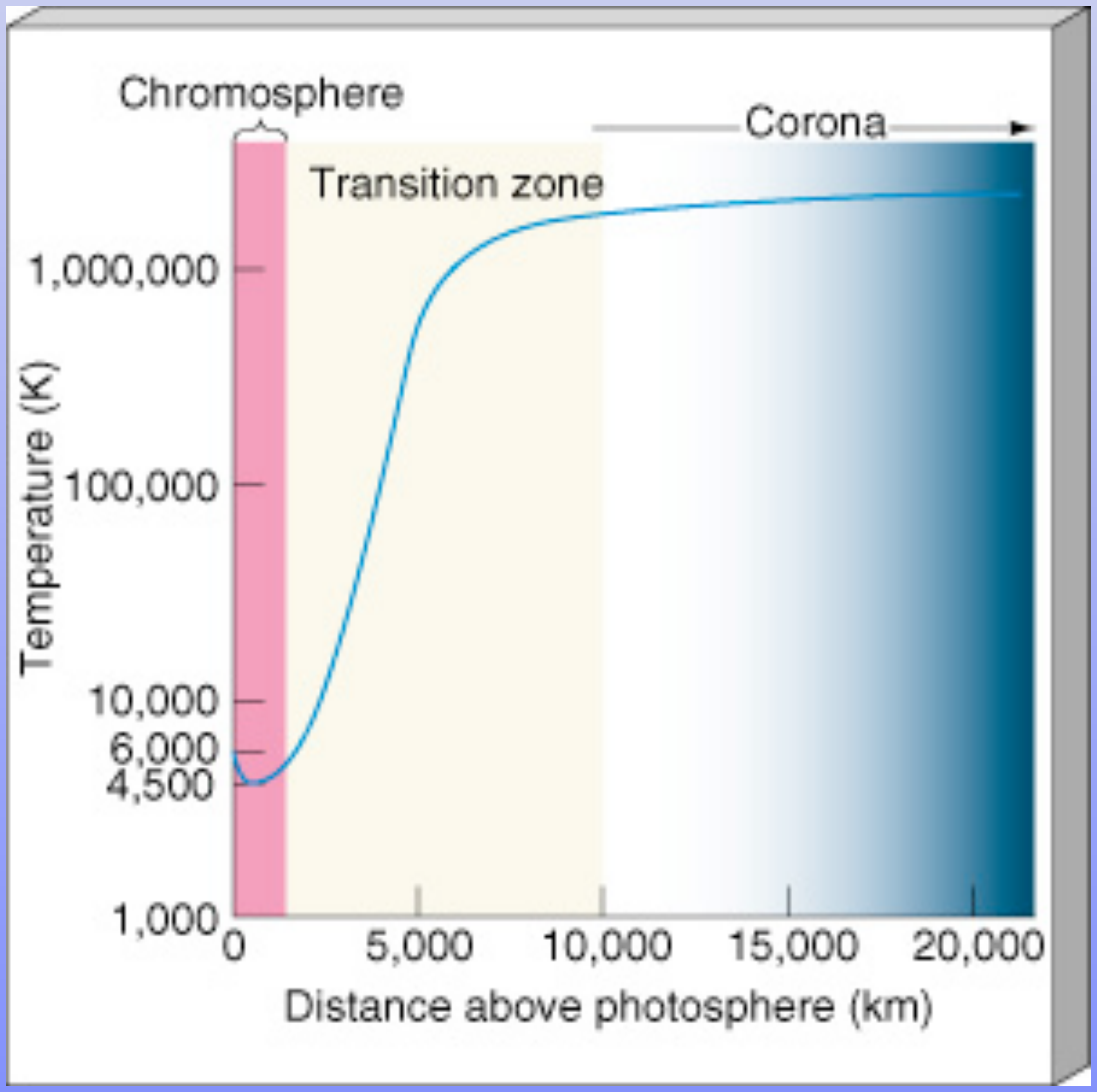
Plasma is commonly studied using:

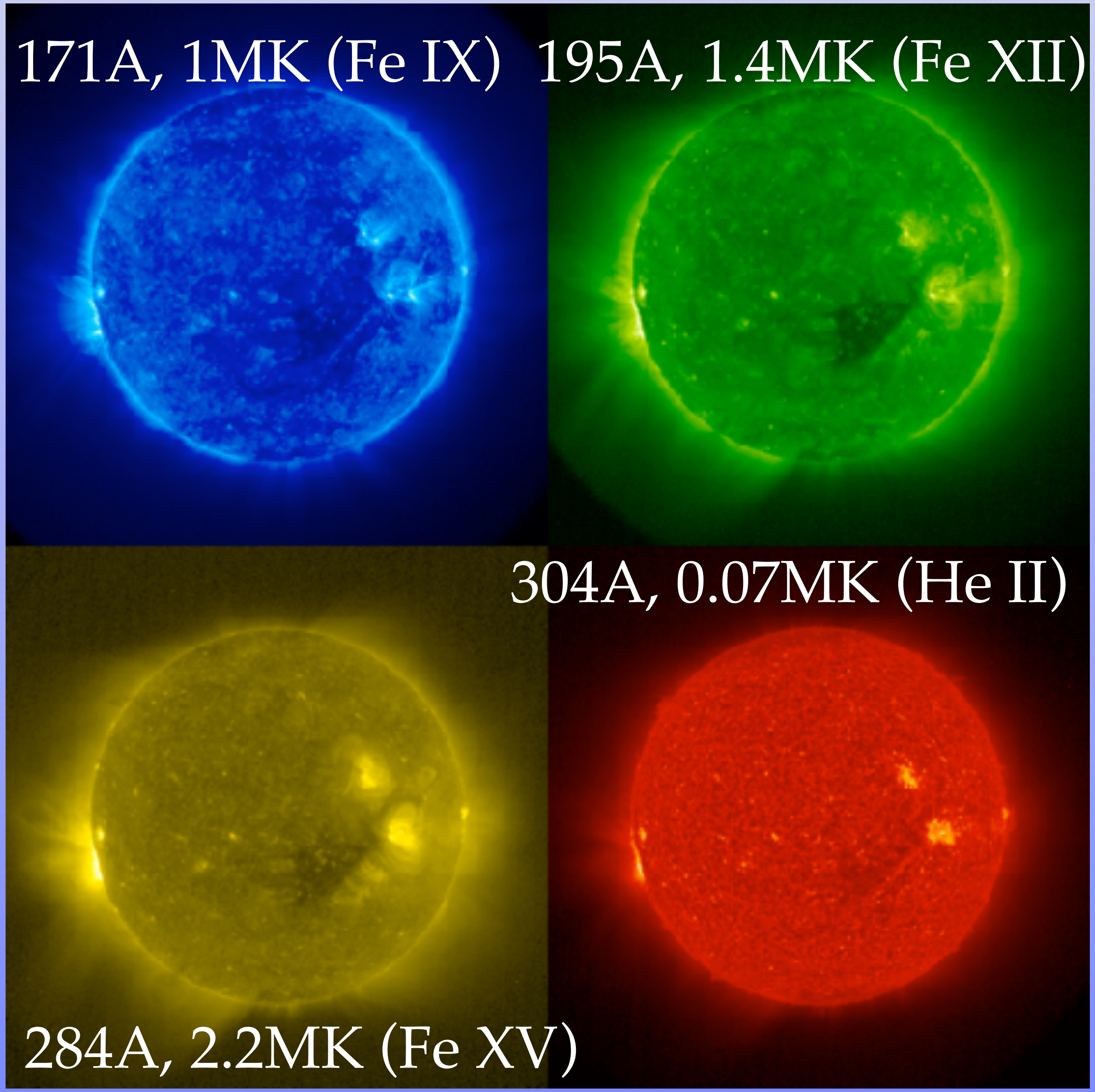
- Fluid approximation - Magnetohydrodynamics (MHD).
- Kinetic treatment - particle description.
- Hybrid methods - kinetic ions, fluid electrons.

Main Science Problems

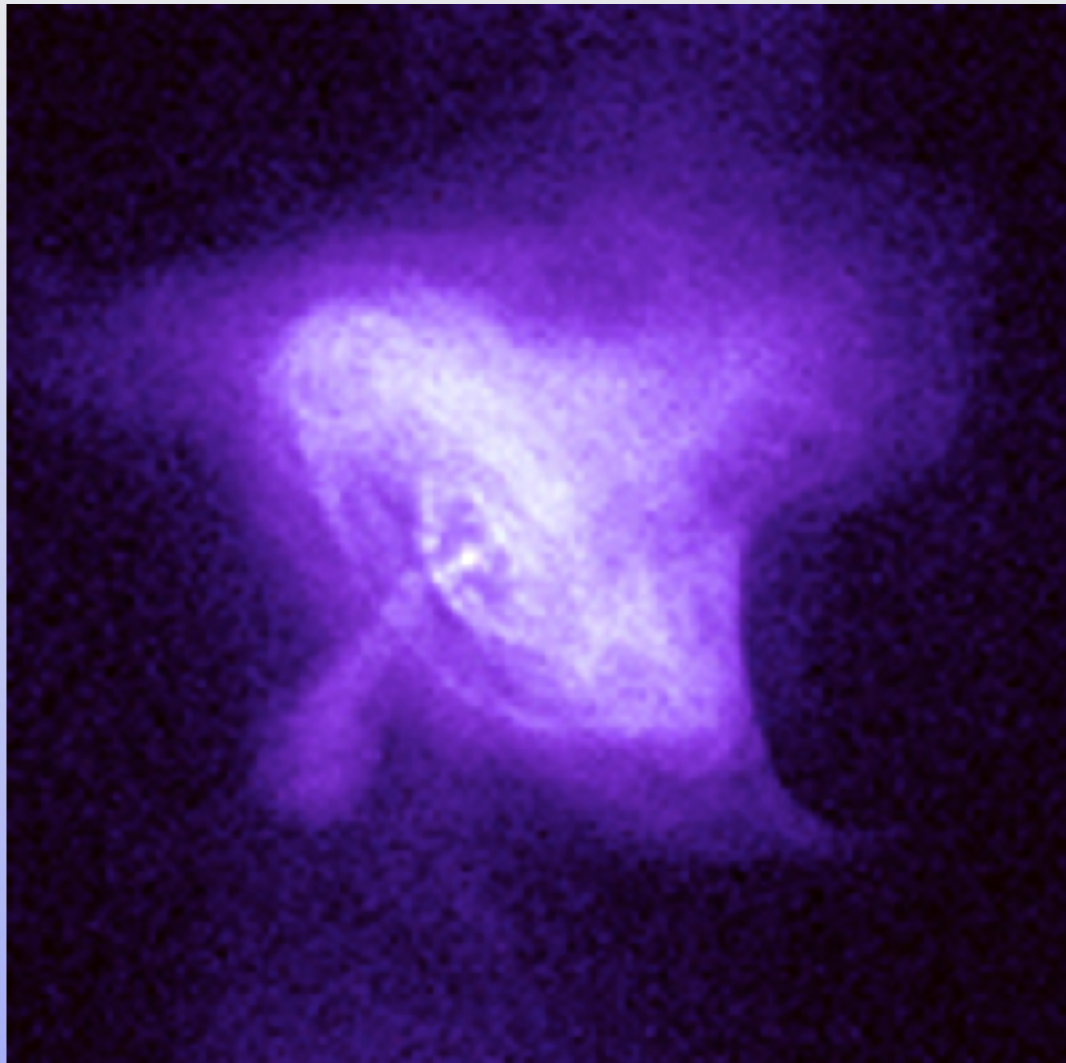
The problem of coronal heating:

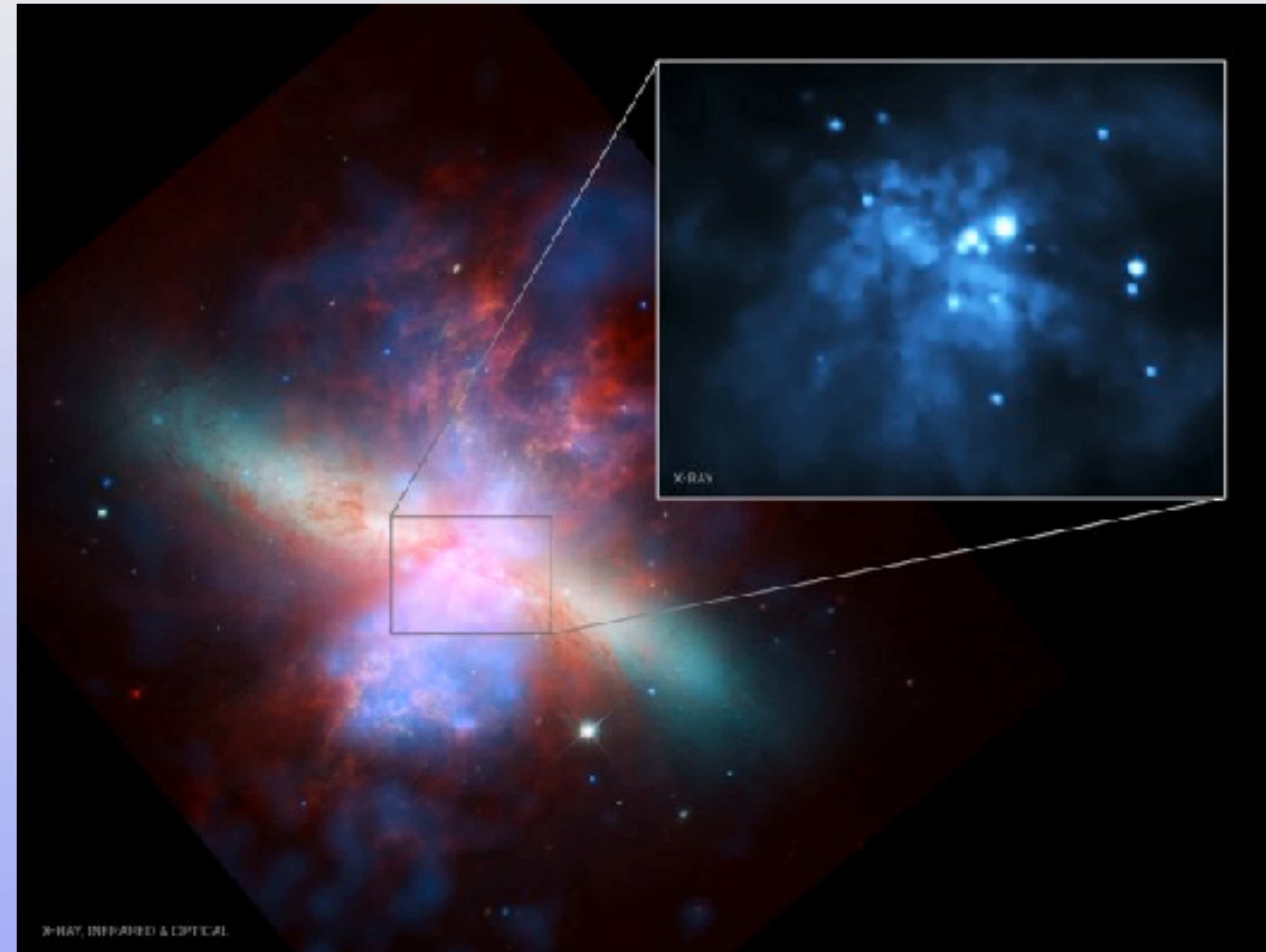
The temperature of the solar corona is over a million degrees Kelvin (5000K at the photosphere).

