PHYS780: Solar and Solar-Terrestrial Physics

Time: 1:00 pm - 2:25 pm, Monday, Tuesday

Place: GITC, room 1403

Instructor: Alexander Kosovichev

e-mail: alexander.g.kosovichev@njit.edu

Phone: 408-239-6874

Office: Cullimore 105F

Office hours: by appointment

URL: http://sun.stanford.edu/~sasha/PHYS780/SOLAR_PHYSICS

NJIT Webex: https://njit.webex.com/join/sasha

Grades: homework (40%), class quizzes (20%), final presentation/essay (40%)

Lecture Plan

1. September 4, Tuesday. **Introduction. Course overview.** **"Big problems of heliophysics": solar neutrinos, rotation, dynamo, magnetic energy release, coronal heating, solar wind.**
2. September 10 Monday. **The Sun as a star.** **General properties, place in the Hertzsprung-Russell diagram. Distance, mass, radius, luminosity, composition, age, evolution, spectral energy distribution.**
3. September 11, Tuesday. **Tools for solar observations I.** **Solar telescopes. Resolution, MTF, seeing. High resolution telescopes. Spectrographs.**
4. September 17, Monday. **Tools for solar observations II.** **Measurements of the line shift. Zeeman effect. Magnetic fields and polarimetry.**
5. September 18, Tuesday. **Tools for solar observations III.** **Solar space missions: SOHO, TRACE, STEREO, Hinode, RHESSI, SDO, IRIS. Neutrino telescopes.** **Quiz #1**
6. September 24, Monday. **Internal structure I.** **Stellar Scaling Laws. Standard model. Evolution. Nuclear reactions. Equation of state. Radiative transfer.**

7. September 25, Tuesday. **Internal structure II.** Stability. Convective energy transfer. Non-standard models. Solar neutrinos, neutrino transitions, MSW effect.
8. October 1, Monday. **Solar oscillations.** Observations. Excitation mechanisms.
9. October 2, Tuesday. **Theory of solar oscillations.** Theory of p-, g-, and r-modes.
10. October 9, Monday. **Principles of helioseismology I. Global helioseismology.** Asymptotic inversion. Variational principle, perturbation theory. Inversions, sound speed and rotation inferences.
11. October 10, Tuesday. **Principles of Helioseismology II. Local-area helioseismology**. Ring-diagrams, acoustic imaging, time-distance tomography. Far-side imaging. Meridional circulation. Emerging magnetic flux. Active region dynamics.
12. October 15, Monday. **Convection.** Granulation, supergranulation, giant cells. Blue shift, models. Energy balance. Superadiabatic layer. Rotational and magnetic effects. Numerical simulations. Quiz #2

13. October 16, Tuesday. Differential rotation. Observations. Heliographic coordinates. Oblateness, quadrupole moment, test of the general relativity. Rotational history. Models of differential rotation.
14. October 22, Monday. Solar MHD. MHD equations, Alfven and magneto-acoustic waves. Instabilities. Shocks.
15. October 23, Tuesday. The Solar Cycle. Global magnetism. "Magnetic carpet".
16. October 29, Monday. Dynamo theory. Mean-field electrodynamics, dynamo models, 3D MHD simulations. Quiz #3
17. October 30, Tuesday. Magnetic energy release. Reconnection. Particle acceleration. Observations. Theories of reconnection, current sheets, MHD and plasma instabilities. Acceleration mechanisms.
18. November 5, Monday. Solar atmosphere. The structure of the solar atmosphere, photosphere, chromosphere, corona. Transition region. Chromospheric network, filaments, prominences, spicules.
19. November 6, Tuesday. Sunspots. Active regions. Flux tubes. Observations. Static models. Flows, Evershed effect. Formation and decay of sunspots. Theories of emerging flux tubes, magnetic buoyancy.

20. November 12, Monday. Flares. Observations. Radiation, radio-, X-, and gamma-rays. Energetic particles. Thin- and thick-target models, evaporation, heat conduction. Radiative and MHD shocks. Moreton waves, "sunquakes".
21. November 13, Tuesday. Corona. CME. Observations, eclipses. White light corona, Thompson scattering. Coronal heating, heat conduction. Large-scale structure, change with the solar cycle. Coronal mass ejections, shocks. Quiz #4
22. November 19, Monday. Solar wind. Observations. Expansion, Parker's model, high- and low-speed wind. Composition, first-ionization potential effect. Sector structure, current sheet.
23. November 26, Monday. Magnetosphere. Interaction of solar wind with the Earth's magnetosphere and planets. Geomagnetic effects.
24. November 27, Tuesday. Ionosphere. Auroras, substorms. Space weather.
25. December 3, Monday. Presentations
26. December 4, Tuesday. Presentations
27. December 10, Monday. Presentations

Textbooks

1. **Stix, M. 2002, "The Sun: An Introduction", (Berlin: Springer)**
2. **"Introduction to Space Physics", ed. M.G. Kivelson & C.T. Russell, Cambridge Univ. Press, 1995**

Recommended books

1. Priest, E.R. 2014, Magnetohydrodynamics of the Sun (Cambridge Univ. Press)
2. Aschwanden, M. J., 2006, Physics of the Solar Corona (Springer)
3. Zirin, H. 1988, Astrophysics of the Sun (Cambridge Univ. Press)
4. Cox, A.N., Lingston, W.C., Matthews, M.S., 1991, Solar Interior and Atmosphere (Tucson, University of Arizona)
5. Bahcall J.N. 1989, Neutrino Astrophysics (Cambridge Univ. Press)
6. Foukal, P. 1990, Solar Astrophysics (New York: Wiley)
7. Golub, L., and Pasachoff, J.M. 1997, The Solar Corona (Cambridge Univ. Press)
8. Sturrock, P. (ed.) 1986, Physics of the Sun, (Kluwer).

Presentations (essays)

- Presentation (essay) topics can be on your research related to the course, or chosen from my list. Your suggestions are welcome.
- Requirements for 20 min presentations:
  - Present observational facts
  - Explain the basic physical processes
  - Briefly review the current state of research
  - Answer questions
- For each topic I will provide references and initial material.

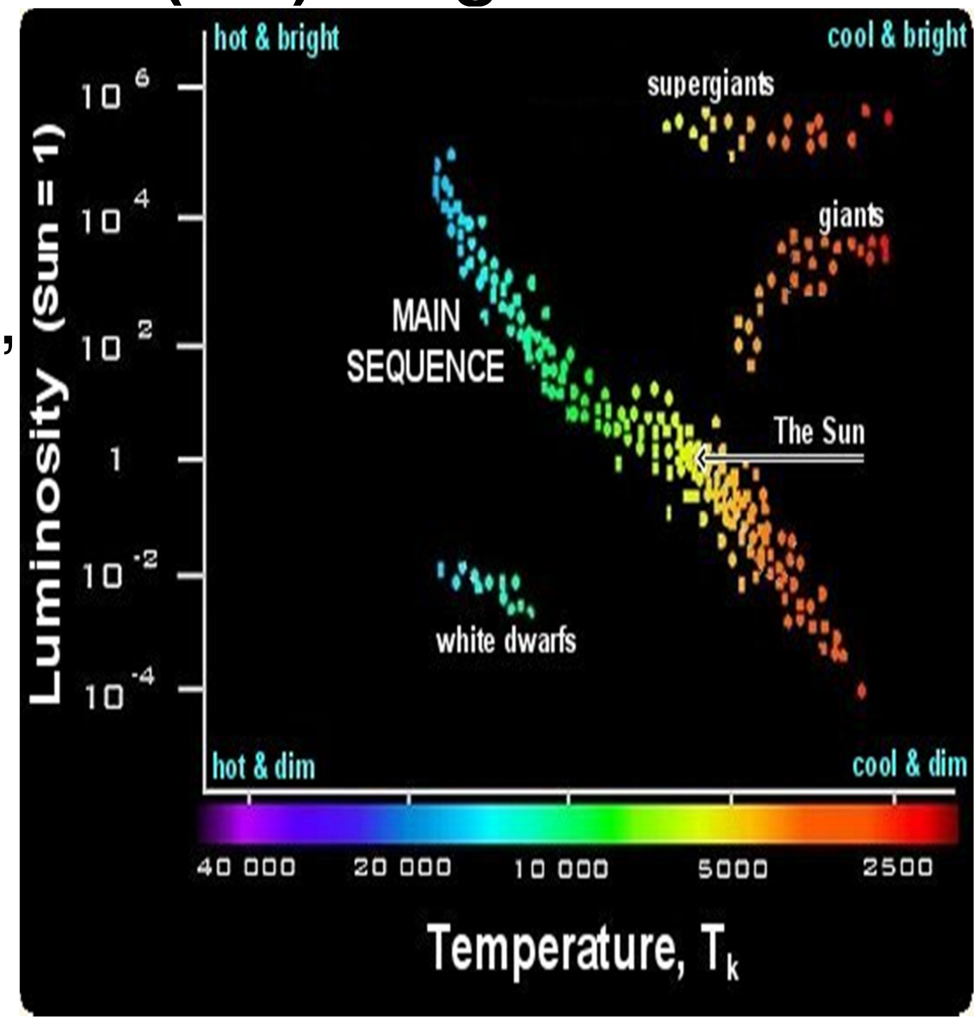
Essay Topics.

1. Solar diameter, oblateness and gravitational quadrupole moment
2. Solar neutrino problem.
3. Predictions of the solar cycle.
4. Spectrum of solar oscillations
5. Helioseismic inverse problem for structure.
6. Helioseismic inverse problem for rotation
7. Excitation of solar oscillations.
8. Solar convection and turbulence.
9. Mechanism of differential rotation.
10. Solar tachocline.
11. Magnetic reconnection.
12. MHD shocks and Moreton waves.
13. Dynamo models.
14. Acceleration mechanisms in solar flares.
15. Sunquakes
16. Coronal mass ejections.
17. Mechanisms of coronal heating.
18. Coronal seismology.
19. Acceleration of solar wind.
20. Waves in magnetosphere

The Sun as a star.

- General properties.
- Place in the HR diagram.
- Distance, mass, radius, luminosity, composition, age, evolution, spectral energy distribution.
- Irradiance spectrum
- Seismic radius
- Solar-type stars

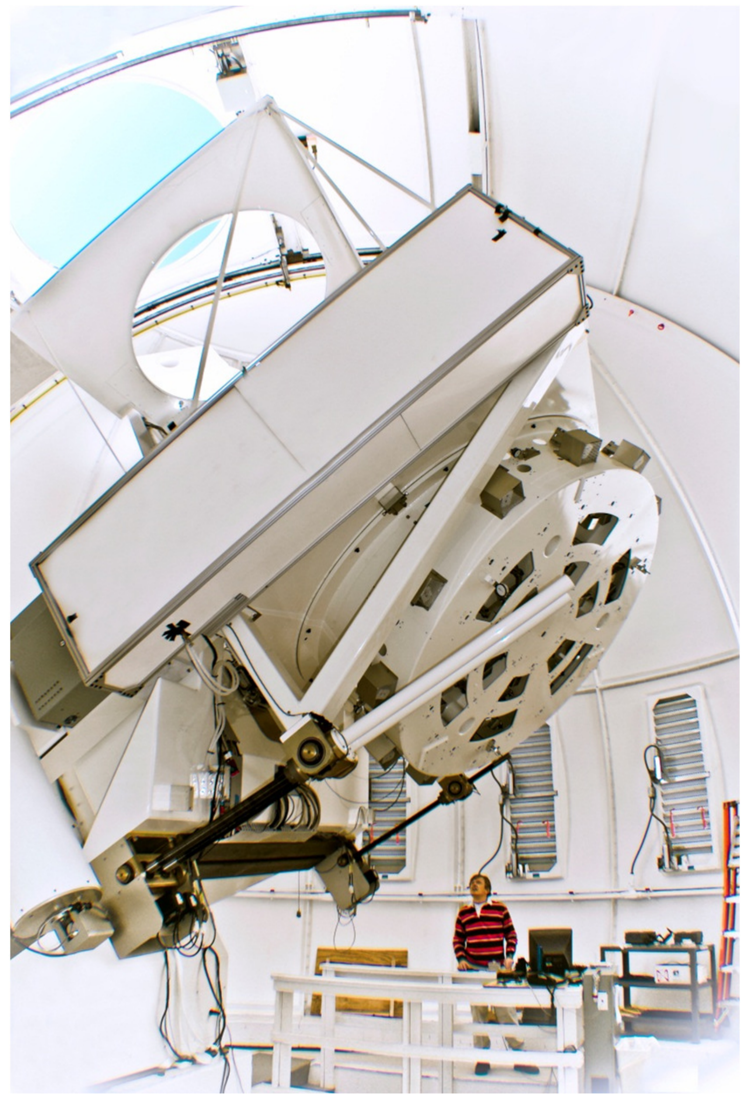
- **Hertzsprung-Russell (HR) Diagram**



Tools for solar observations I.