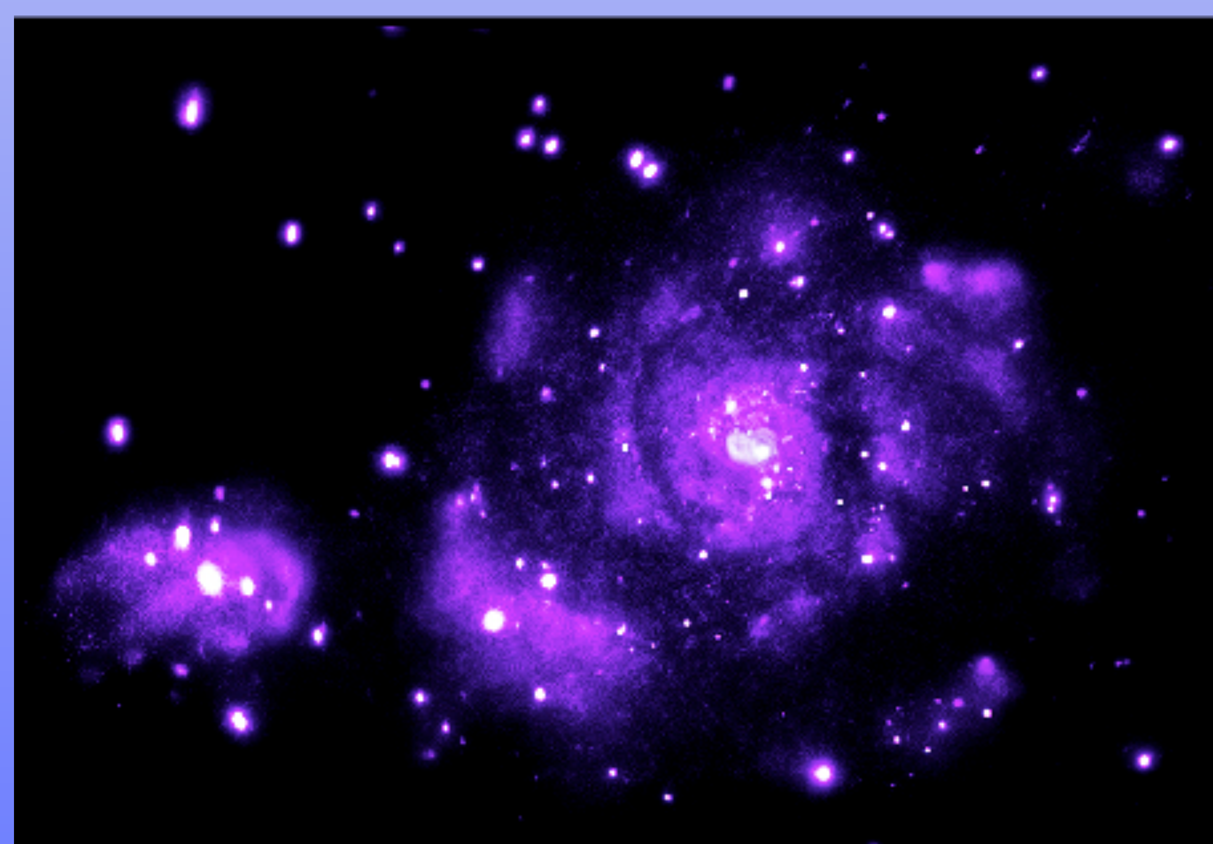




STEREO



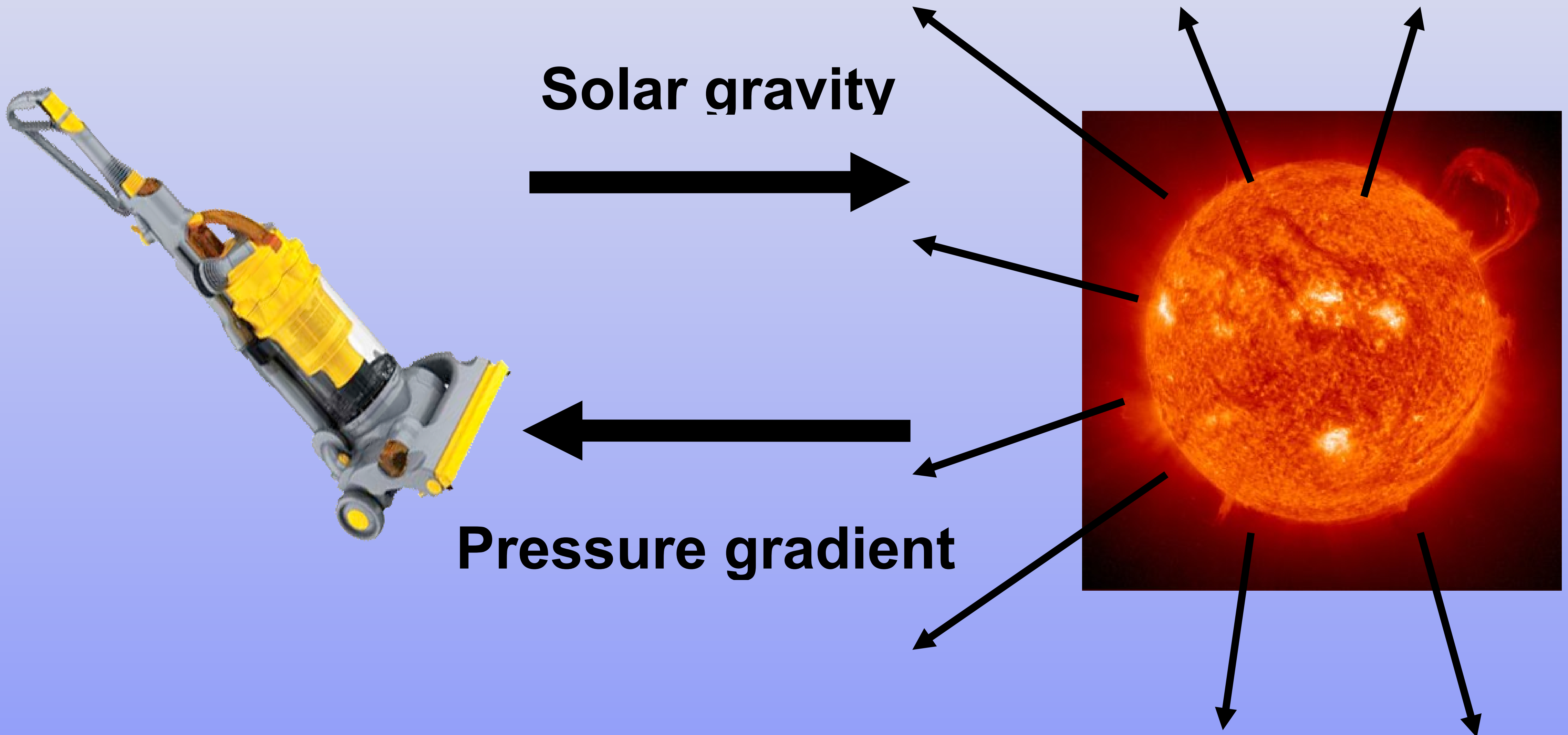




NASA

The origin and evolution of stellar winds:

Hydrodynamic expansion (Parker 1958):



1. Bimodal - fast wind and slow wind populations.
2. Faster than predicted this hydrodynamic model.
3. Inverse relations between wind speed and electron temperature - contradicts the hydrodynamic model.

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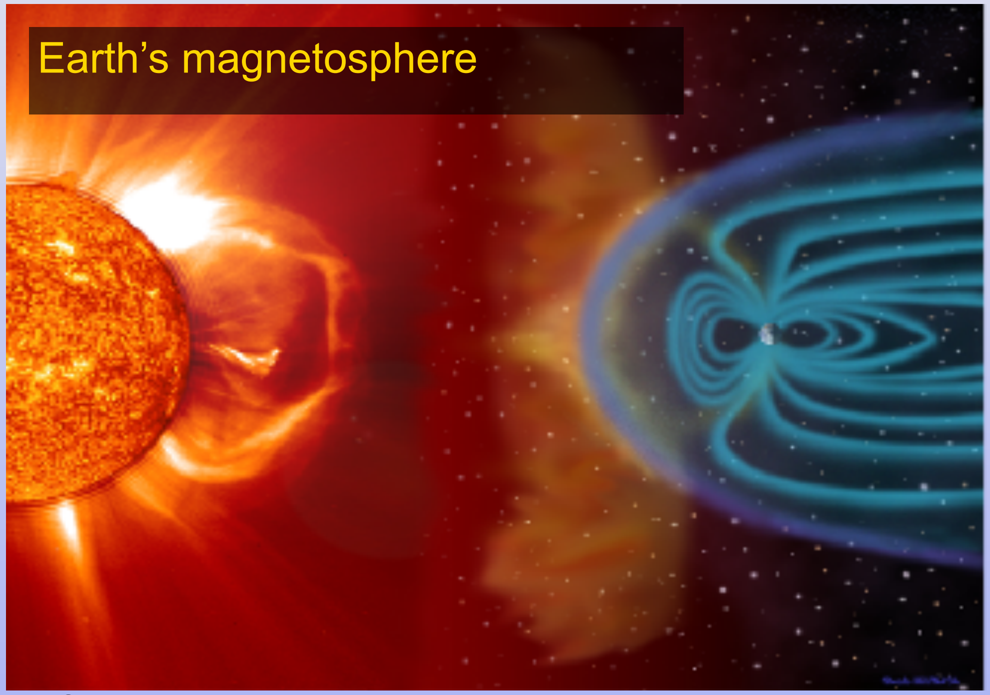
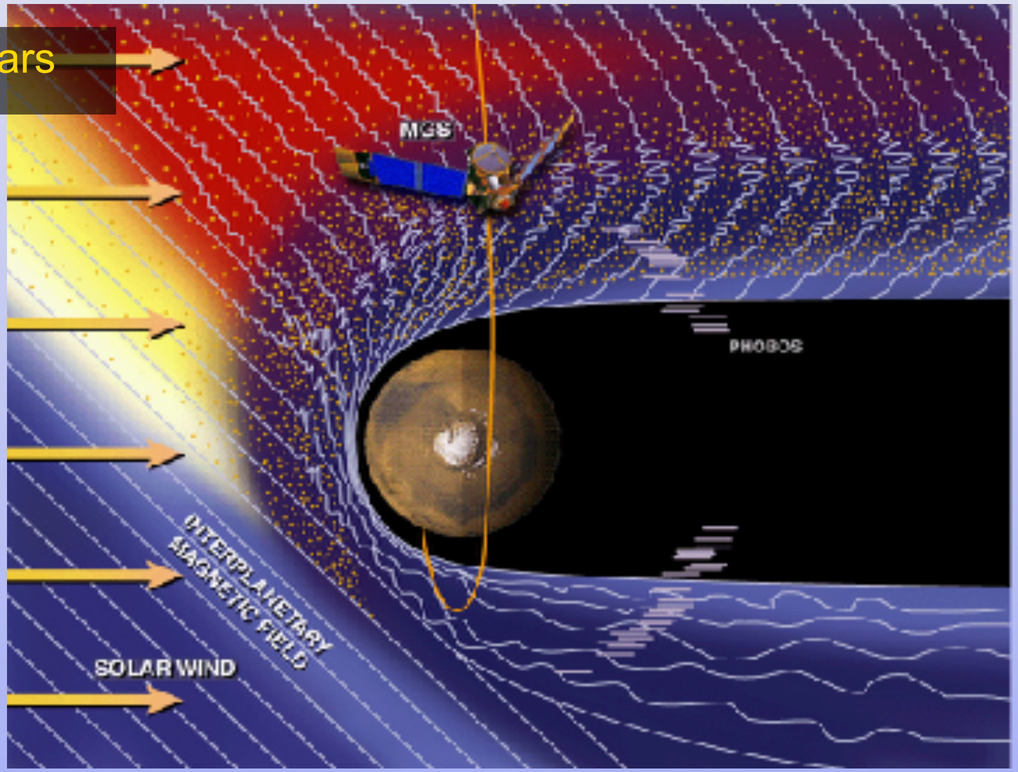
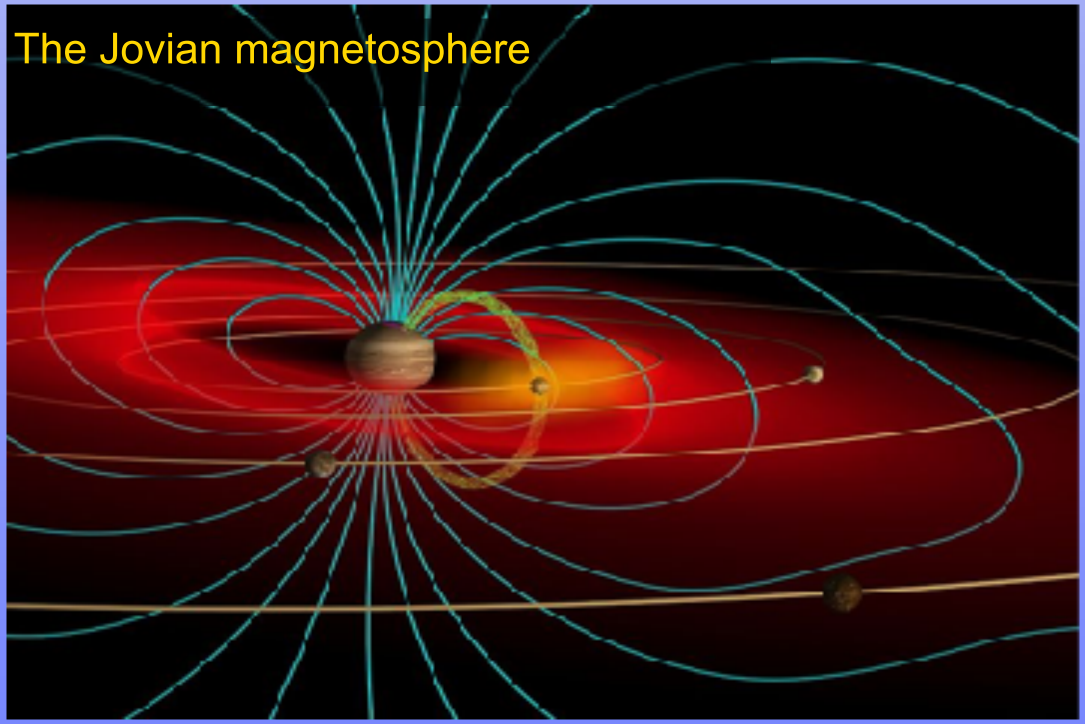
Solar wind - planet interaction in the solar system:



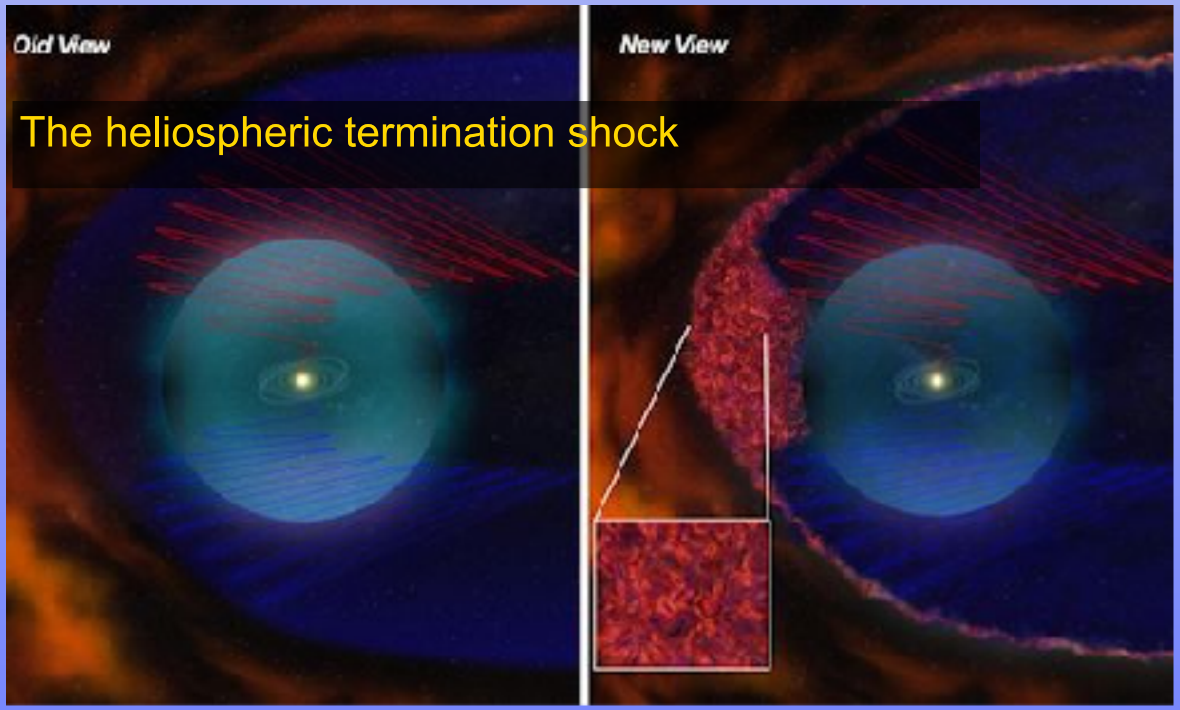
NASA illustration



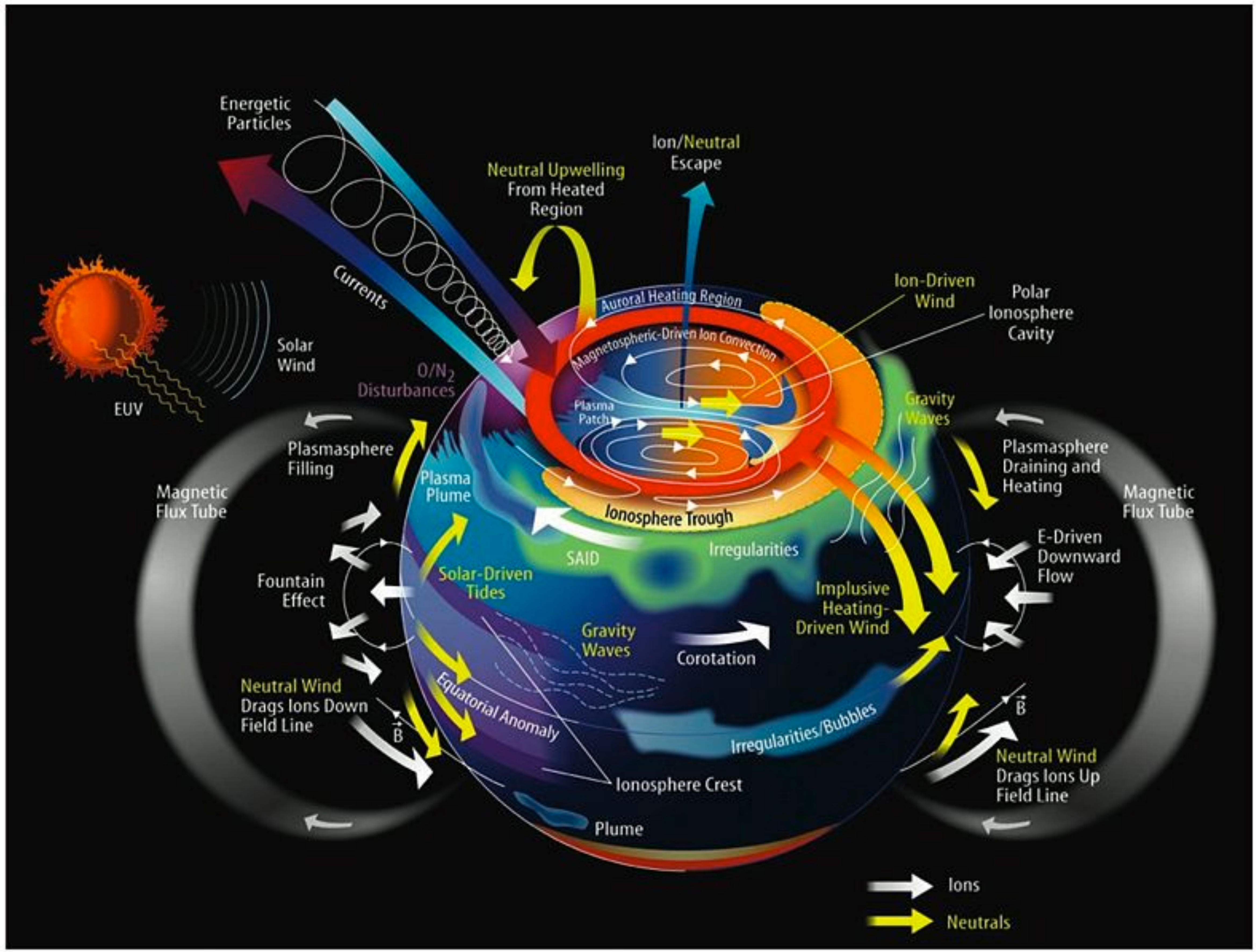
http://mgs-mager.gsfc.nasa.gov/



http://lasp.colorado.edu/



BU Astronomy homepage



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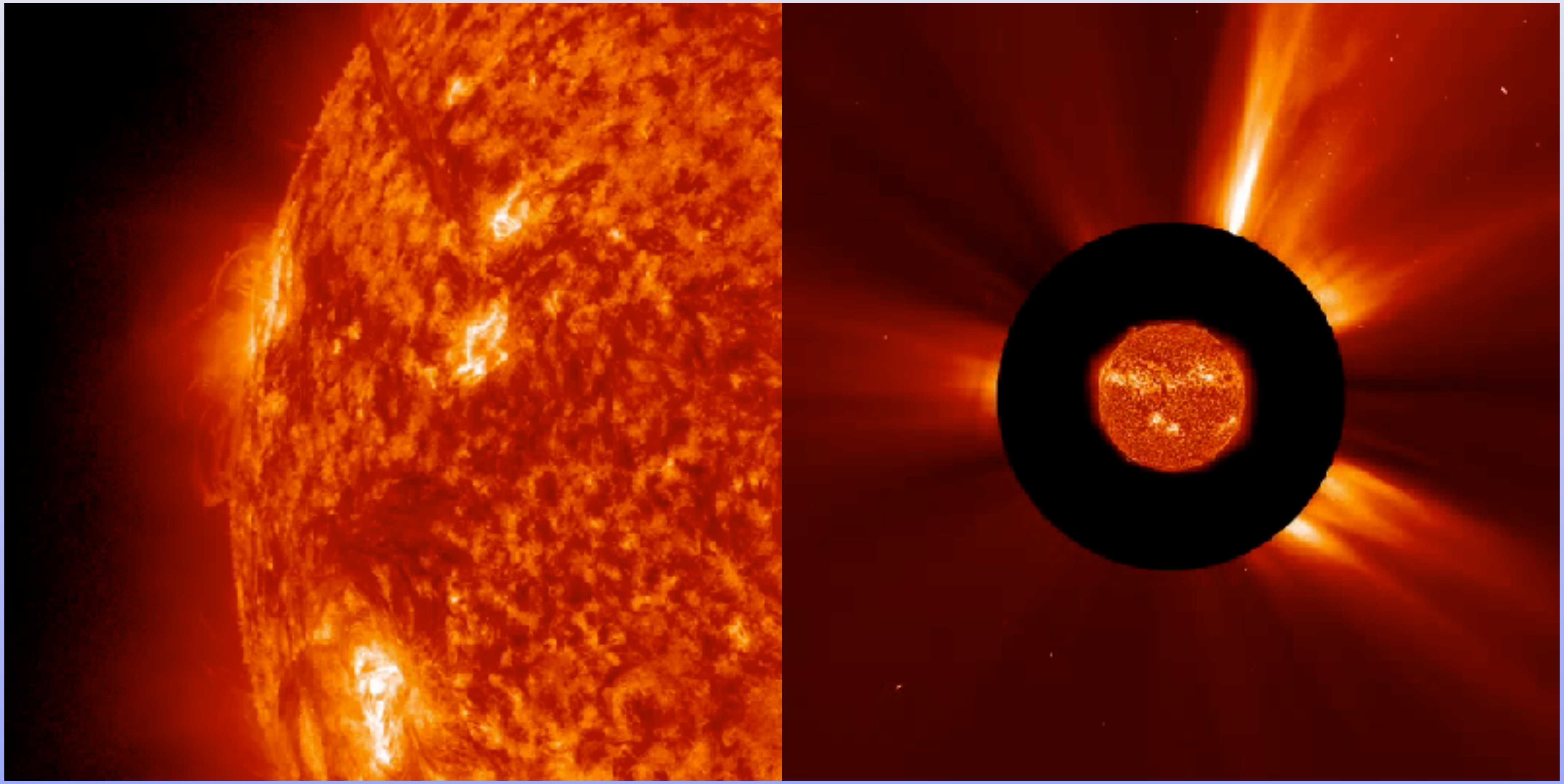
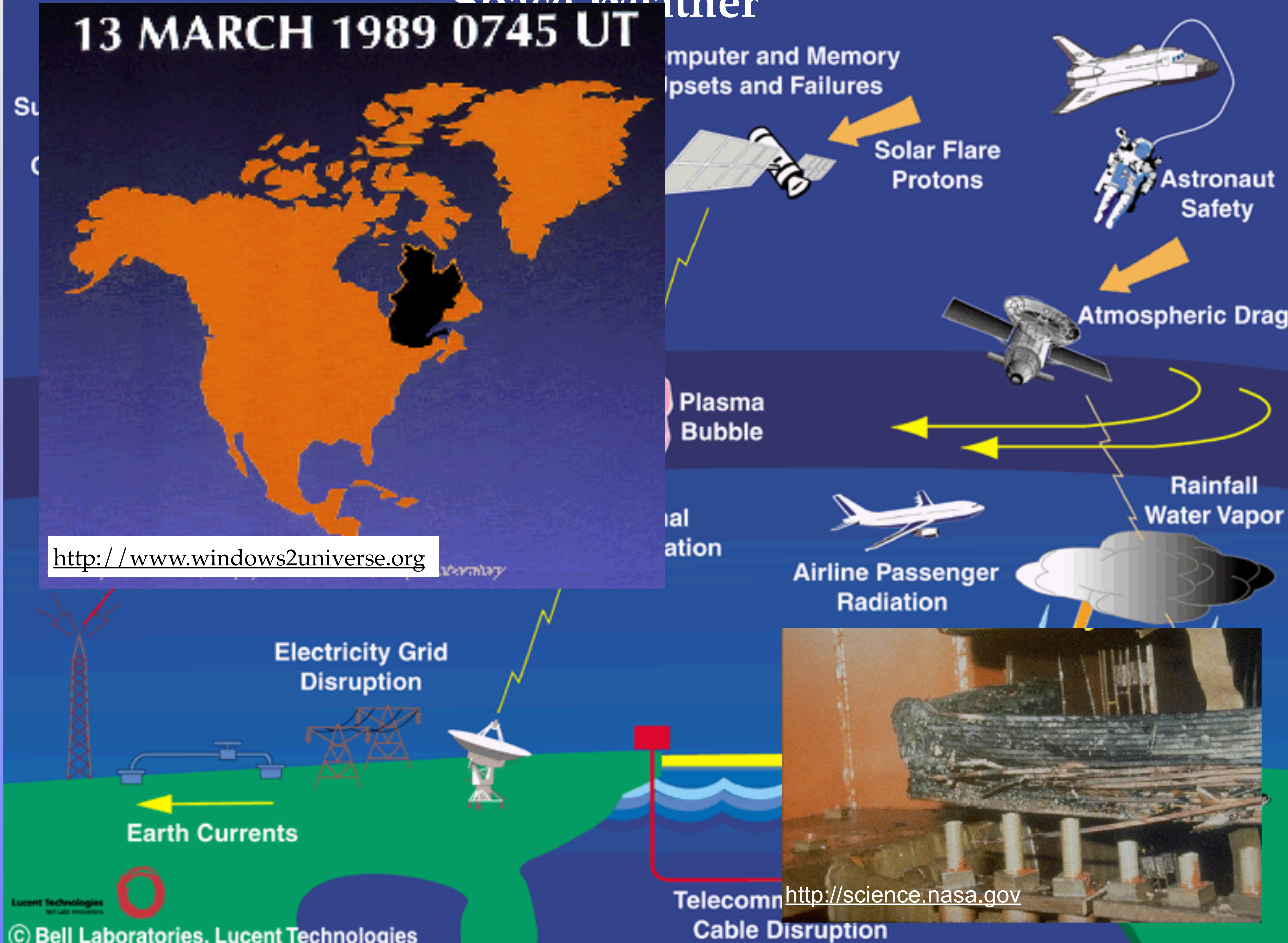
Coronal Mass Ejections (CMEs):



1000 billion kg, about 10^{15} ergs, average speed of 500 km/s

Geomagnetic storms - space weather

Space Weather



Developing Universal Numerical Models for Non-relativistic Plasma Environments

Theoretical challenges:

- Theoretical framework is incomplete.
- Physics-base.
- Reproduce the observations.