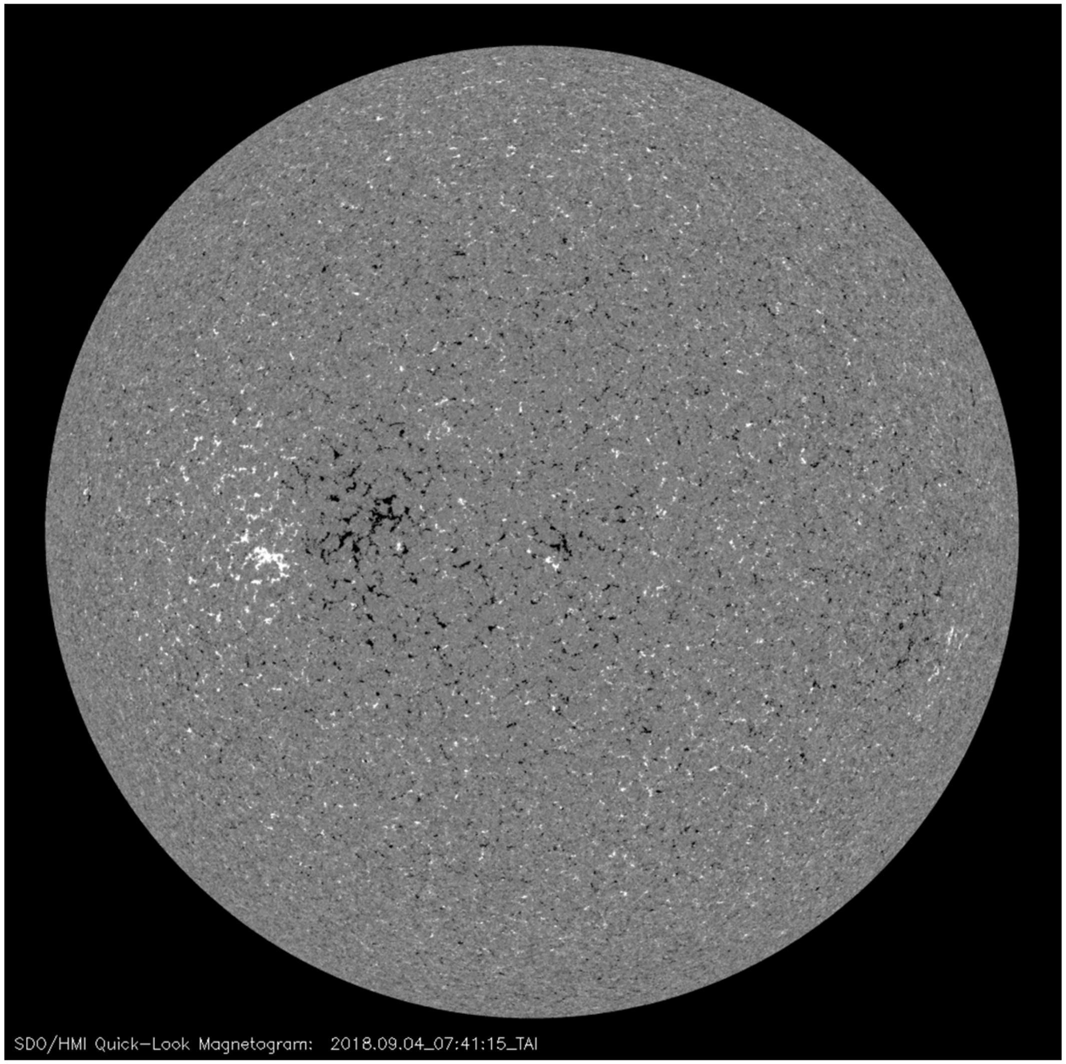
- Solar telescopes
- Resolution, MTF (Modulation Transfer Function), seeing.
- High resolution telescopes.
- Spectrographs.

1.6m Solar Telescope at BBSO



Tools for solar observations II.

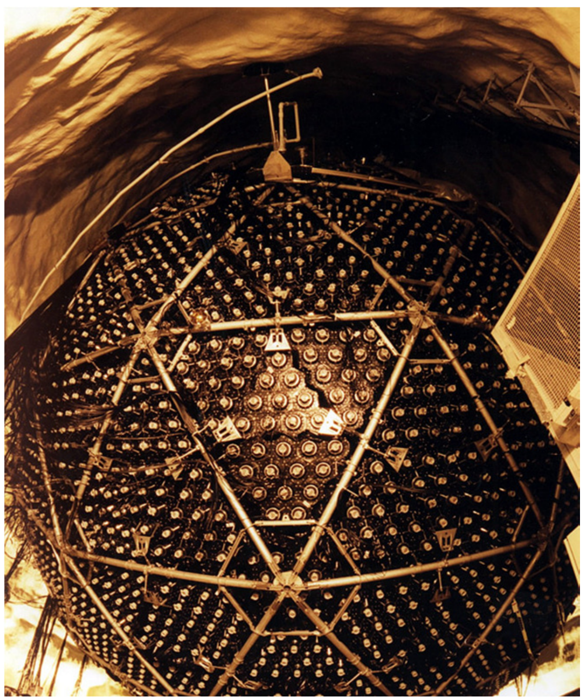
- Spectroscopy
- Measurements of the line shift.
- Zeeman effect.
- Magnetic fields and polarimetry.



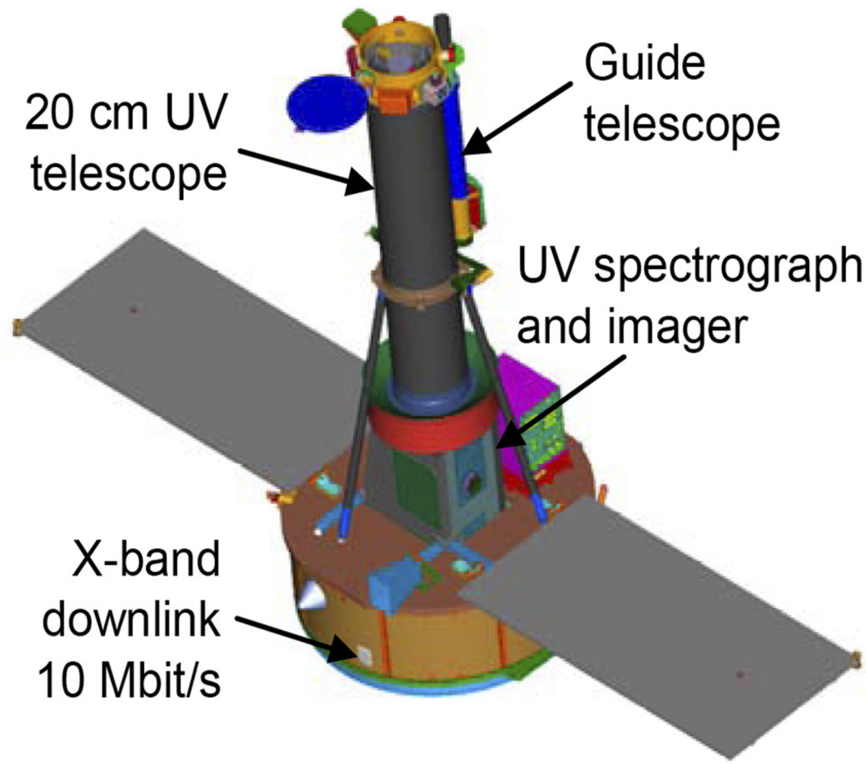
Tools for solar observations III.

- Solar space missions: SOHO, TRACE, STEREO, Hinode, RHESSI, SDO, IRIS.
- Neutrino telescopes.

Sudbury Neutrino Observatory detects solar neutrinos through their interactions with a large tank of heavy water.

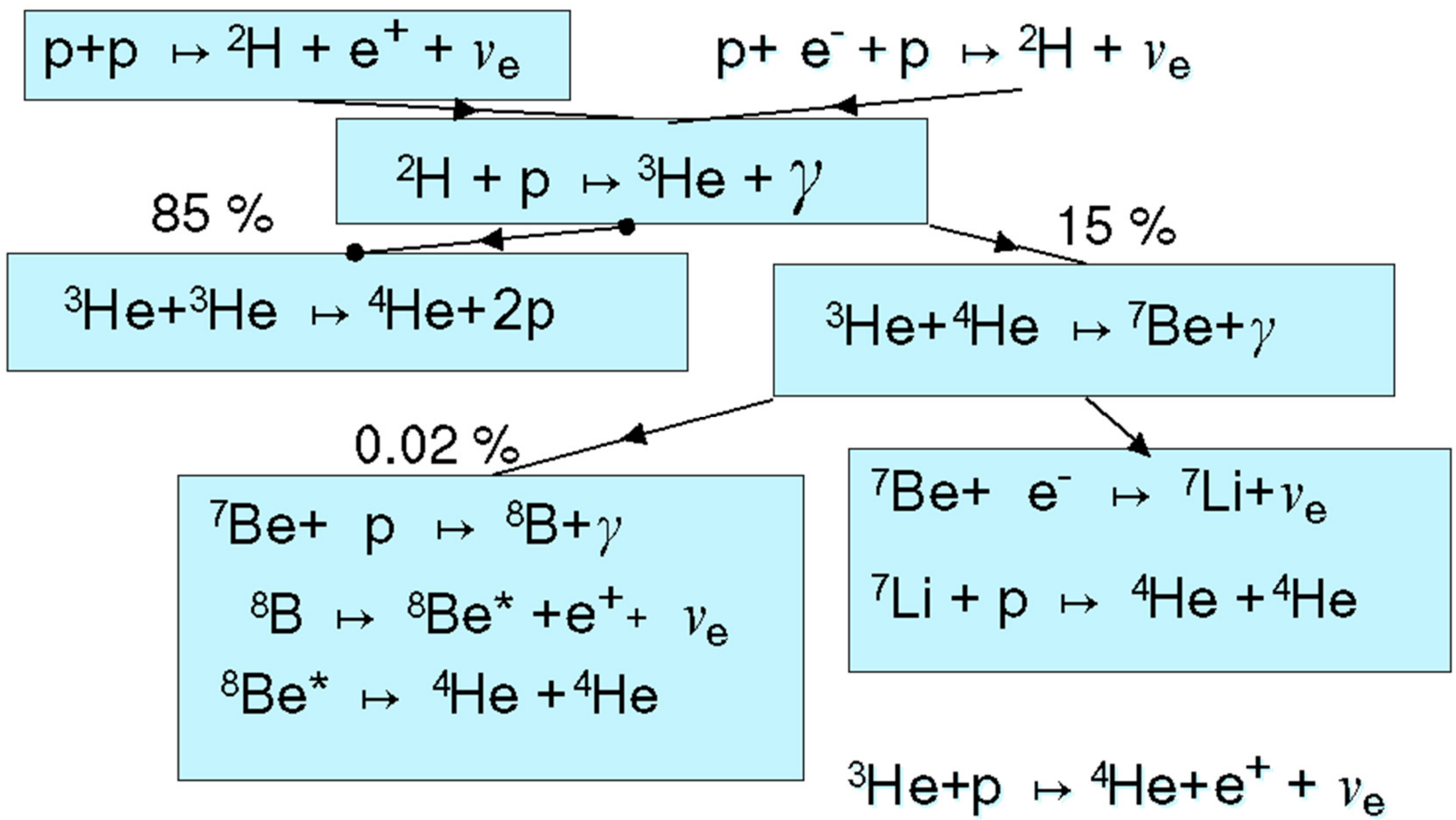


- Interface Region Imaging Spectrograph (IRIS) explorer



Internal structure I.

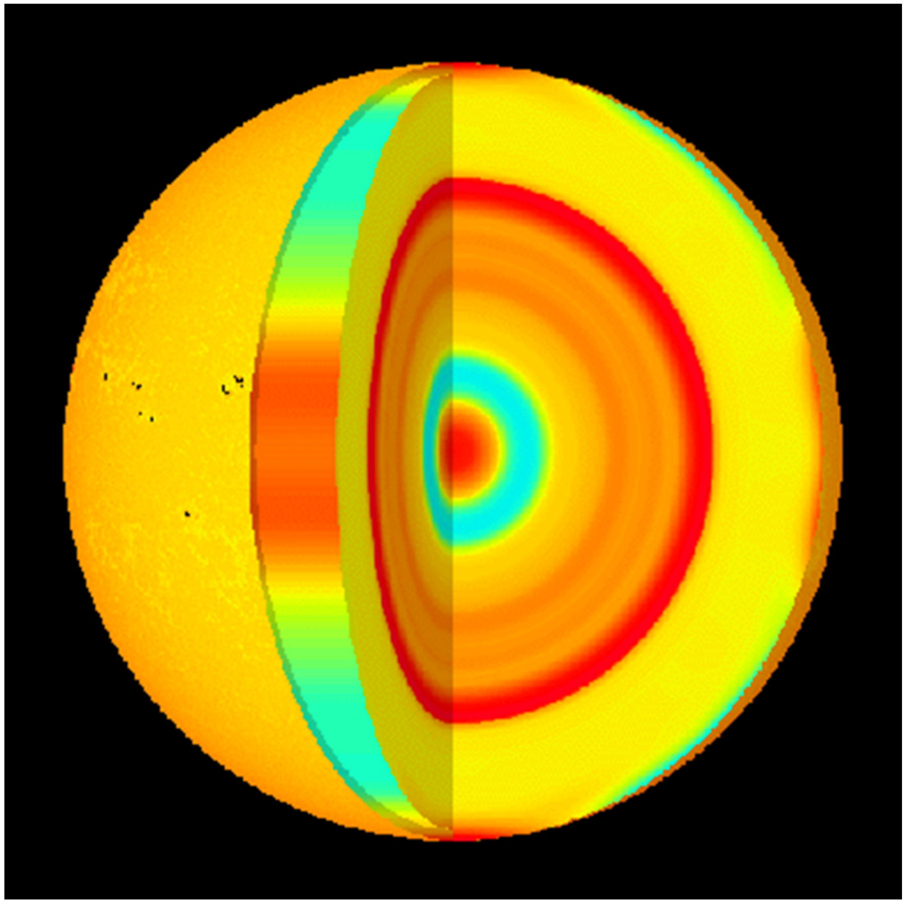
- Stellar Scaling Laws. Standard model. Evolution. Nuclear reactions. Equation of state. Radiative transfer.



Internal structure II.

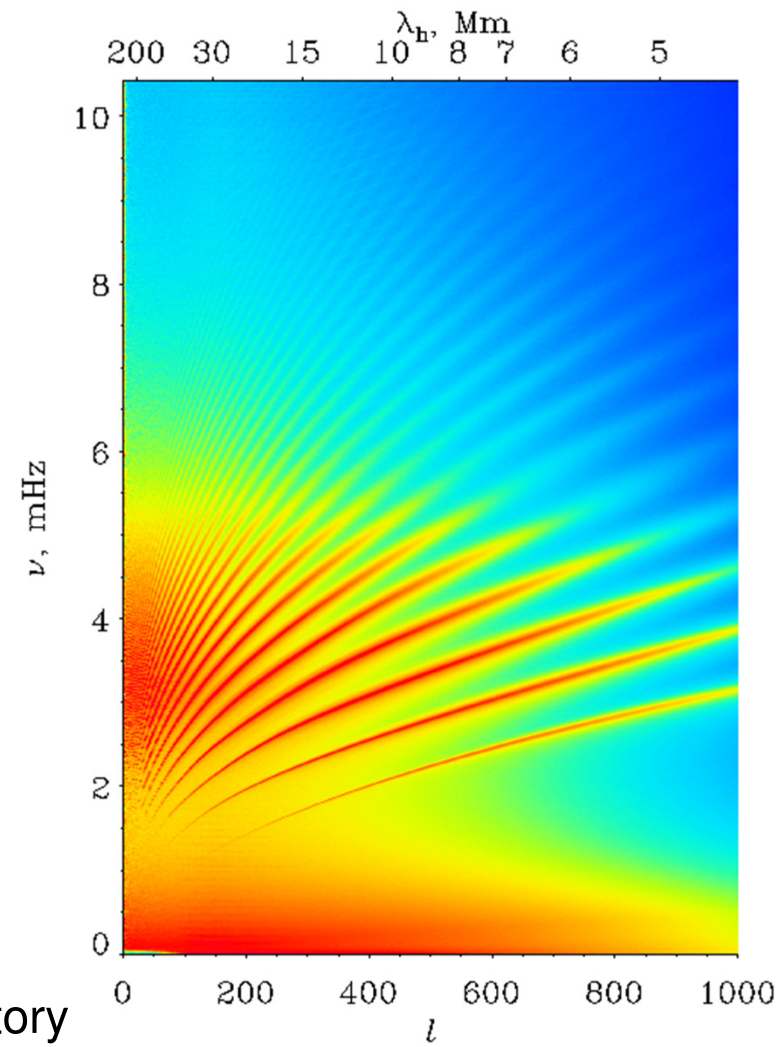
- Convective instability.
- Convective energy transfer.
- Non-standard solar models.
- Solar neutrinos, neutrino transitions, MSW effect.

- Variations of the sound speed detected by helioseismology



Solar oscillations.

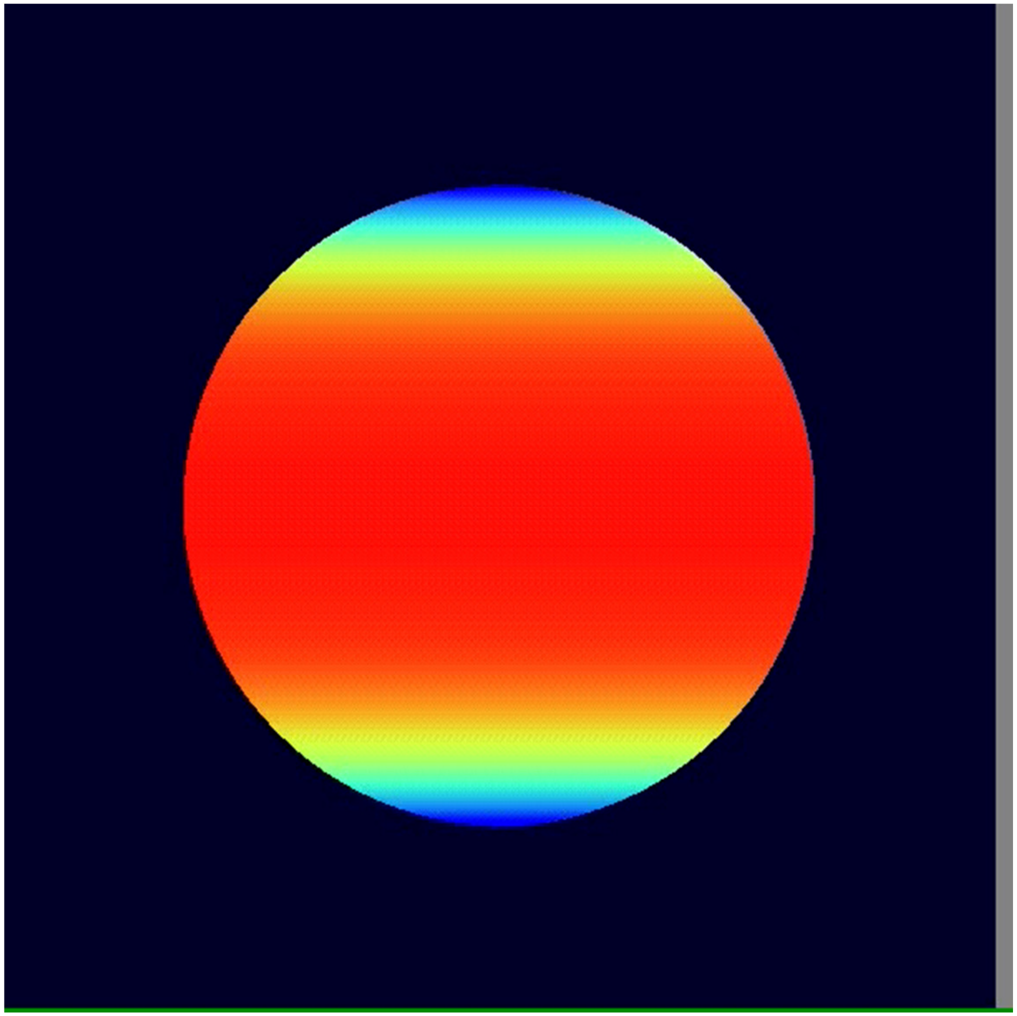
- Observations.
- Theory of p-, g-, and r-modes.
- Excitation mechanisms.
- Oscillations of solar-type stars.



Oscillation power spectrum from
Solar and Heliospheric Observatory

Principles of Helioseismology I.

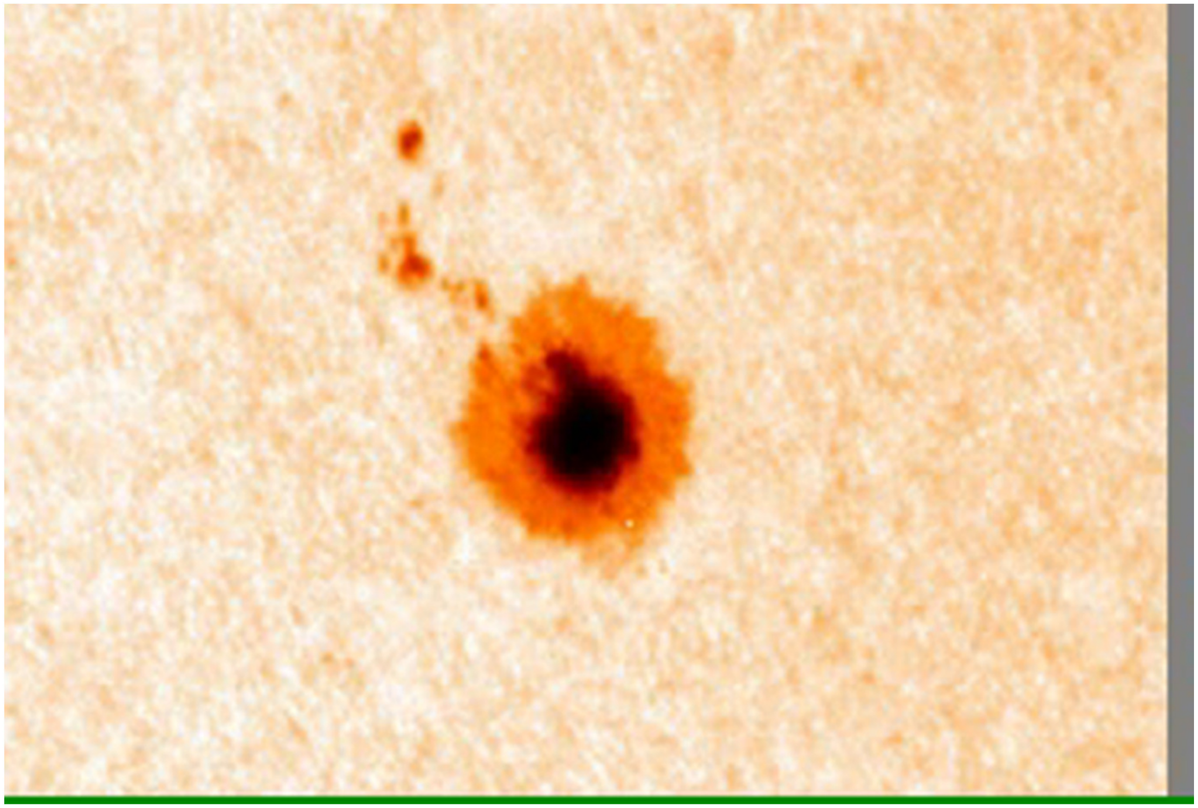
- Variational principle
- Perturbation theory.
- Inversions, sound speed and rotation inferences.



Principles of Helioseismology II.