Numerical Challenge: Wide range of spatial and temporal scales:

*2^0 - Earth's radius (5000 km)
*2^8-2^9 - Solar radius (500,000 km)
*2^{16} - 1AU (10^8 km)

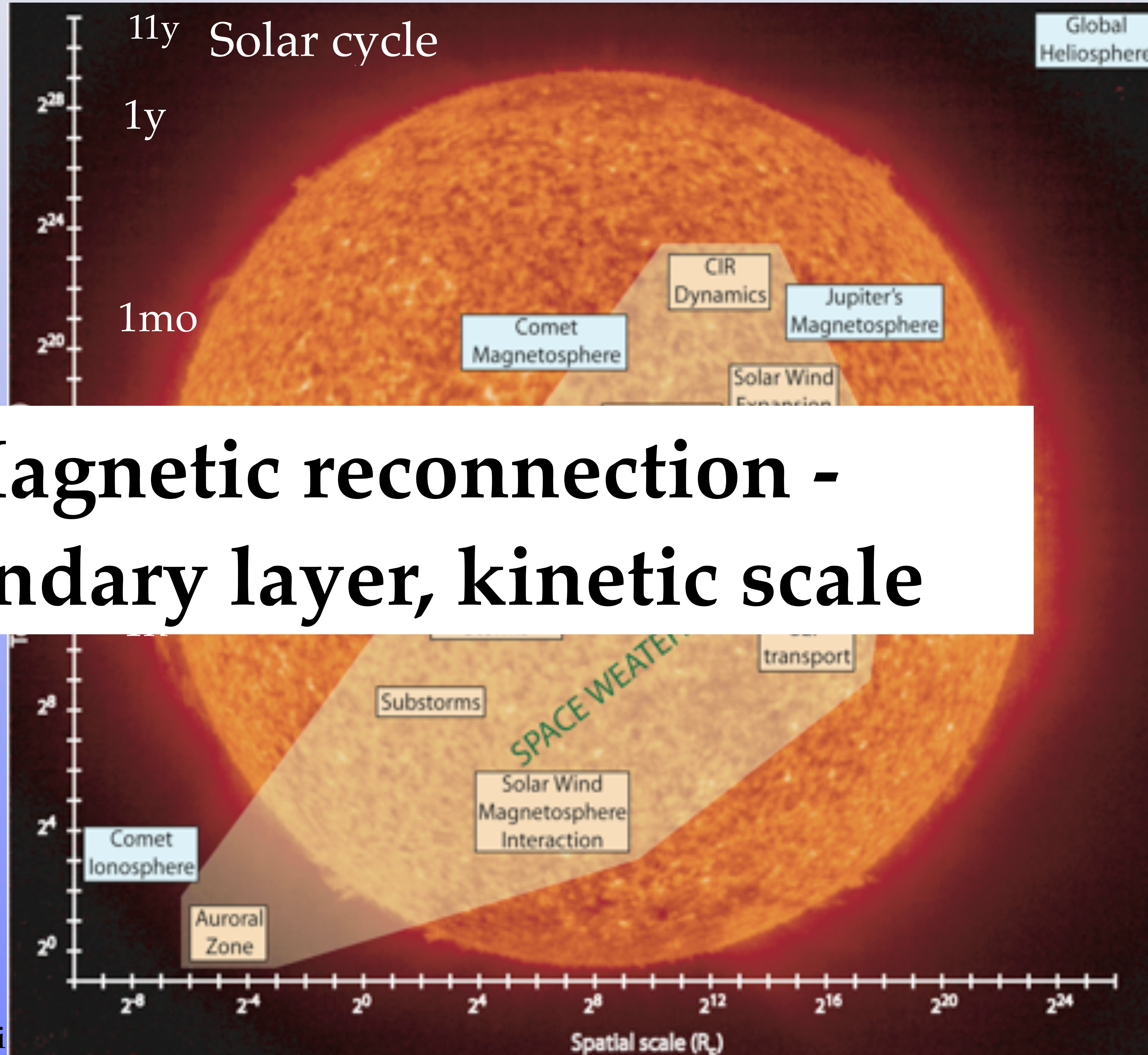


Image by T. Gombosi

Magnetic reconnection - boundary layer, kinetic scale

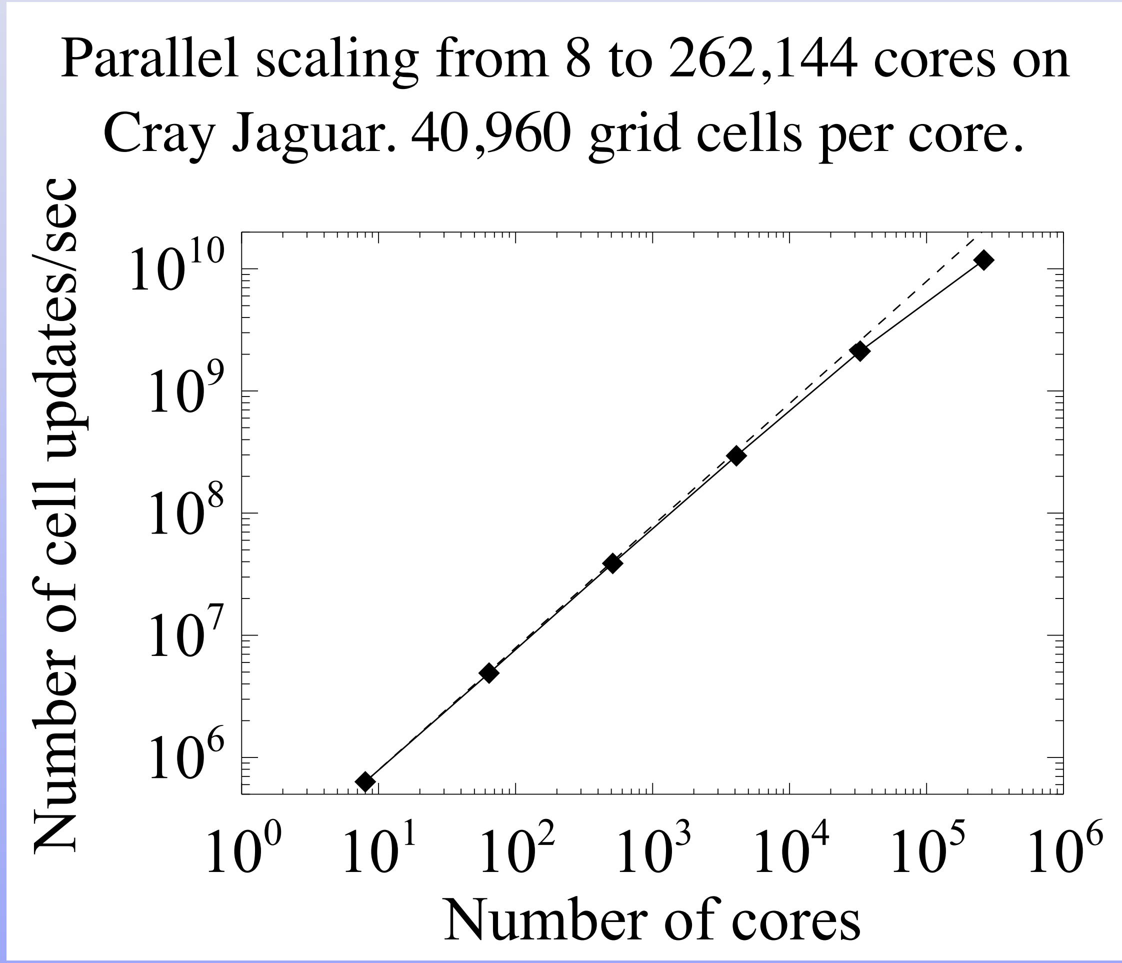
Spatial scale

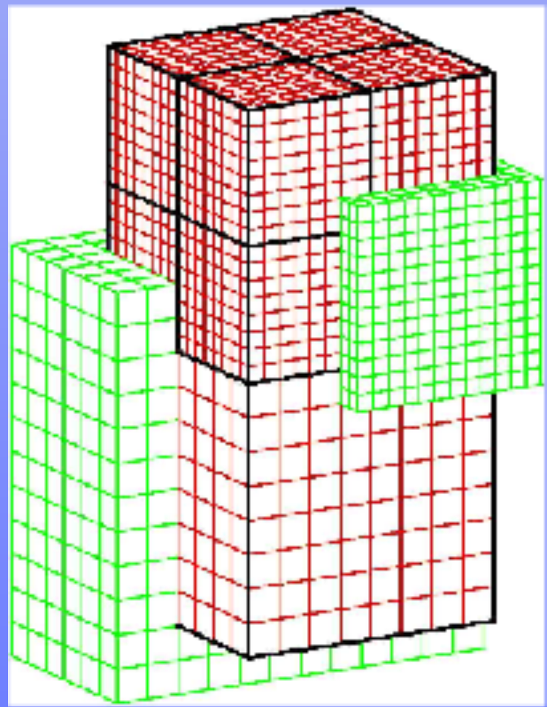
10^{11-13} m

- Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATSRUS) - magnetohydrodynamic code
- Space Weather Modeling Framework (SWMF)
- Developed since the late 1990s - UM Space & Aerospace departments
- Tamas Gombosi
- Gabor Toth

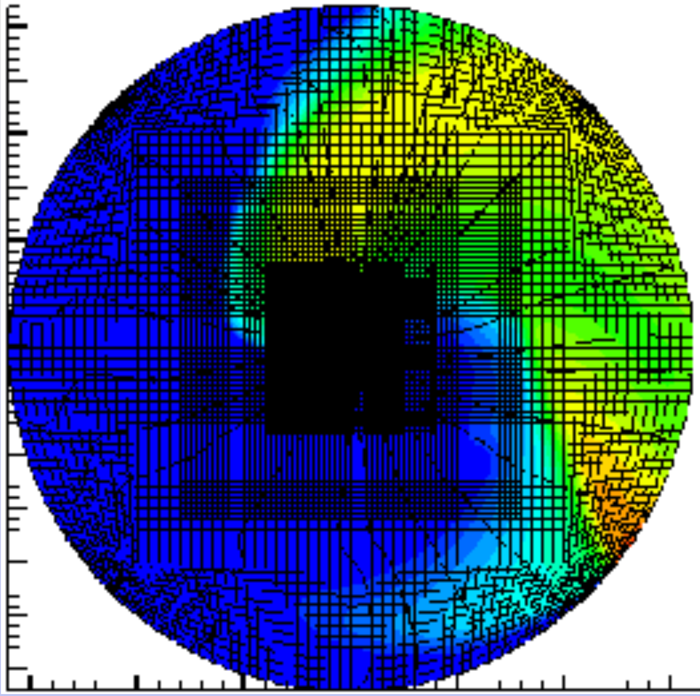
BATS-R-US

- **Physics**
  - Classical, semi-relativistic and Hall MHD
  - Multi-species, multi-fluid, 5-moment
  - anisotropic pressure for ion fluids
  - Radiation hydrodynamics multigroup diffusion
  - Multi-material, non-ideal equation of state
  - Heat conduction, viscosity, resistivity
  - Alfven wave turbulence and heating
- **Numerics**
  - Parallel Block-Adaptive Tree Library (BATL)
  - Cartesian and generalized coordinates
  - Splitting the magnetic field into $B_0 + B_1$
  - Divergence B control: 8-wave, CT, projection, parabolic/hyperbolic
  - Numerical fluxes: Godunov, Rusanov, AW, HLLE, HLLD, Roe, DW
  - Explicit, local time stepping, limited time step, sub-cycling
  - Point-, semi-, part and fully implicit time stepping
  - Up to 4th order accurate in time and 5th order in space
- **Applications**
  - Heliosphere, sun, planets, moons, comets, HEDP experiments
- **150,000+ lines of Fortran 90+ code with MPI parallelization**

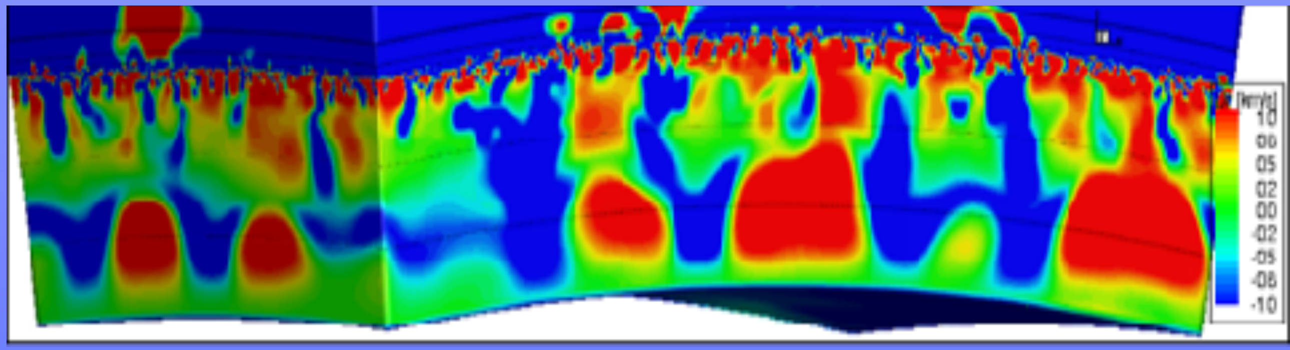




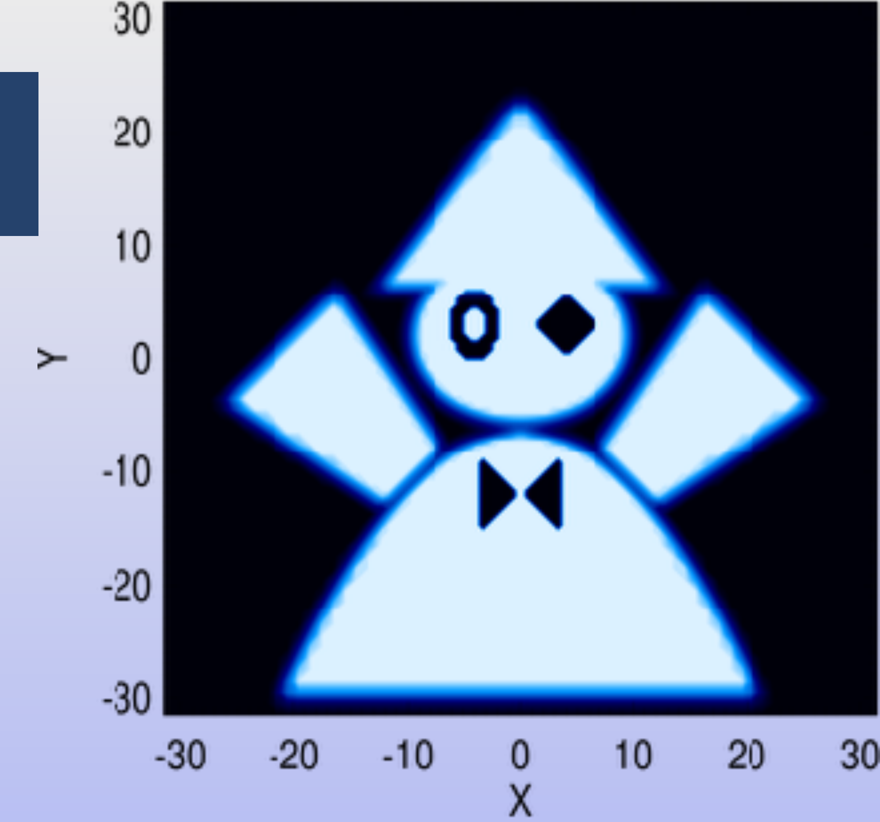
What's New in BATS-R-US?



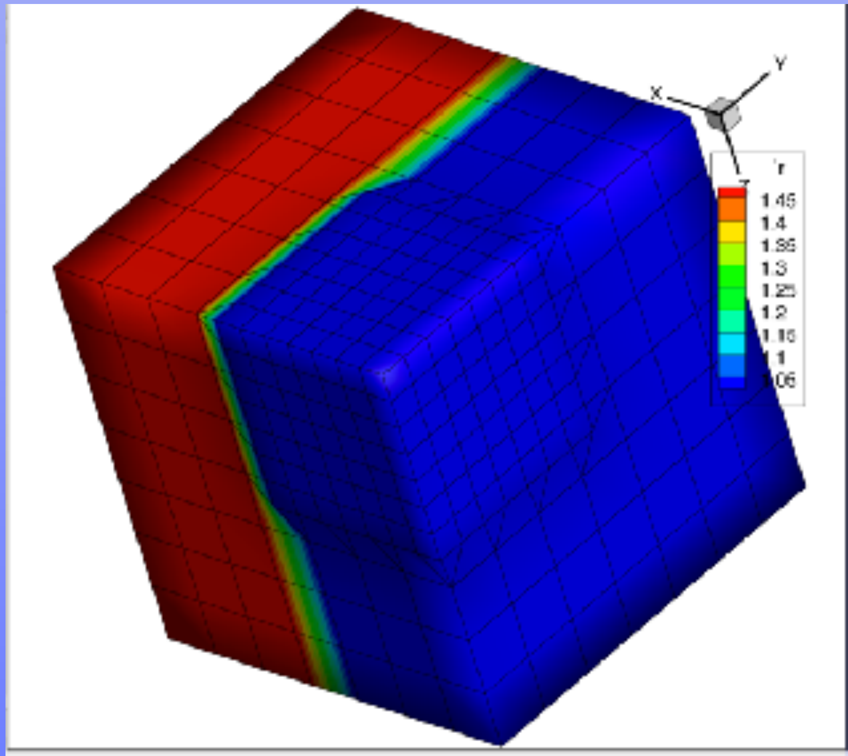
- **Equations**
  - Multi-fluid MHD with improved wave speeds, anisotropic pressure option (van der Holst, Toth)
  - 5-moment closure: ion + electron fluids and Maxwell equations for B and E (van der Holst, Toth)
- **Schemes**
  - Dominant Wave + Rusanov/HLL (van der Holst, Toth)
  - 5th order scheme with full AMR (Chen)
  - Subcyling (Chen, Toth)
  - Limited time step (Chen, Huang)
  - Improved semi-implicit scheme (Chen, Toth)
- **Grids**
  - round cube grid (Shou, Toth)
  - limited generalized coordinates (van der Holst, Manchester, Toth)



What's New in BATS-R-US?



- **Boundary conditions**
  - Mixed cell and face based boundaries (Zhou)
  - Resistive body (Jia, Daldorff, Chen, Zhou, Toth)
  - Solid body (van der Holst)
- **Geometric control of schemes/features**
  - For AMR, Hall MHD, resistivity, viscosity, high order scheme (Toth)
  - Load balancing for multiple schemes/features (Chen)
- **Plotting options**
  - Cuts in generalized coordinates (Toth)
  - Shell/surface/circle plots (Welling)
  - Box/plane/line plots (Szente)
  - More scalar parameters (xSI, Mi...) saved (Toth)
  - IDL macros improved in many ways (Toth)
  - Cell centered Tecplot (3d tcp) output (Toth)



From Codes To Framework

- *A software framework is a universal, reusable software environment that provides particular functionality (Wikipedia)*
- The Sun-Earth system consists of many different interconnecting domains that are **independently** modeled traditionally.
- Each physics domain model is a separate application, which has its own **optimal** mathematical and numerical representation.
- Our goal is to integrate models into a flexible **software framework.**
- The framework incorporates physics models with **minimal changes.**
- The framework can be **extended** with new models and components.
- The **performance** of a well designed framework can supersede monolithic codes or ad hoc couplings of models.

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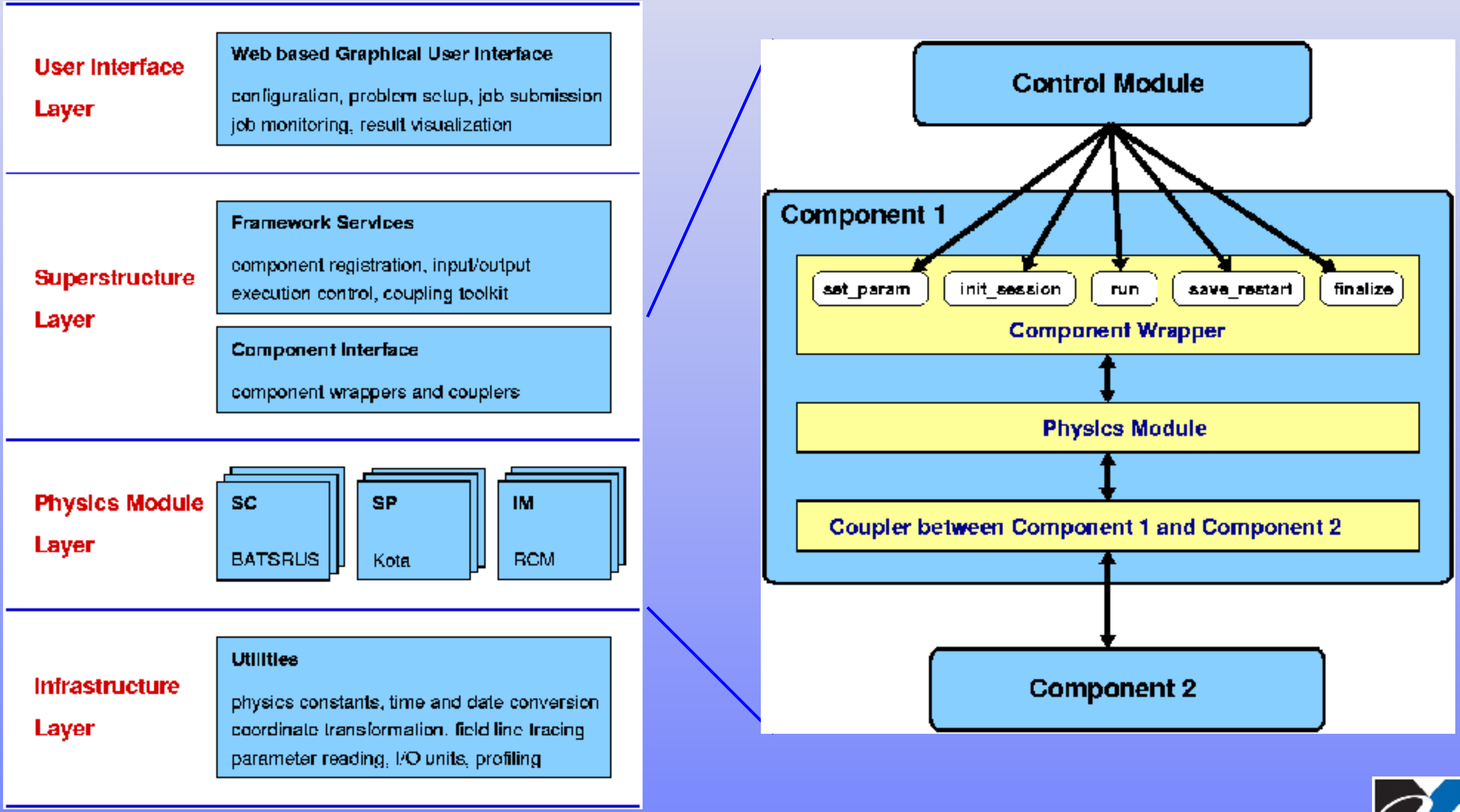
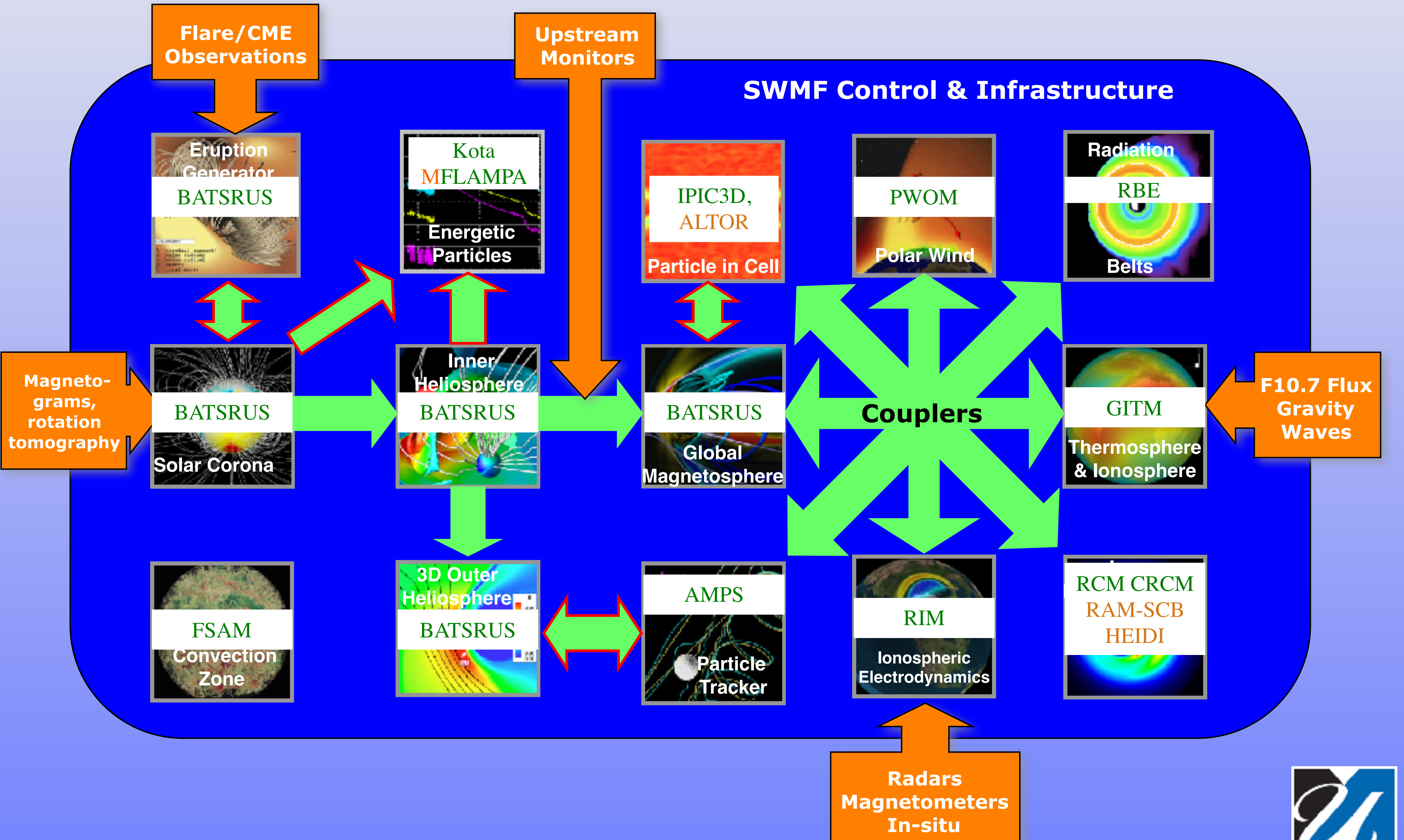
SWMF Architecture