- Local-area helioseismology
- Ring-diagrams
- Acoustic imaging
- Time-distance tomography.

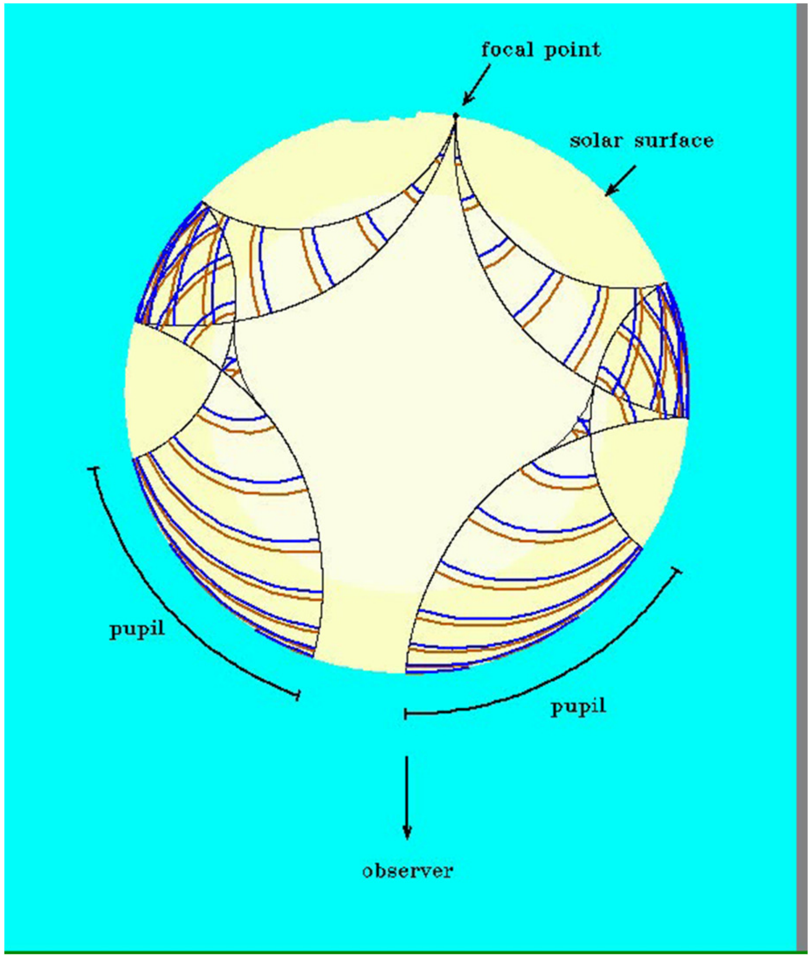
Subsurface structure of sunspot



Subsurface structure and dynamics.

- Current helioseismology results.
- Far-side imaging.
- Meridional circulation.
- Emerging magnetic flux.
- Active region dynamics.

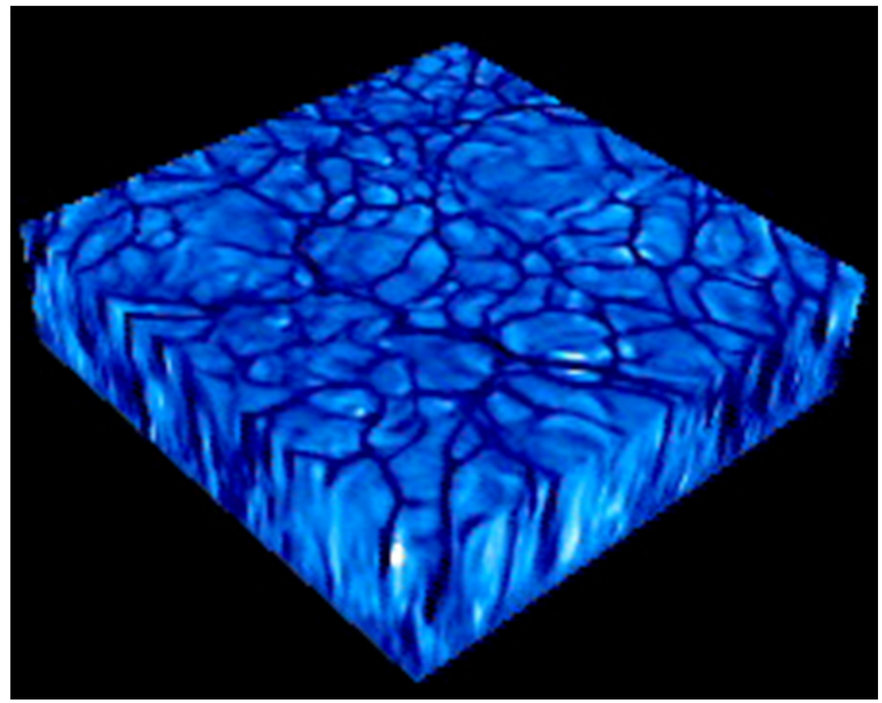
Illustration of far-side imaging of active regions



Convection.

- Granulation, supergranulation, giant cells.
- Convective blue shift.
- Energy balance.
- Superadiabatic layer.
- Rotational and magnetic effects.
- Numerical simulations.

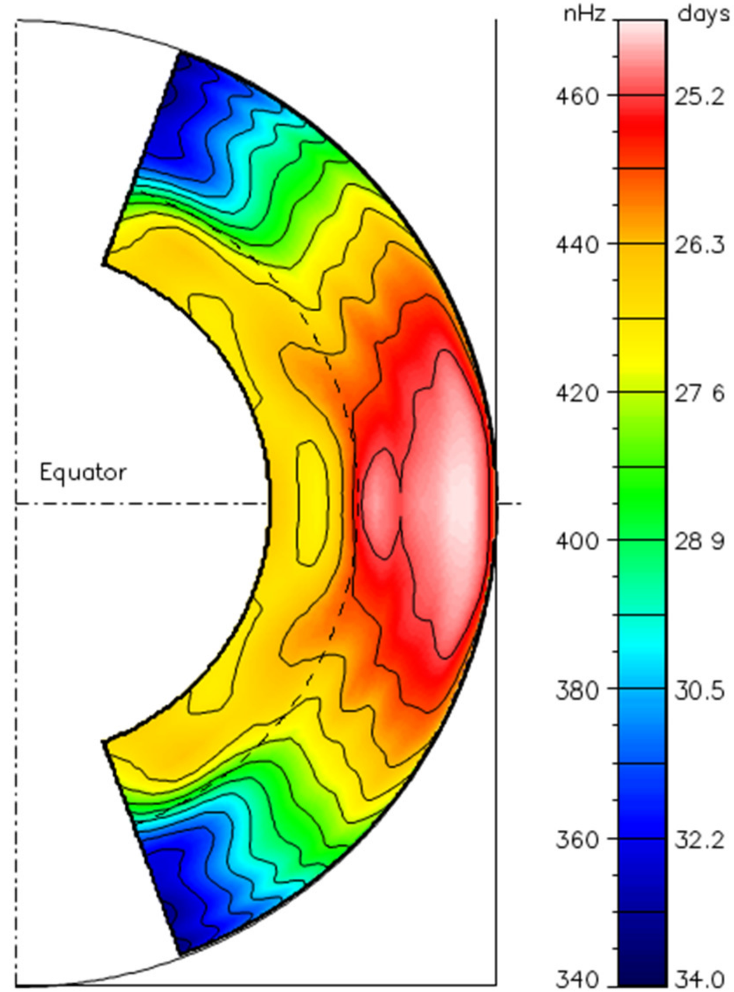
3D numerical simulations of solar granulation



Differential rotation.

- Observations.
- Heliographic coordinates.
- Oblateness, quadrupole moment, test of the general relativity.
- Rotational history.
- Models of differential rotation.
- Rotation of solar-type stars.

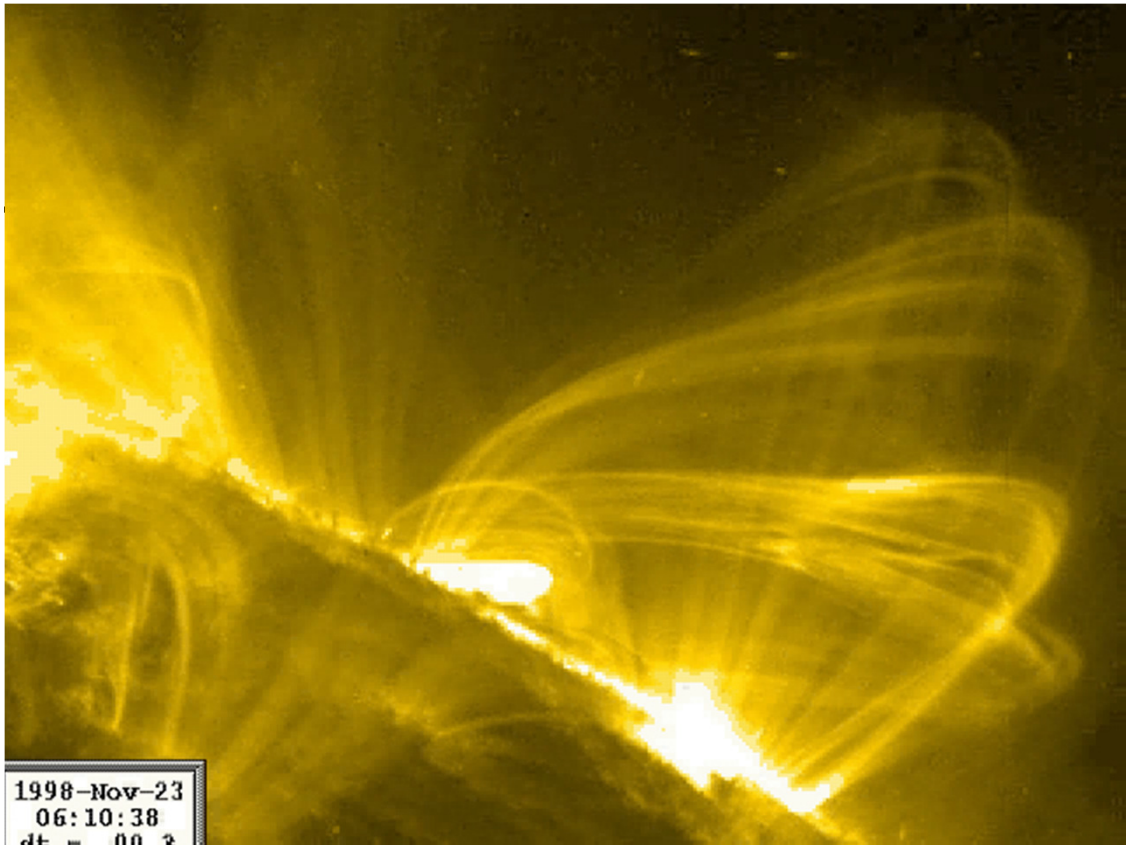
Rotation rate inside the Sun determined by helioseismology



Solar MHD.

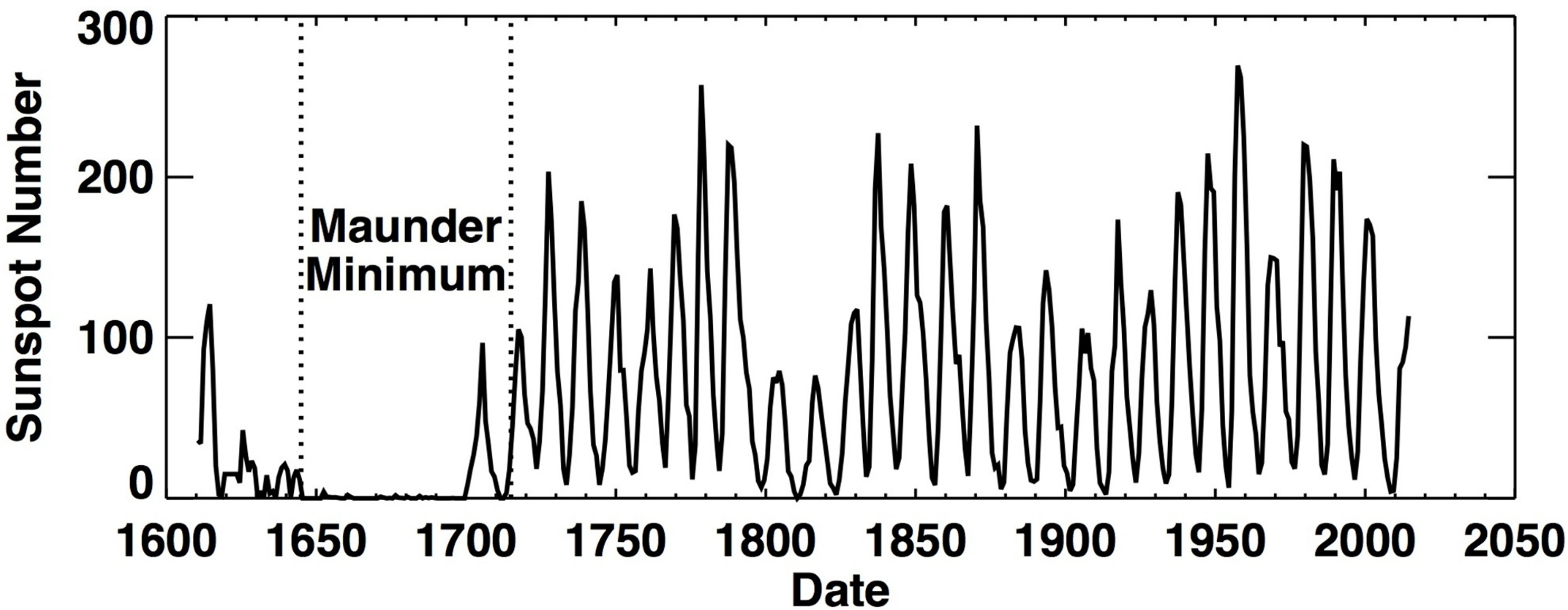
- MHD (magneto-hydrodynamics) equations
- Alfven and magneto-acoustic waves.
- Instabilities.
- Shocks.

Excitation of MHD waves by solar flare



The Solar Cycle

- Global magnetism. "Magnetic carpet".
- Sunspot cycles for the whole history of solar observations



Dynamo theory.

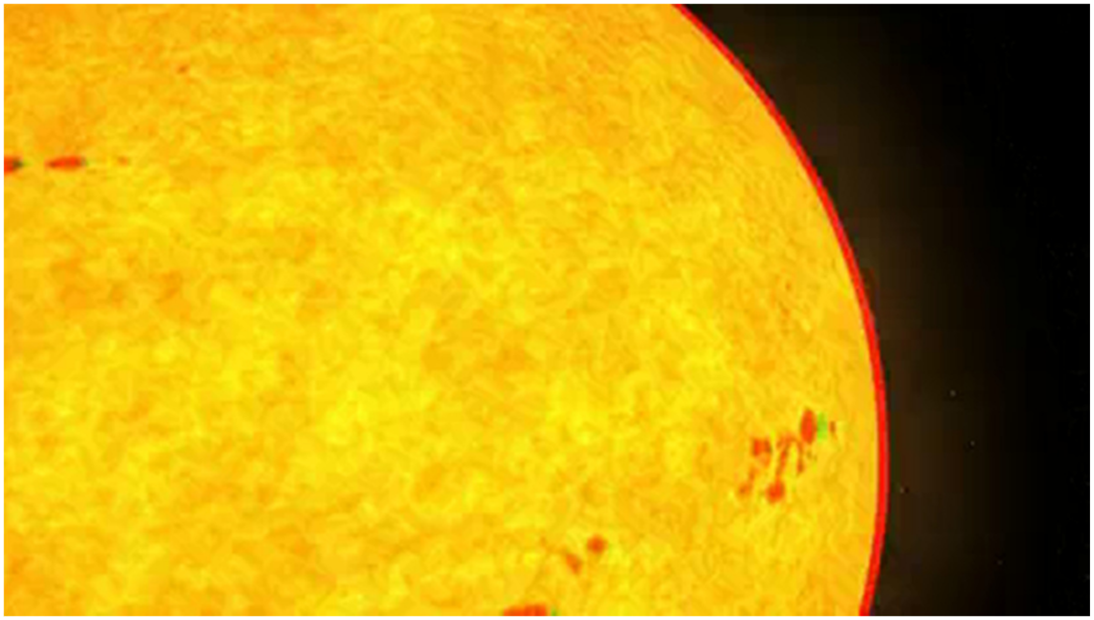
- Mean-field electrodynamics.
- Alpha- and Omega-effects.
- Dynamo models.
- 3D MHD simulations.

Animation of the solar dynamo

Magnetic energy release.

- Magnetic reconnection.
- Particle acceleration.
- Observational evidence.
- Theories of reconnection, current sheets, MHD and plasma instabilities.
- Acceleration mechanisms.

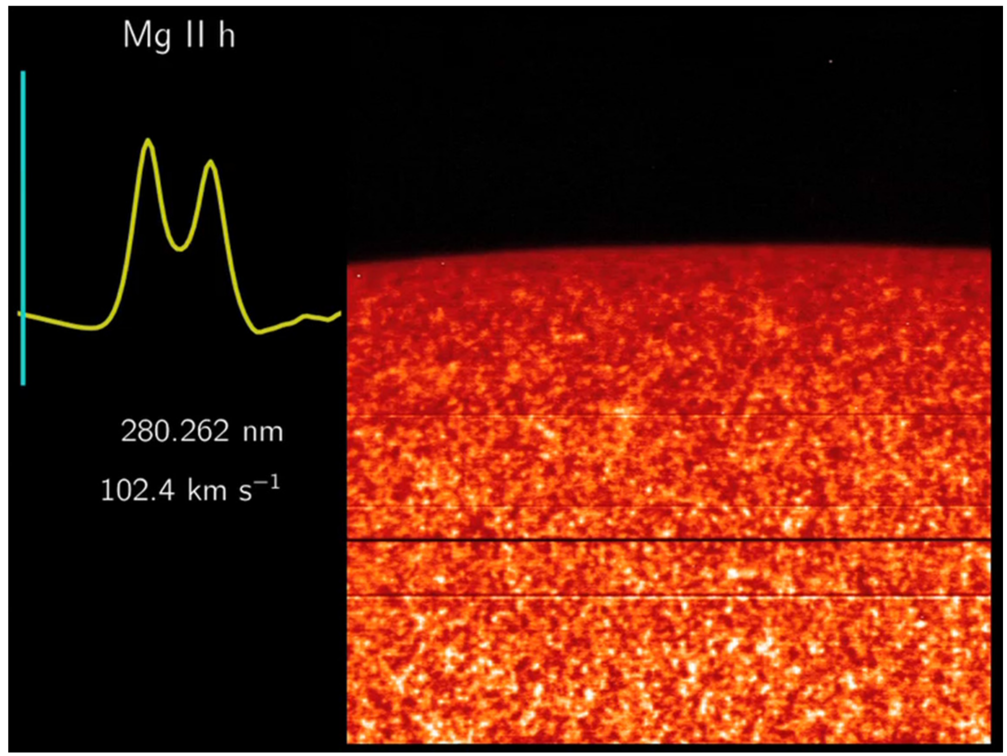
Animation of magnetic reconnection in the magnetosphere initiated by coronal mass ejection



Solar atmosphere.

- The structure of the solar atmosphere.
- Photosphere, chromosphere, corona.
- Chromosphere-corona transition region.
- Chromospheric network, filaments, prominences, spicules.

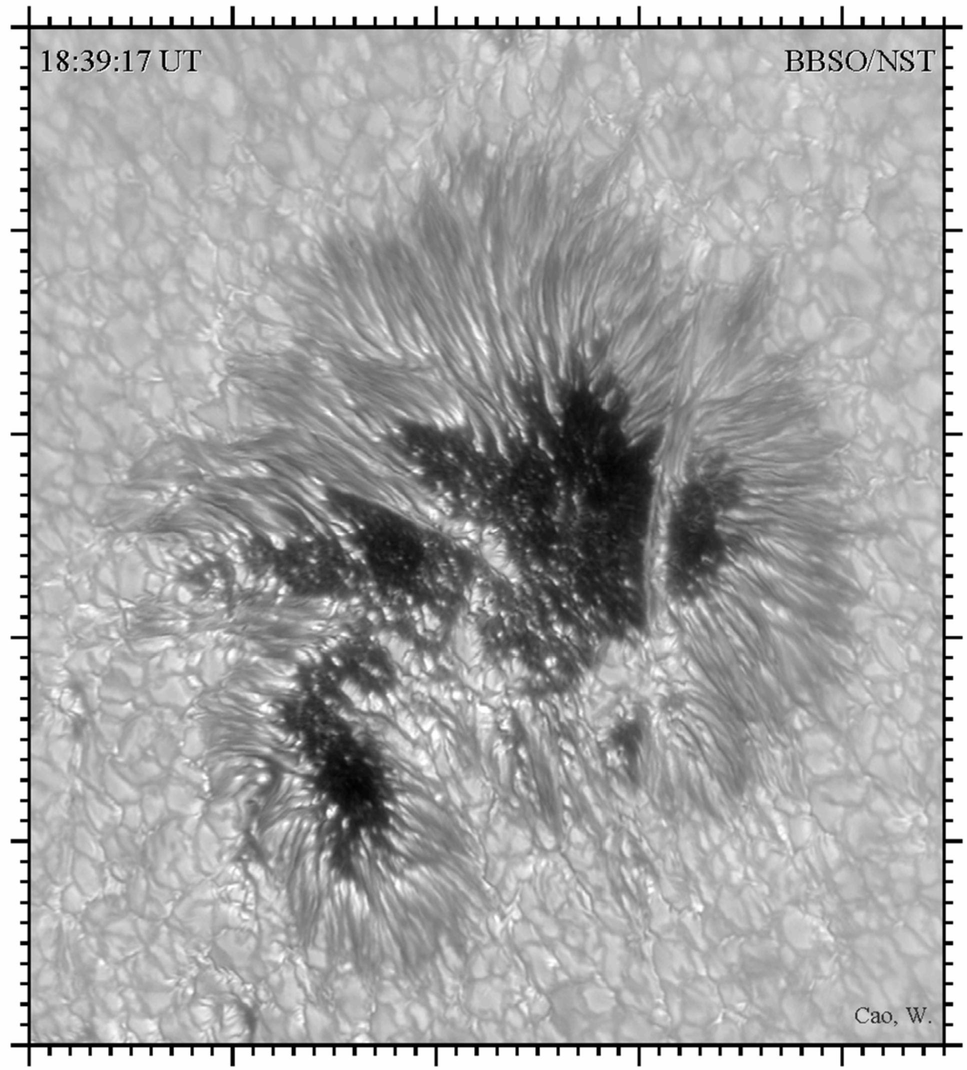
Spectroscopic observations of the chromosphere and transition regions from IRIS (T=15,000 K)



Sunspots.

- Active regions and sunspots.
- Magnetic flux tubes. Observations. Static models.
- Sunspot flows, Evershed effect.
- Formation and decay of sunspots.
- Theories of emerging flux tubes, magnetic buoyancy.

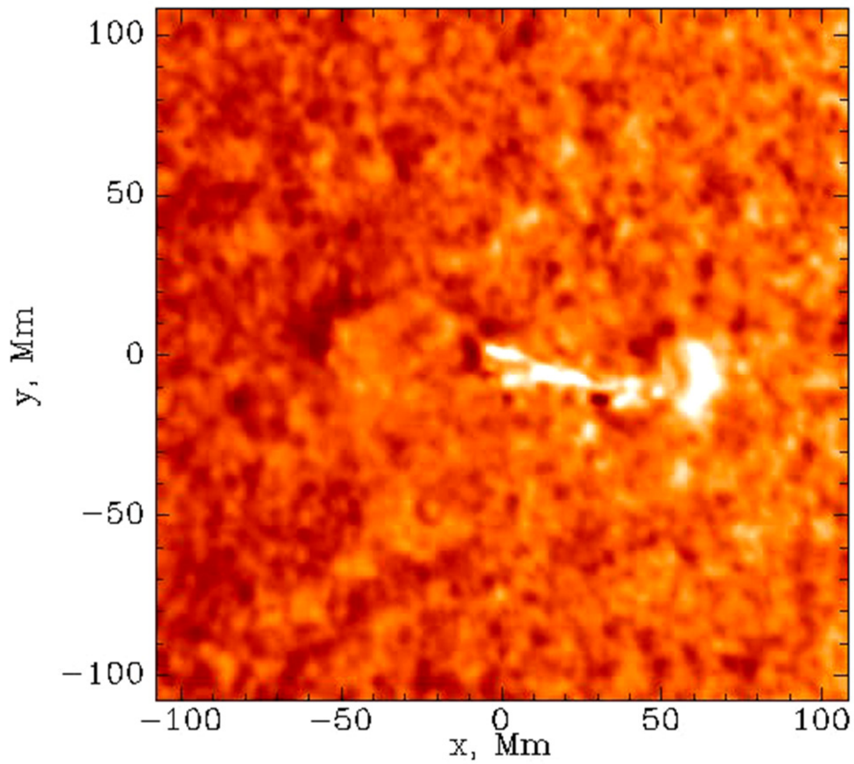
High-resolution observations of a sunspot from BBSO



Flares.