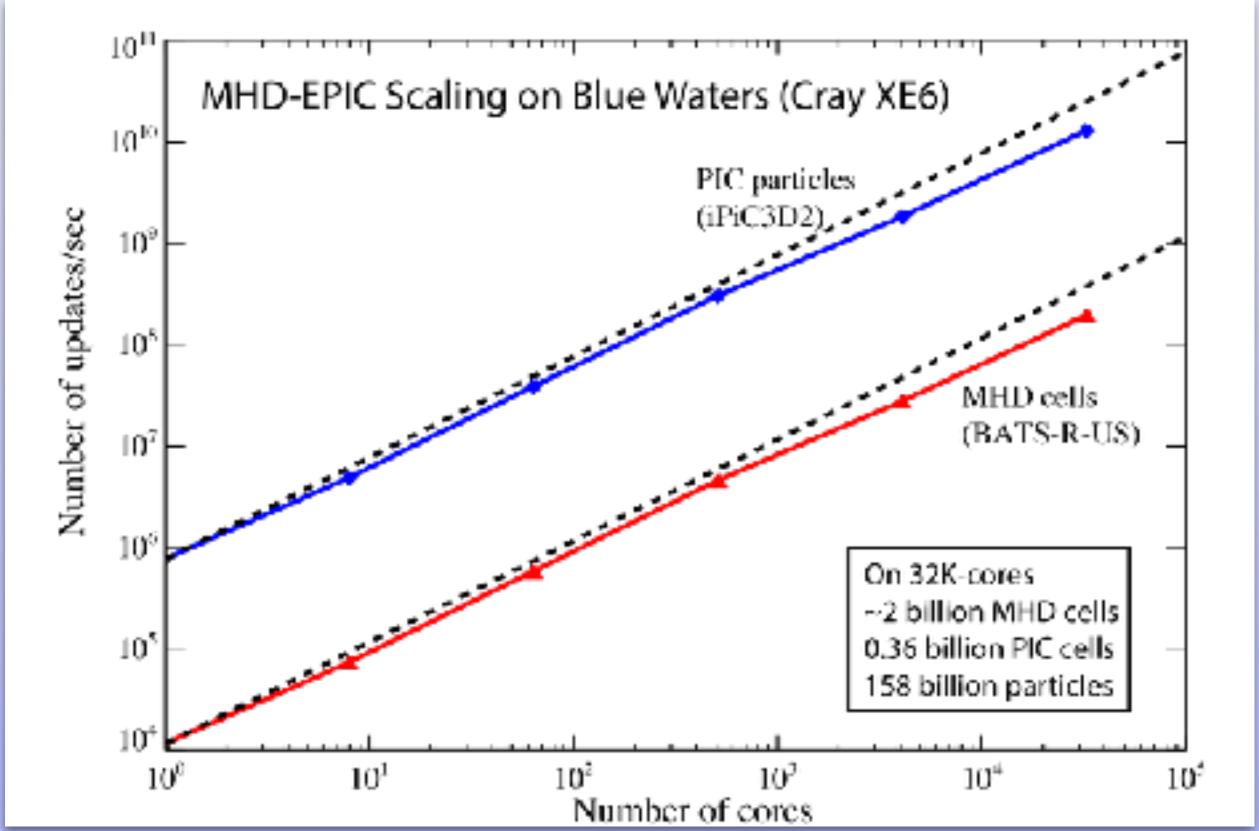


SWMF in 2017



SWMF is freely available at http://csem.engin.umich.edu and via CCMC

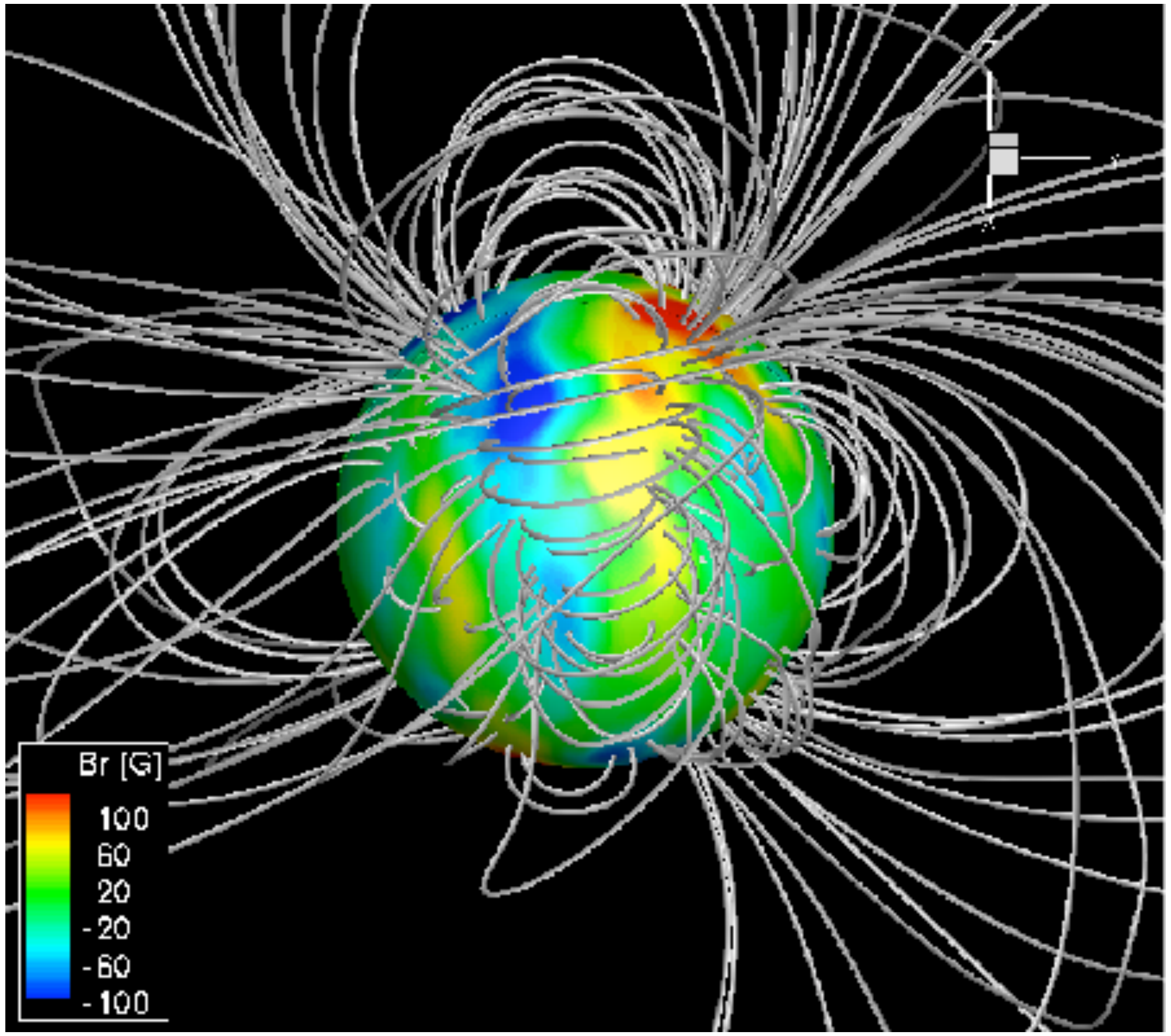
SWMF Code Summary 2014 → 2017

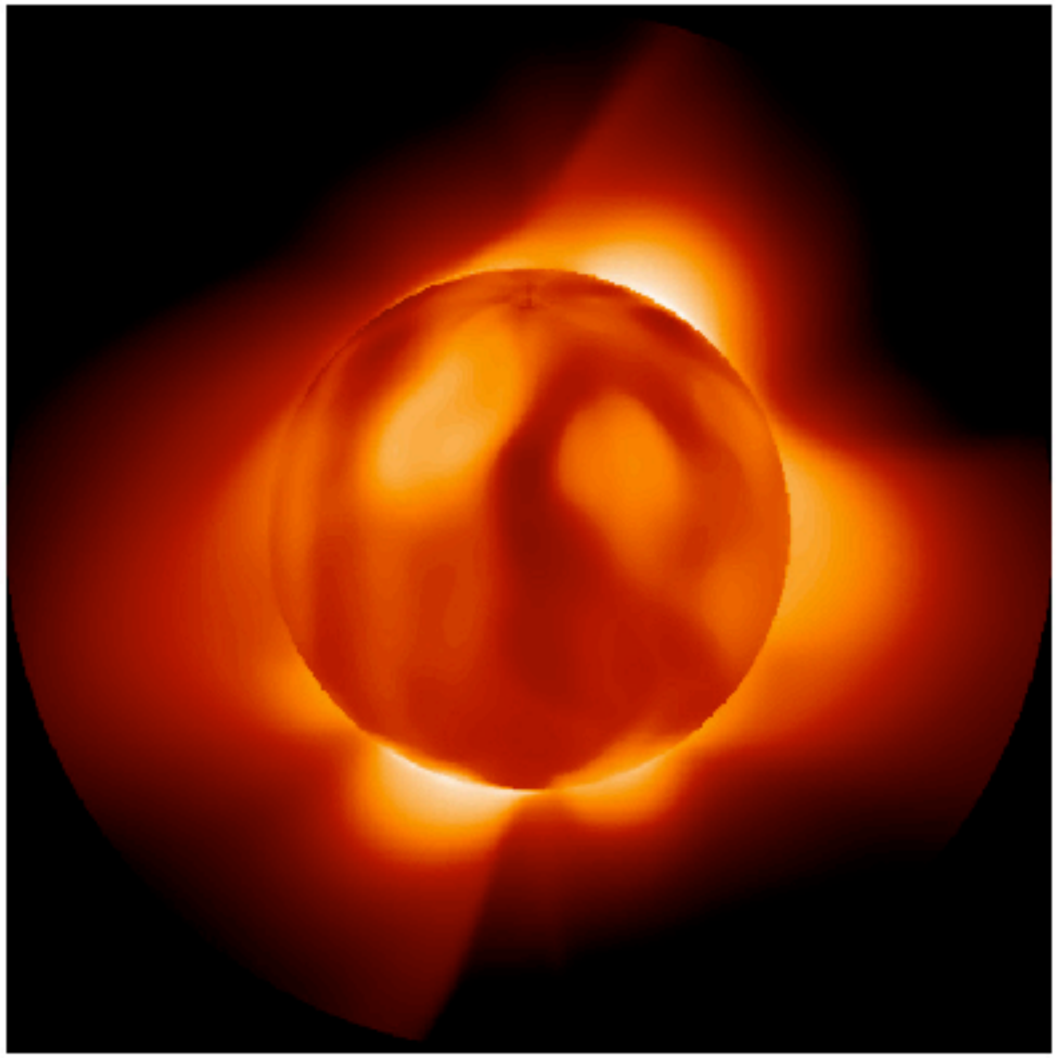


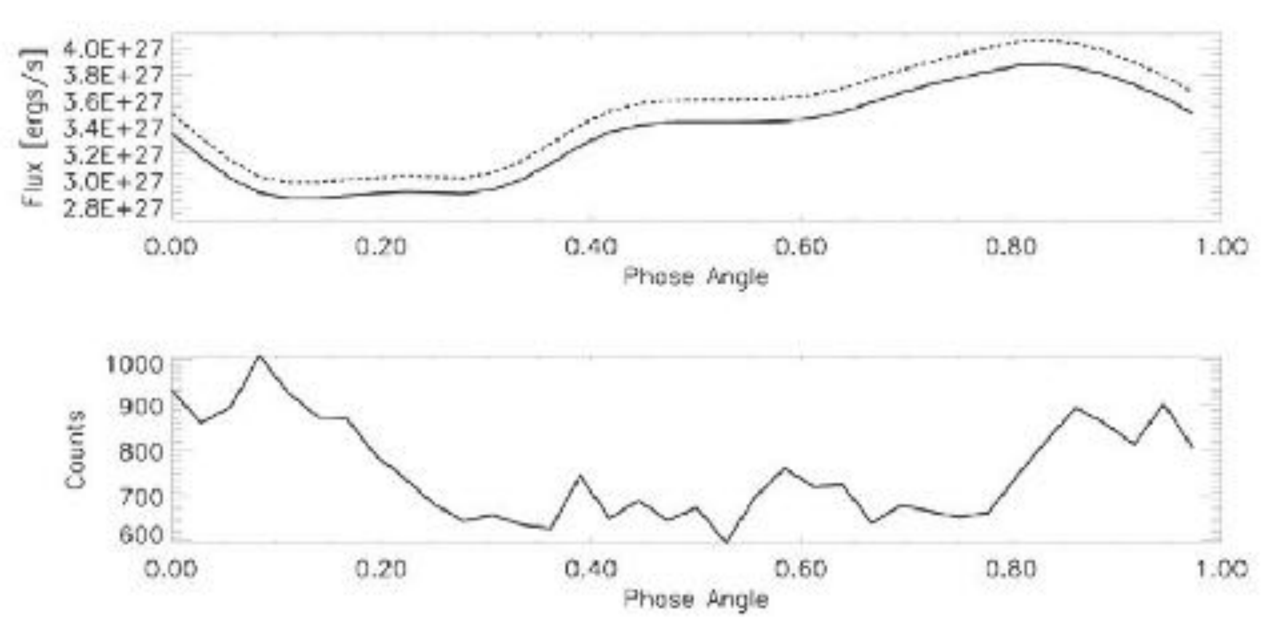
- **Source code:**
  - 520K ➔ 770K lines of source code
  - 447K ➔ 594K lines of Fortran
  - 76K ➔ 177K lines of C++
  - 30K ➔ 52K lines of Perl and shell scripts
  - 0K ➔ 3K lines of Python scripts
  - 20K ➔ 22K lines of IDL plotting scripts
  - 18K ➔ 22K lines of Fortran and C in the wrappers and couplers
  - 14K ➔ 24K lines of Makefiles
  - 10K ➔ 13K lines of XML description of input parameters
- **SWMF runs on Unix/Linux/OSX systems with Fortran 95 and C++ compilers, MPI library, HDF5, OpenMP, and Perl interpreter.**
- **The SWMF can run on a laptop or on tens of thousands of processors.**
- **User manual with documentation of input parameters**
- **Fully automated nightly testing with several machine/compiler combinations**
- **These tests provide working examples for running the code**