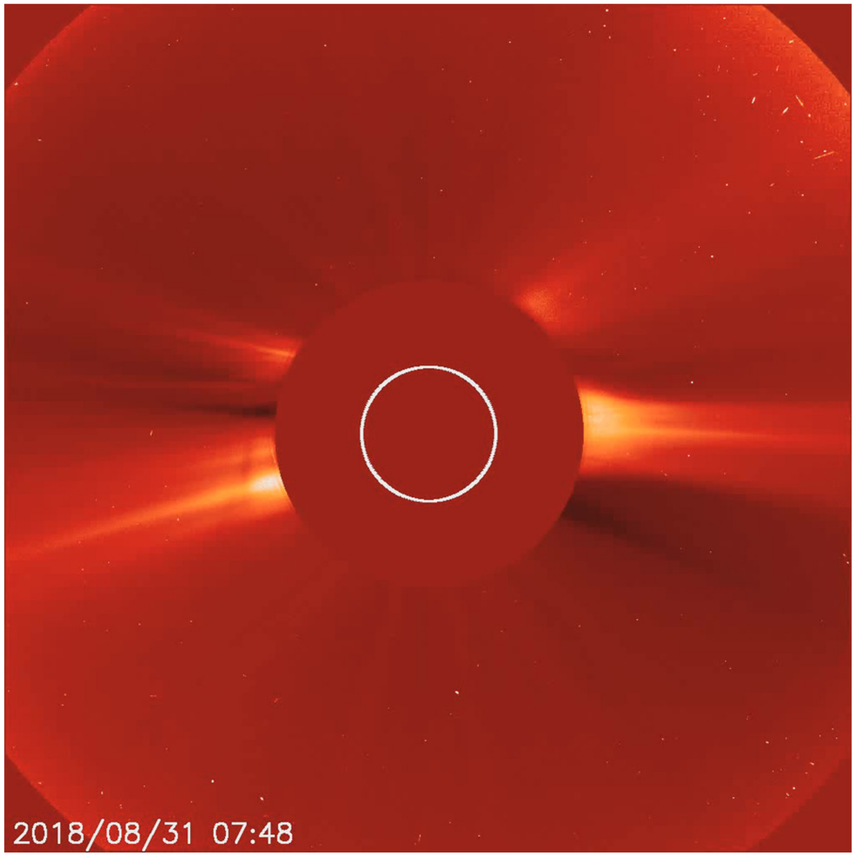
- Observations.
- Radiation, radio-, X-, and gamma-rays.
- Energetic particles.
- Thin- and thick-target models, chromospher evaporation, heat conduction.
- Radiative and MHD shocks. Moreton wav "sunquakes".

Sunquakes – helioseismic waves excited by solar flares



Corona.

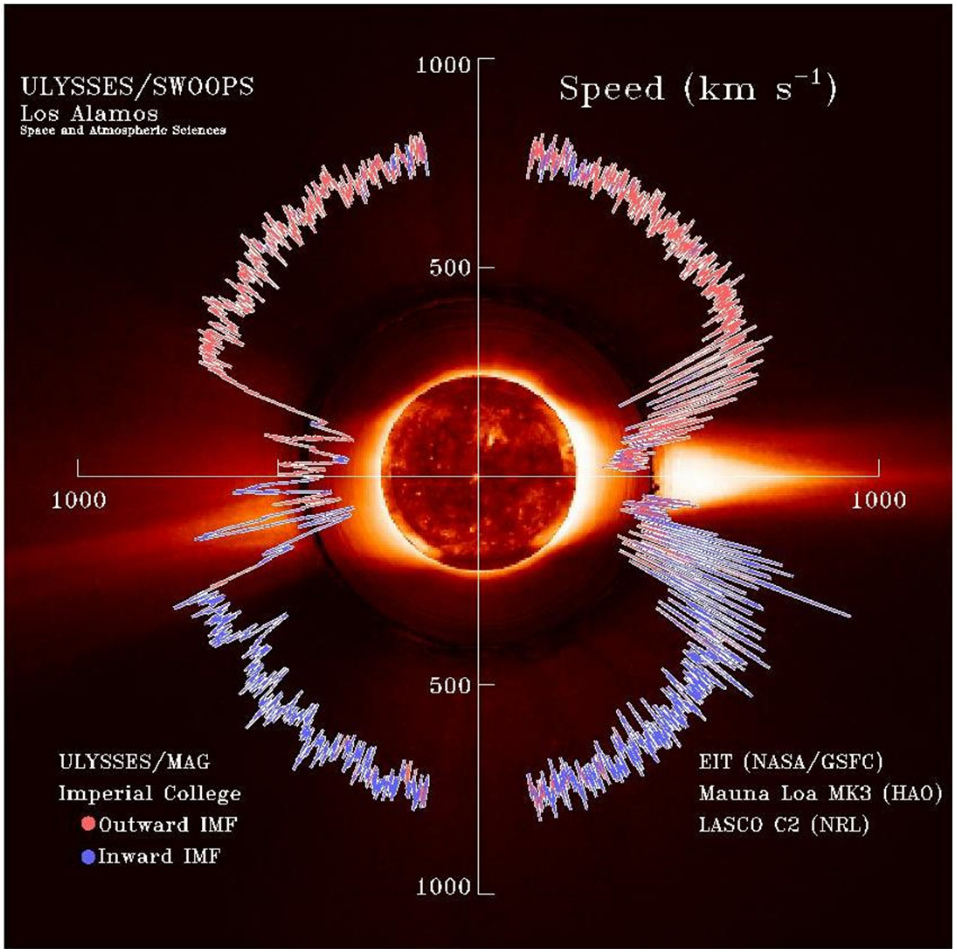
- Coronal Mass Ejections (CME).
- Observations, eclipses.
- White light corona, Thompson scattering.
- Coronal heating, heat conduction.
- Large-scale structure, change with the solar cycle. Coronal mass ejections, shocks.



Solar wind.

- Observations.
- Coronal expansion.
- Parker's model
- High- and low-speed wind.
- Composition, first-ionization potential effect.
- Sector structure, current sheet.

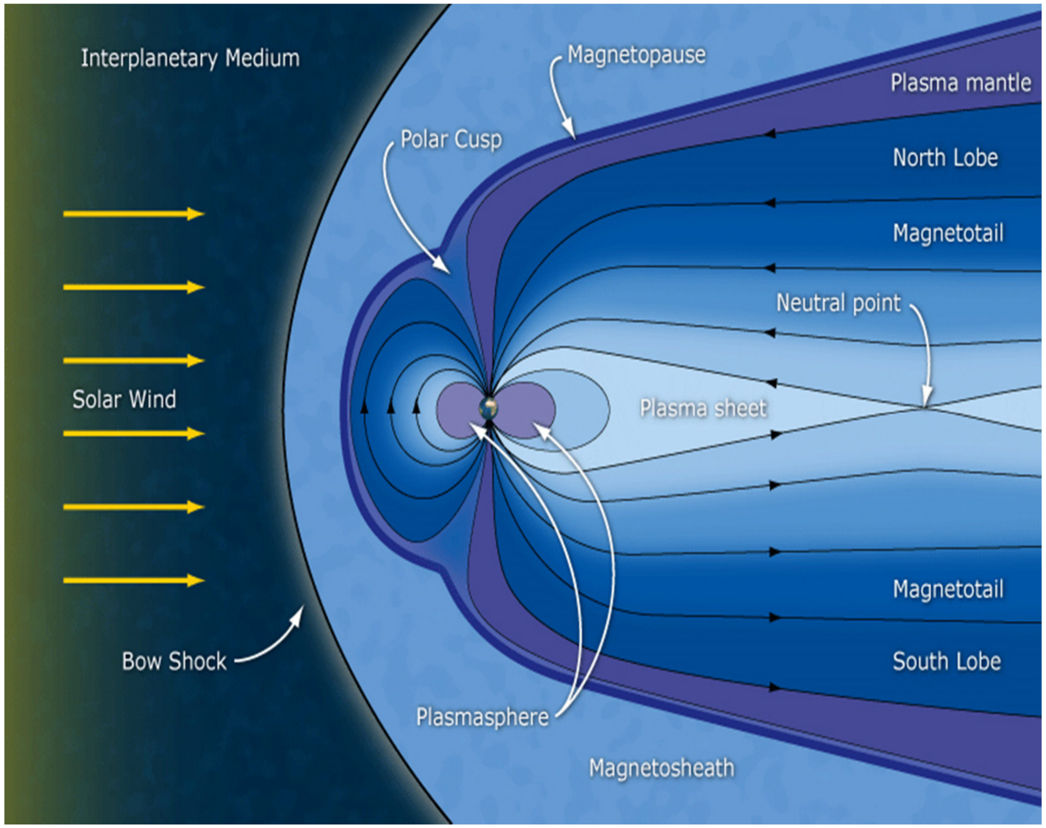
- Observations of the solar wind speed from Ulysses spacecraft



Magnetosphere.

- Interaction of solar wind with the Earth's magnetosphere and planets.
- Geomagnetic effects.

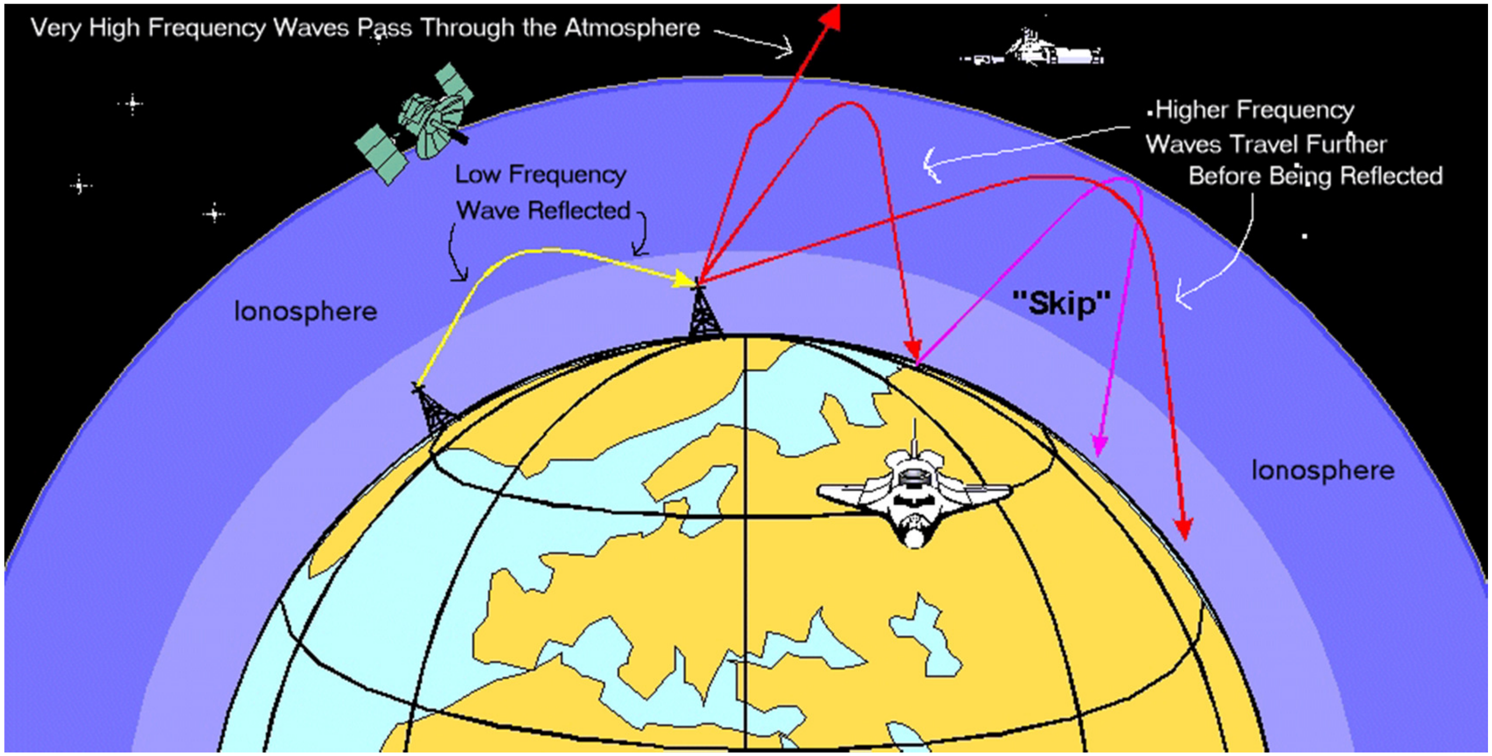
- Schematic structure of the magnetosphere



Ionosphere.

- Auroras, substorms. Space weather.

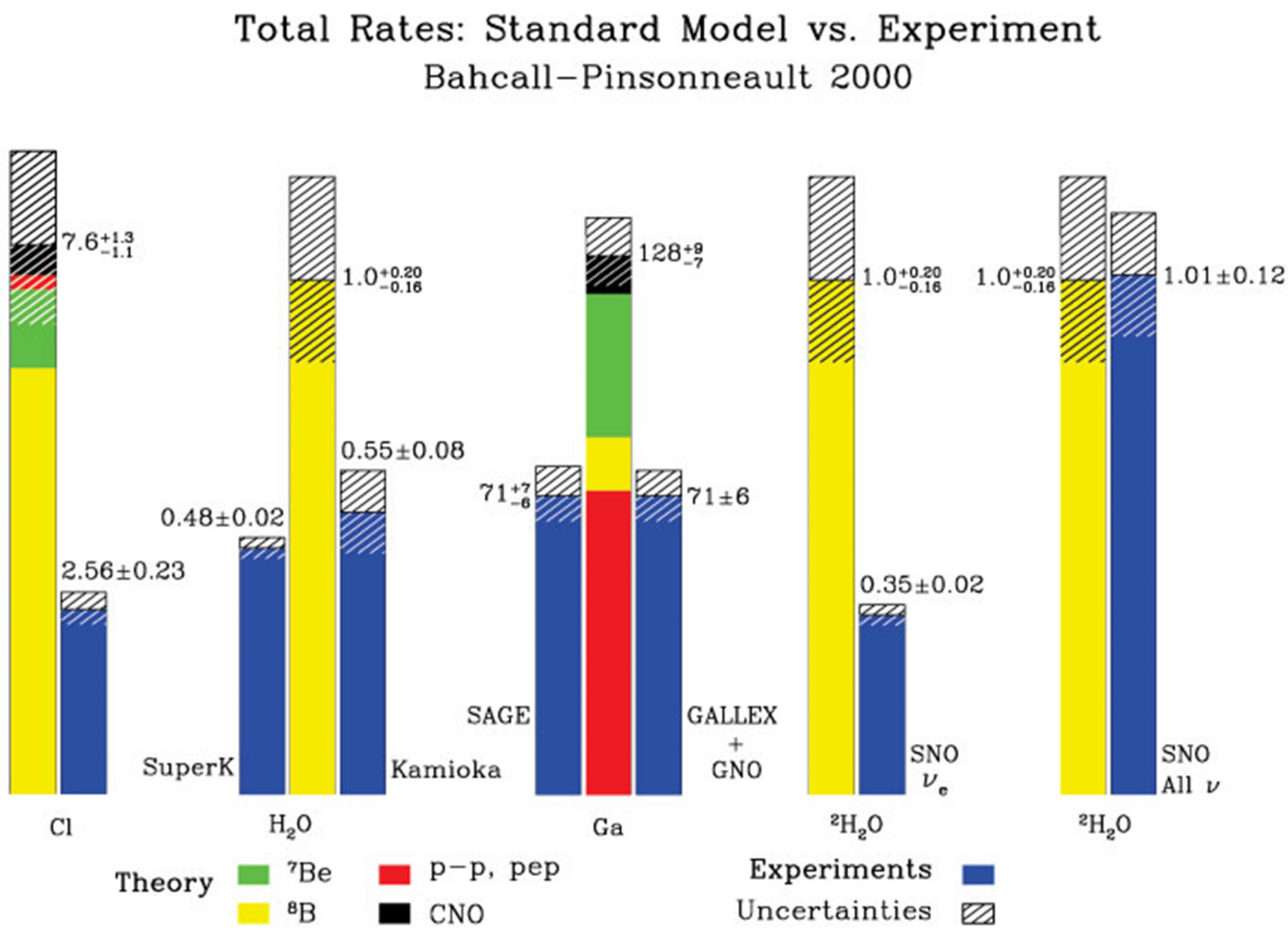
- Propagation of radiowaves in the ionosphere



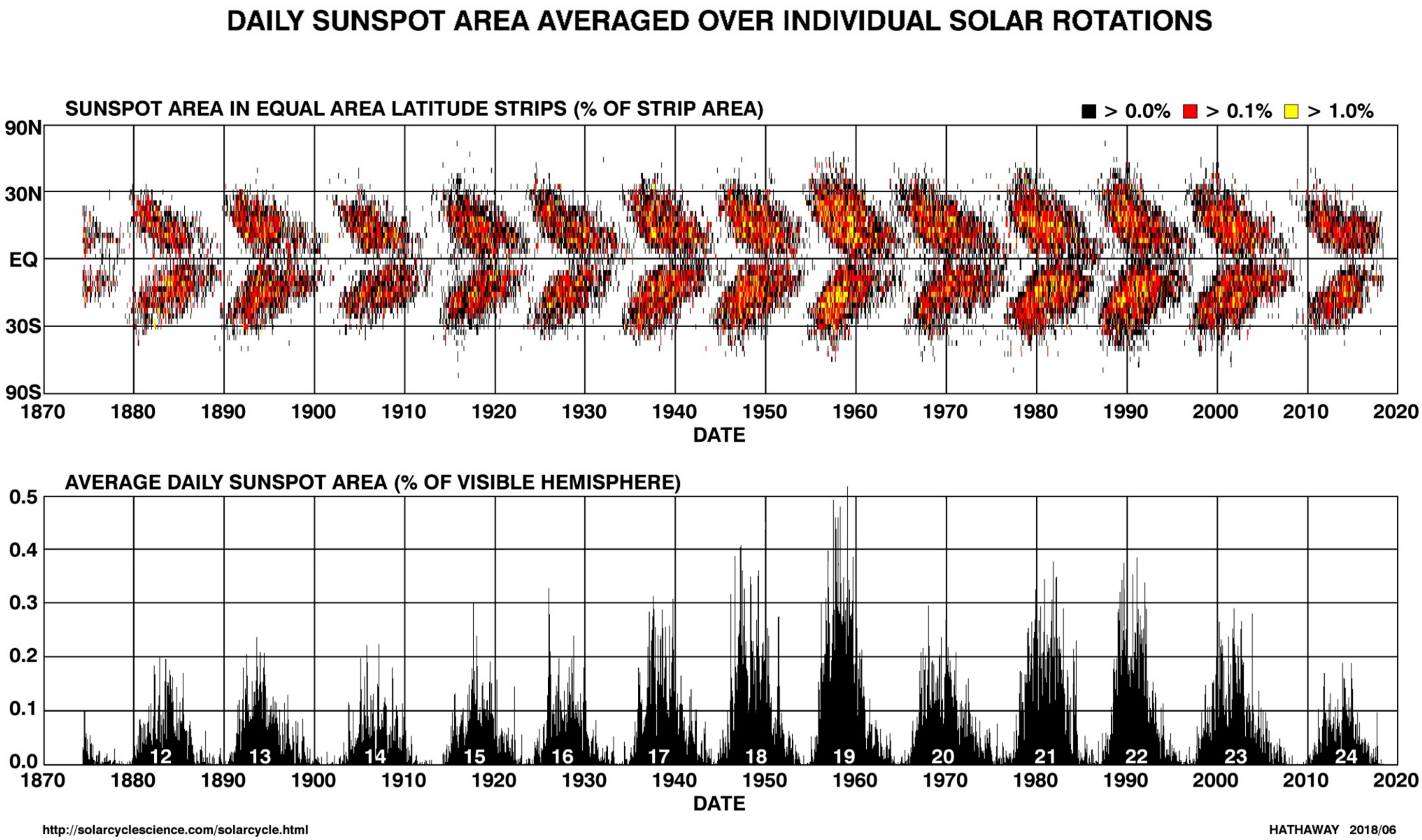
“Big” problems in solar physics

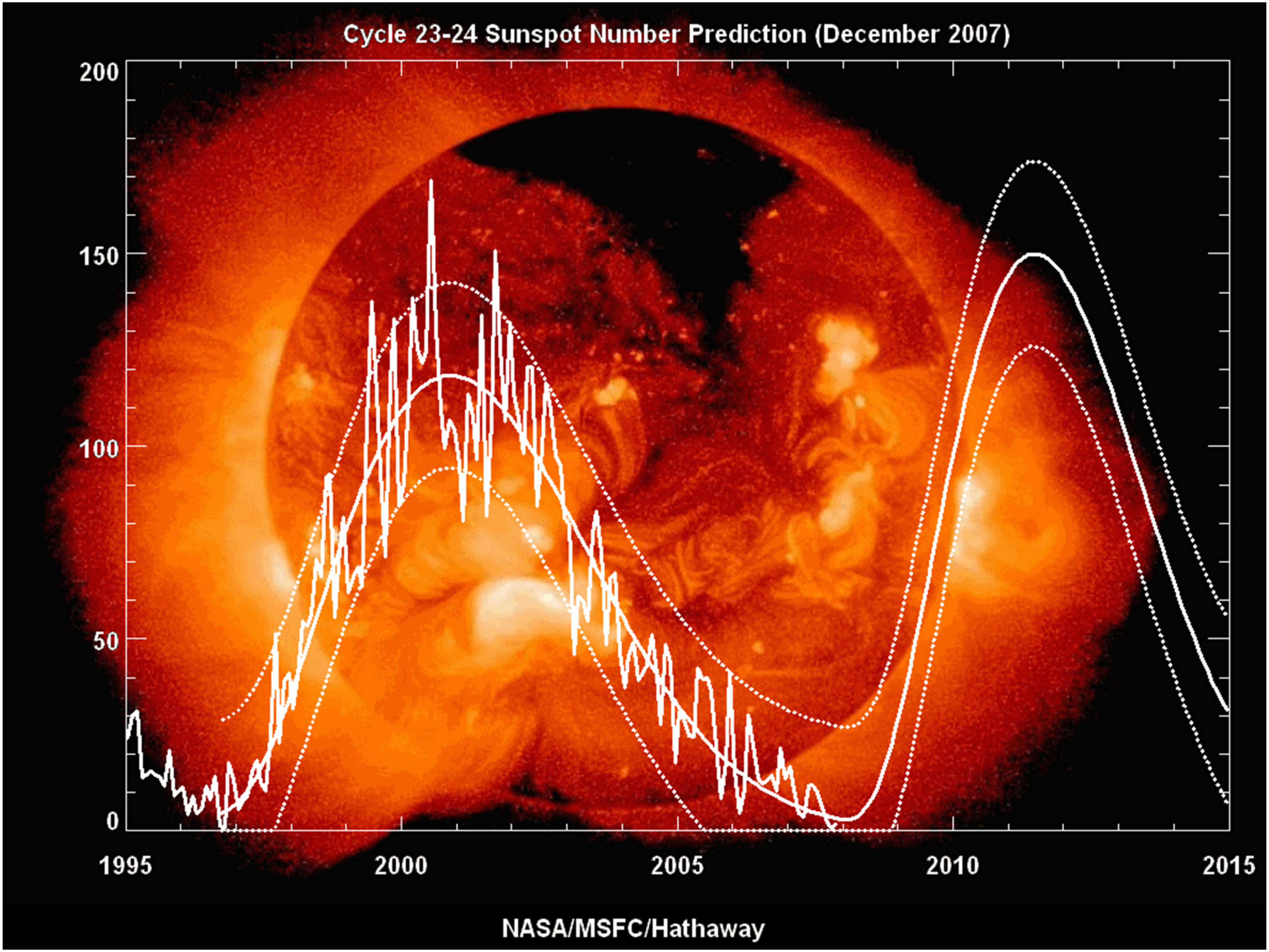
- Solar neutrino problem
- Solar cycle and dynamo
- Magnetic energy storage and release
- Particle acceleration
- Coronal heating
- Source of solar wind