My Work

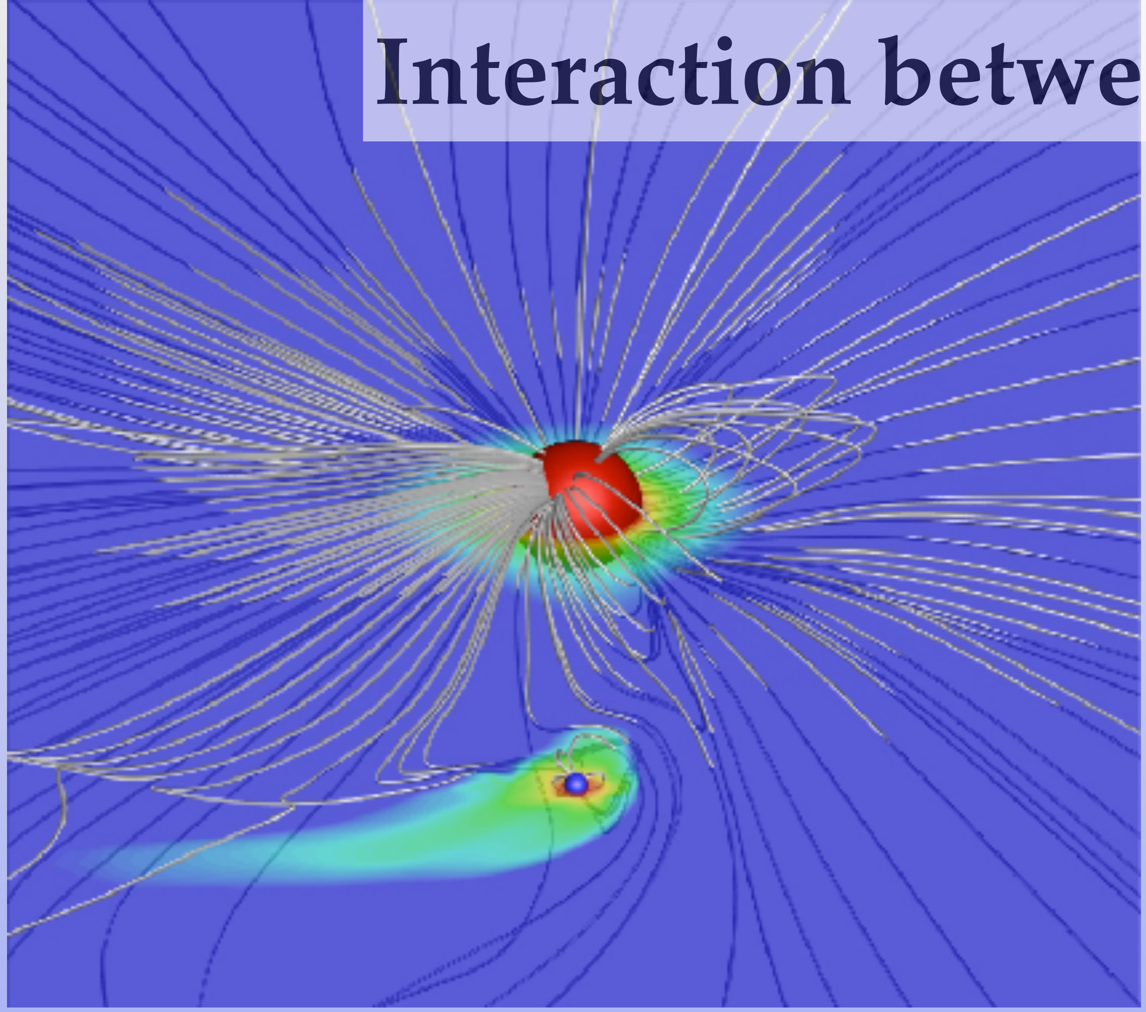
Structure and dynamics of stellar coronae

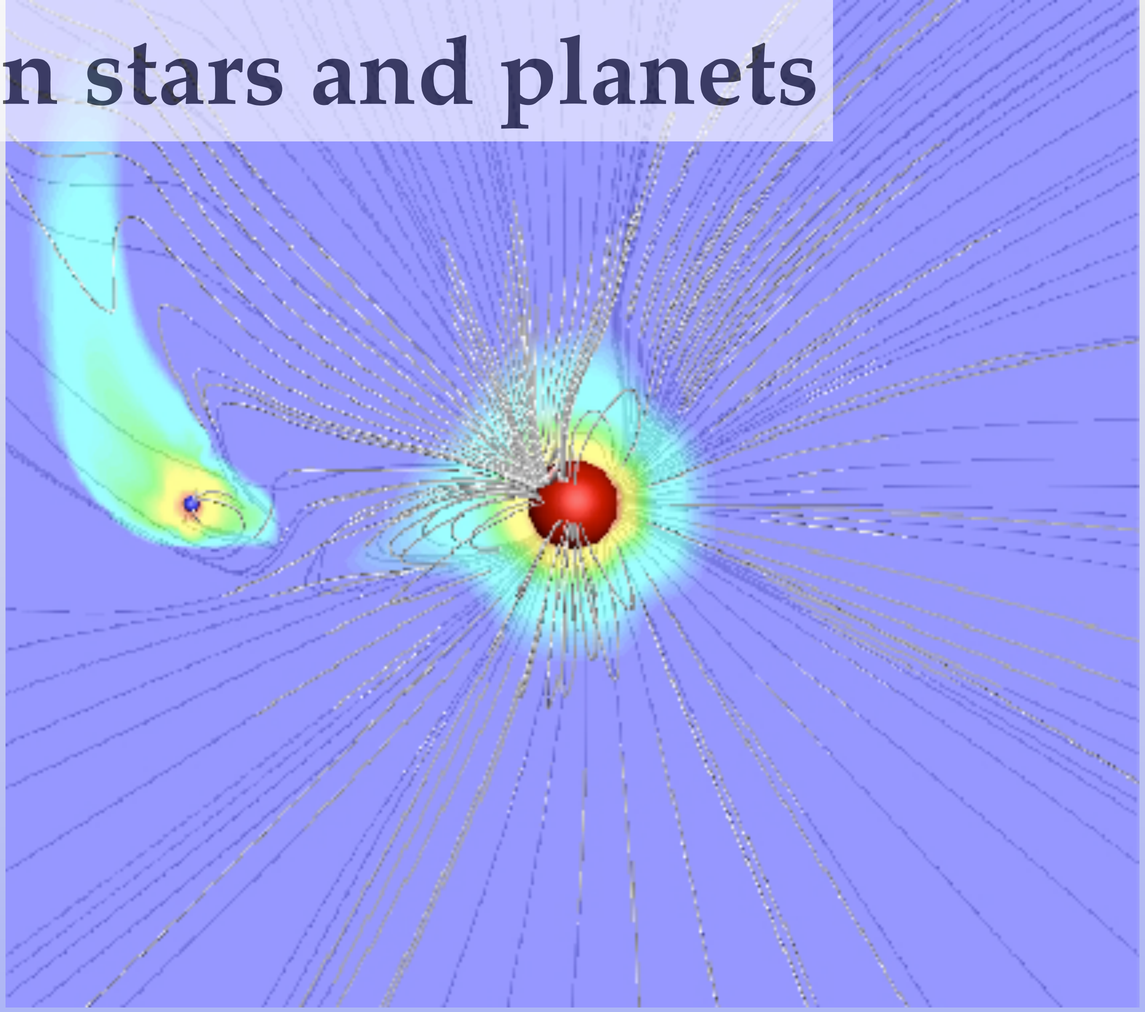


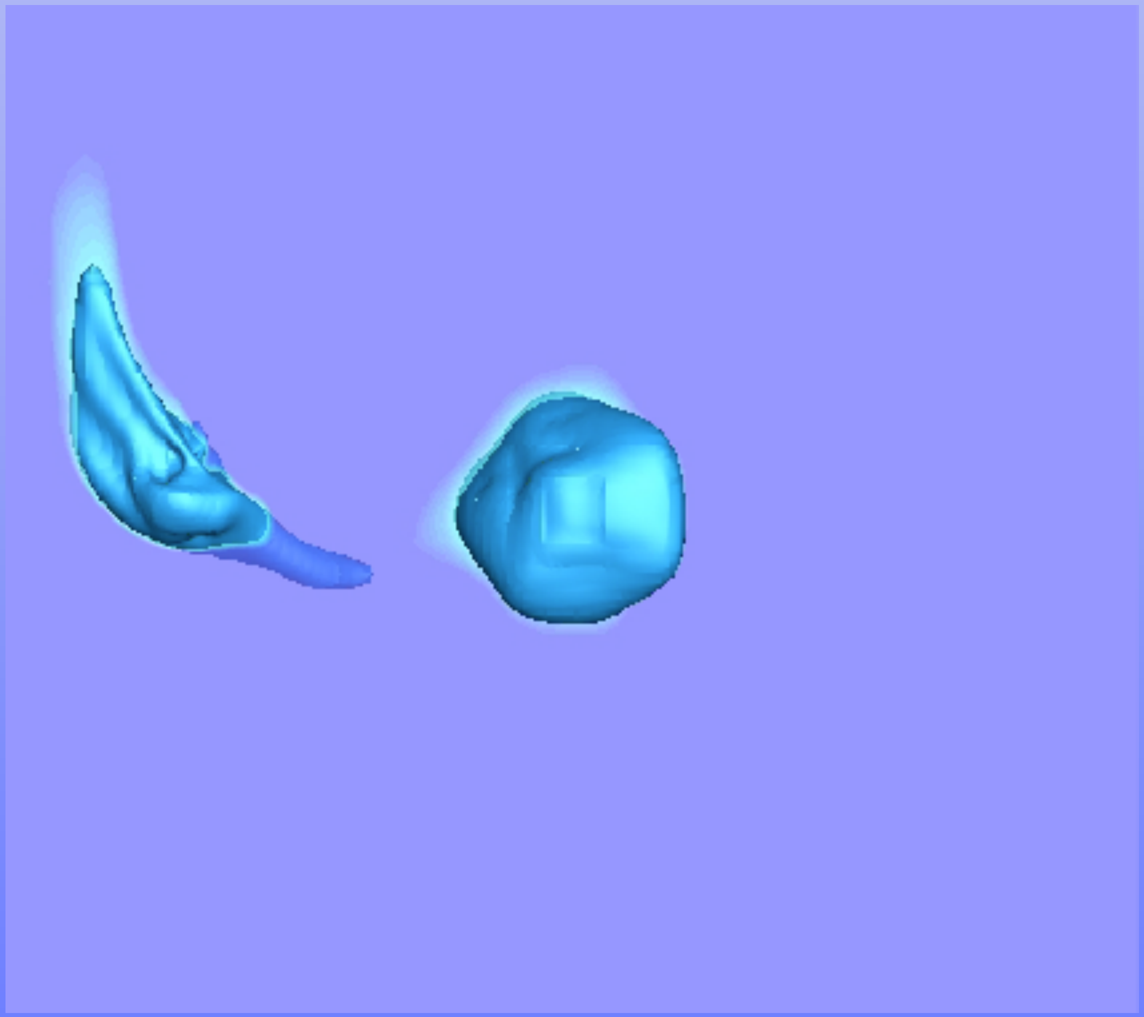




Interaction between stars and planets



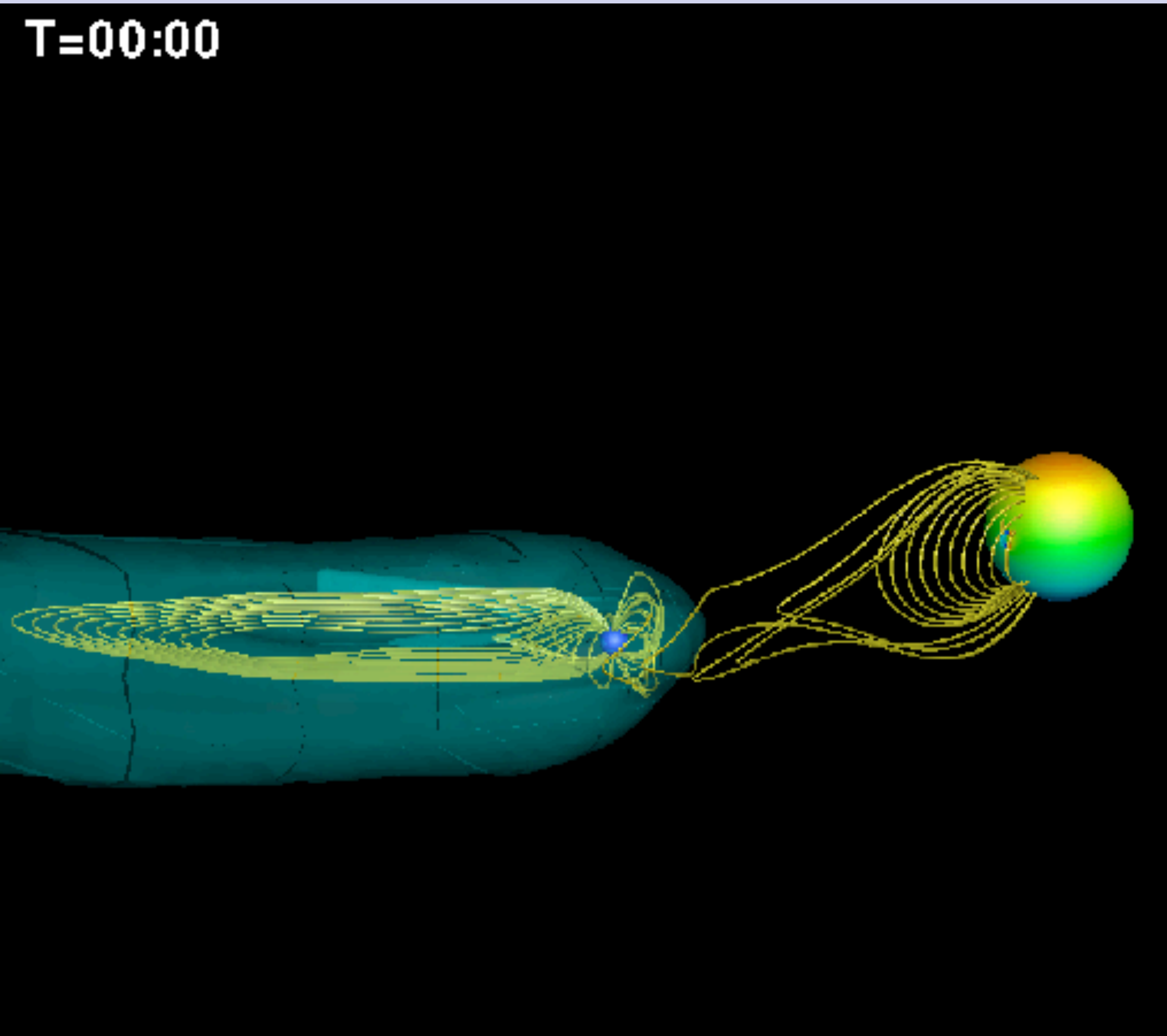


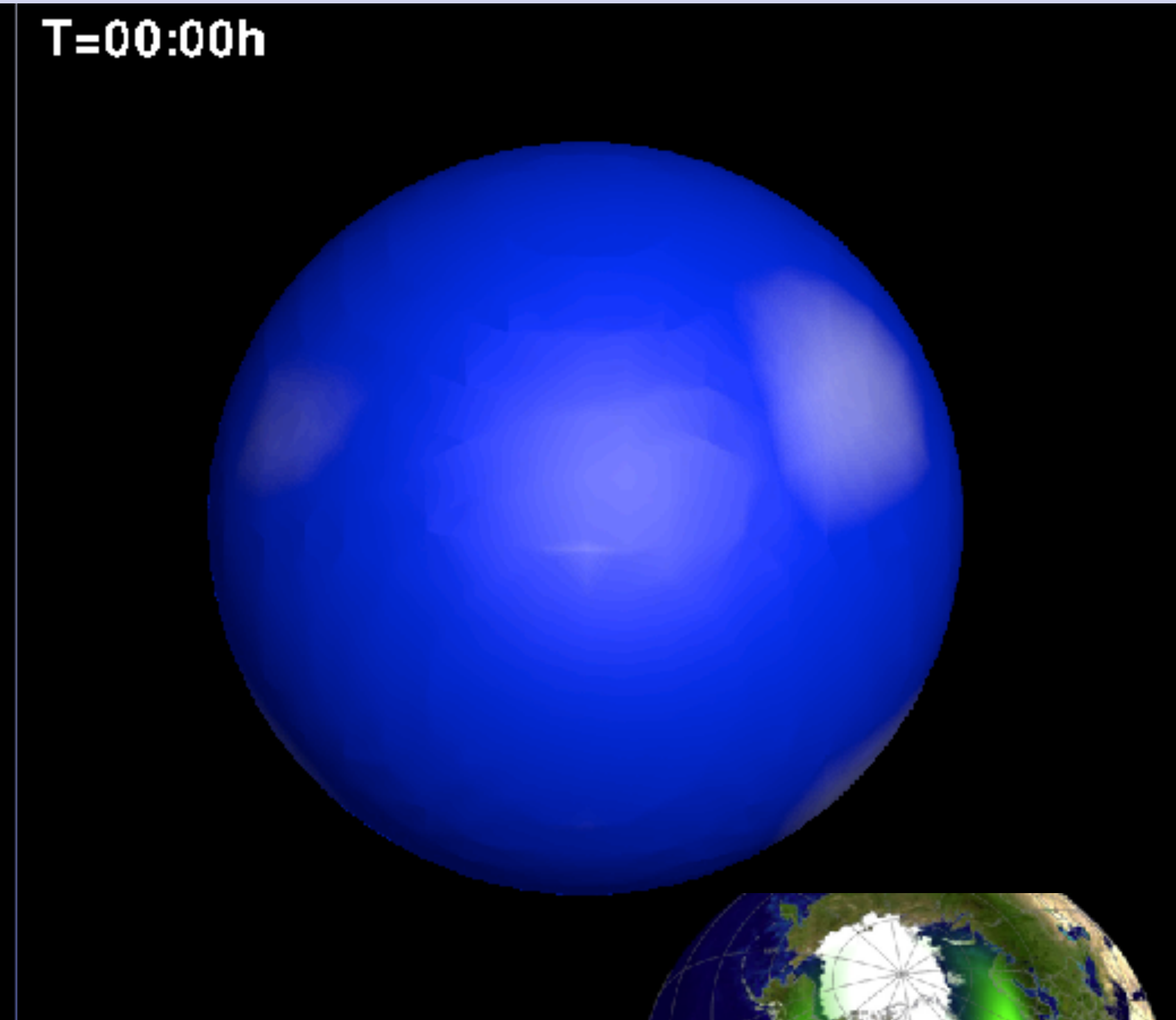


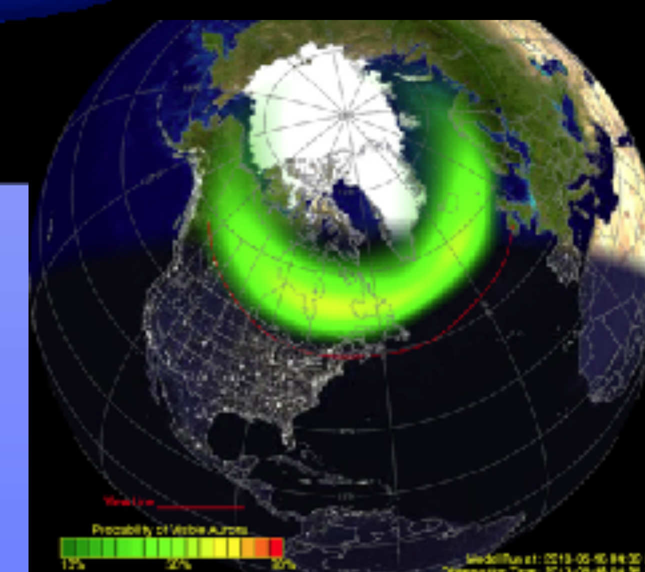
Stellar eruptions on close-in planets

3D view

Predicted Auroral structure

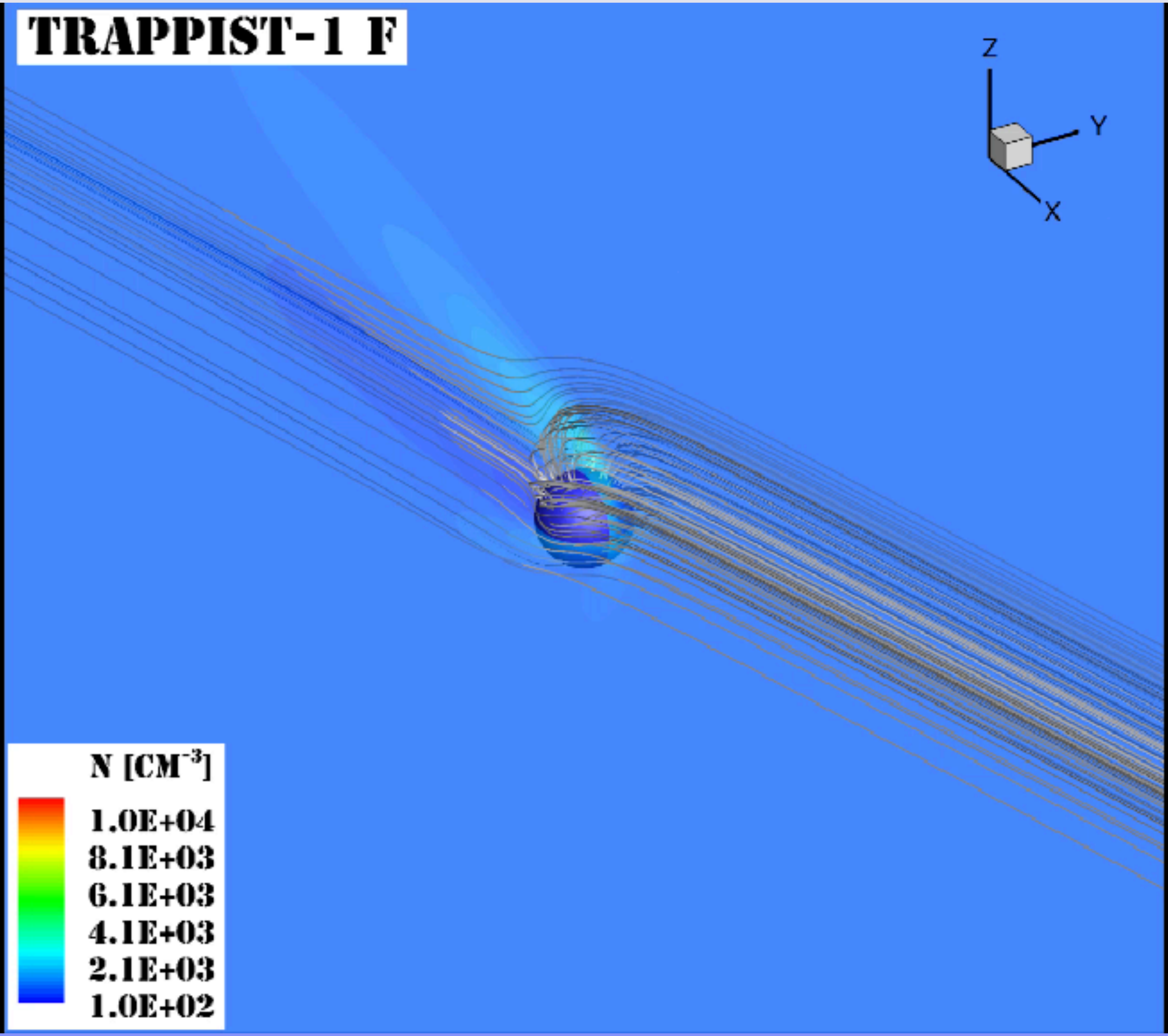






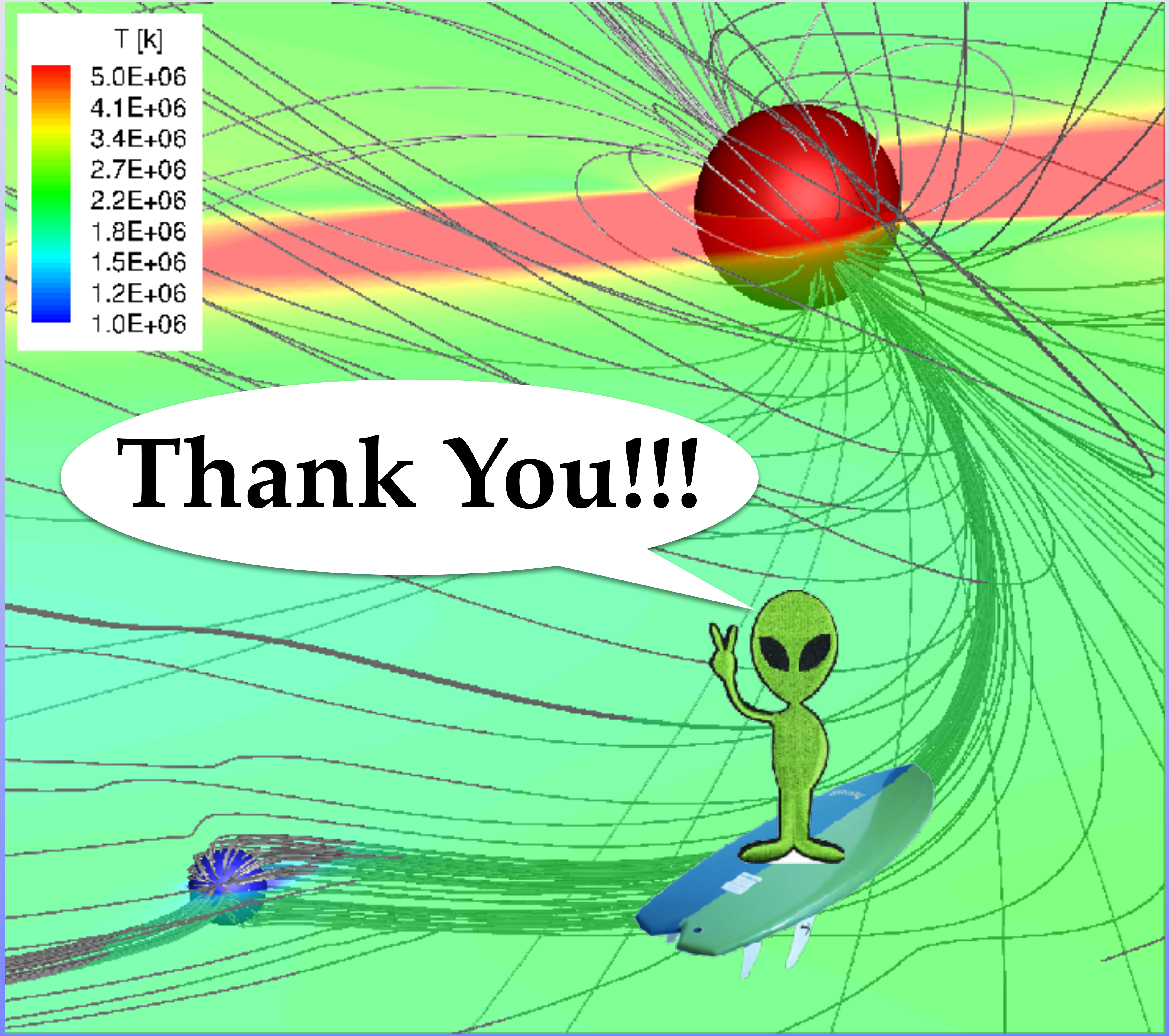
Cohen et. al 2011

Can close-orbit planet sustain their atmospheres?



Summary

- Computational plasma physics is challenging due to the wide range of scales and incomplete theory.
- The BATSRUS MHD code is highly versatile, advanced code to study non-relativistic plasmas.
- The SWMF enables to study multi-physics systems with much more accuracy and details.
- BATSRUS/SWMF are used to study different applications in space physics and astrophysics.


T [k]
5.0E+06
4.1E+06
3.4E+06
2.7E+06
2.2E+06
1.8E+06
1.5E+06
1.2E+06
1.0E+06
Thank You!!!