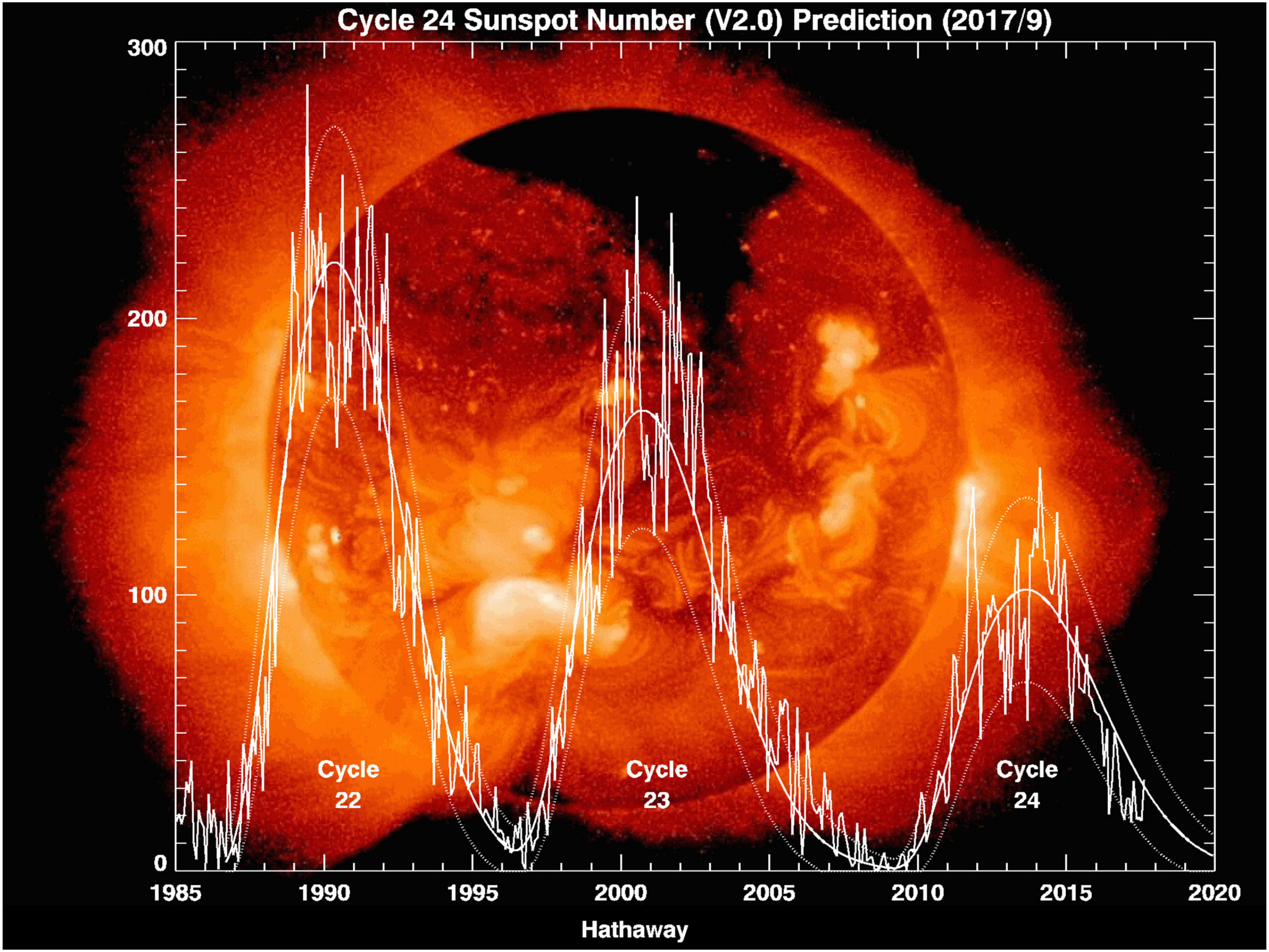
Solar Neutrino Problem



Solar cycle and dynamo

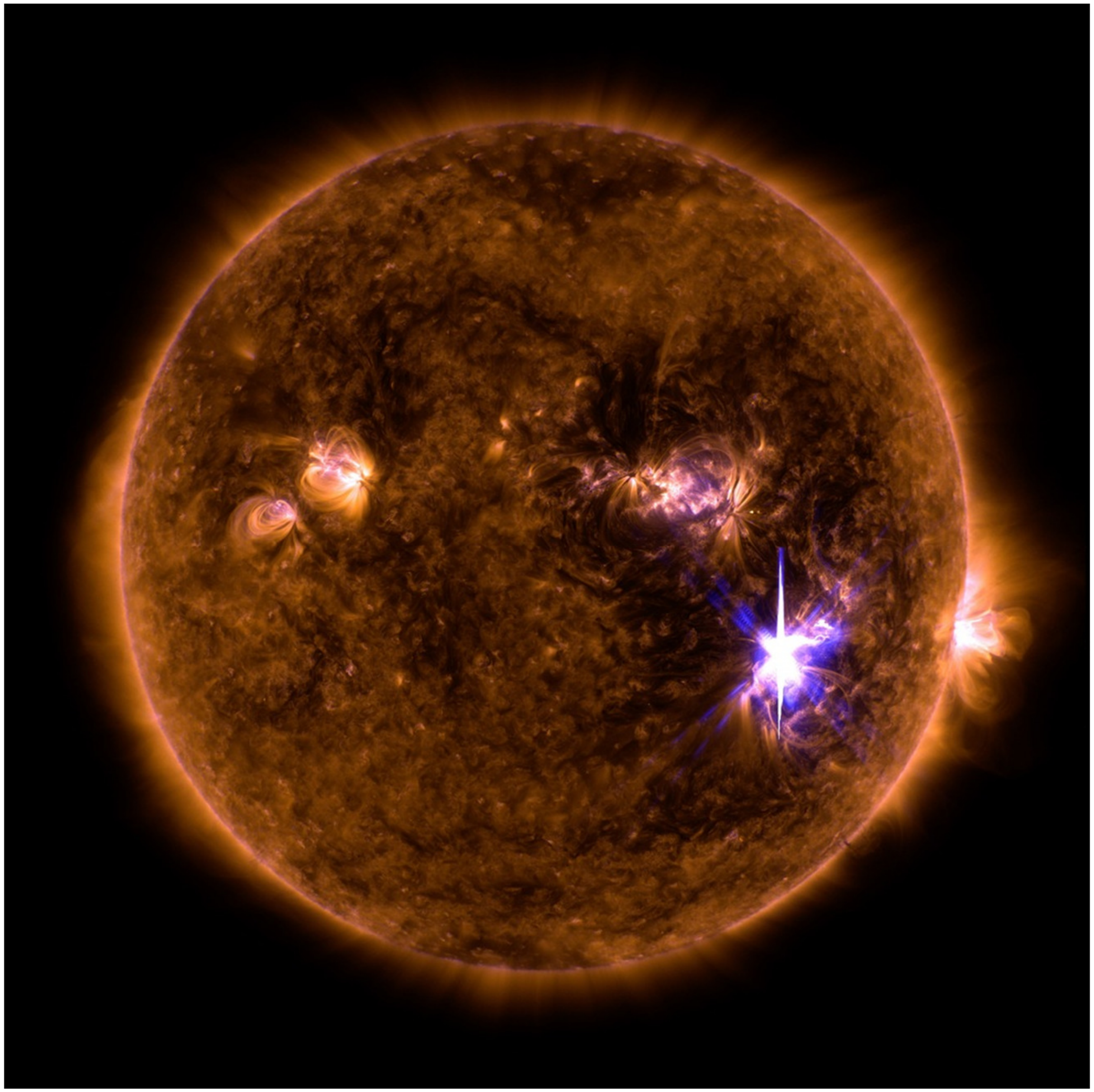



Cycle 23-24 Sunspot Number Prediction (December 2007)
200
150
100
50
0
1995
2000
2005
2010
2015
NASA/MSFC/Hathaway



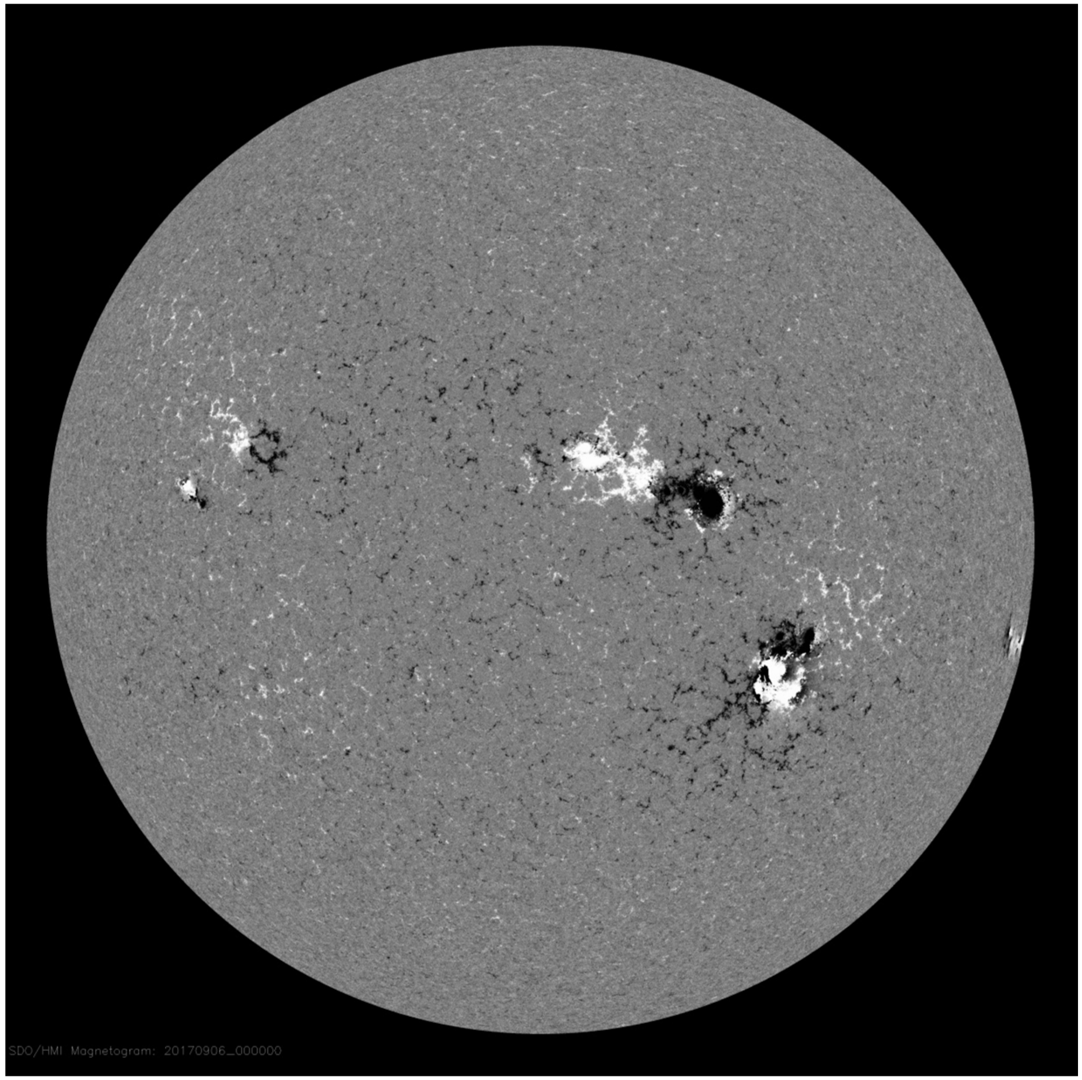
Cycle 24 Sunspot Number (V2.0) Prediction (2017/9)
300
200
100
0
1985
1990
1995
2000
2005
2010
2015
2020
Cycle 22
Cycle 23
Cycle 24
Hathaway

Magnetic energy storage and release

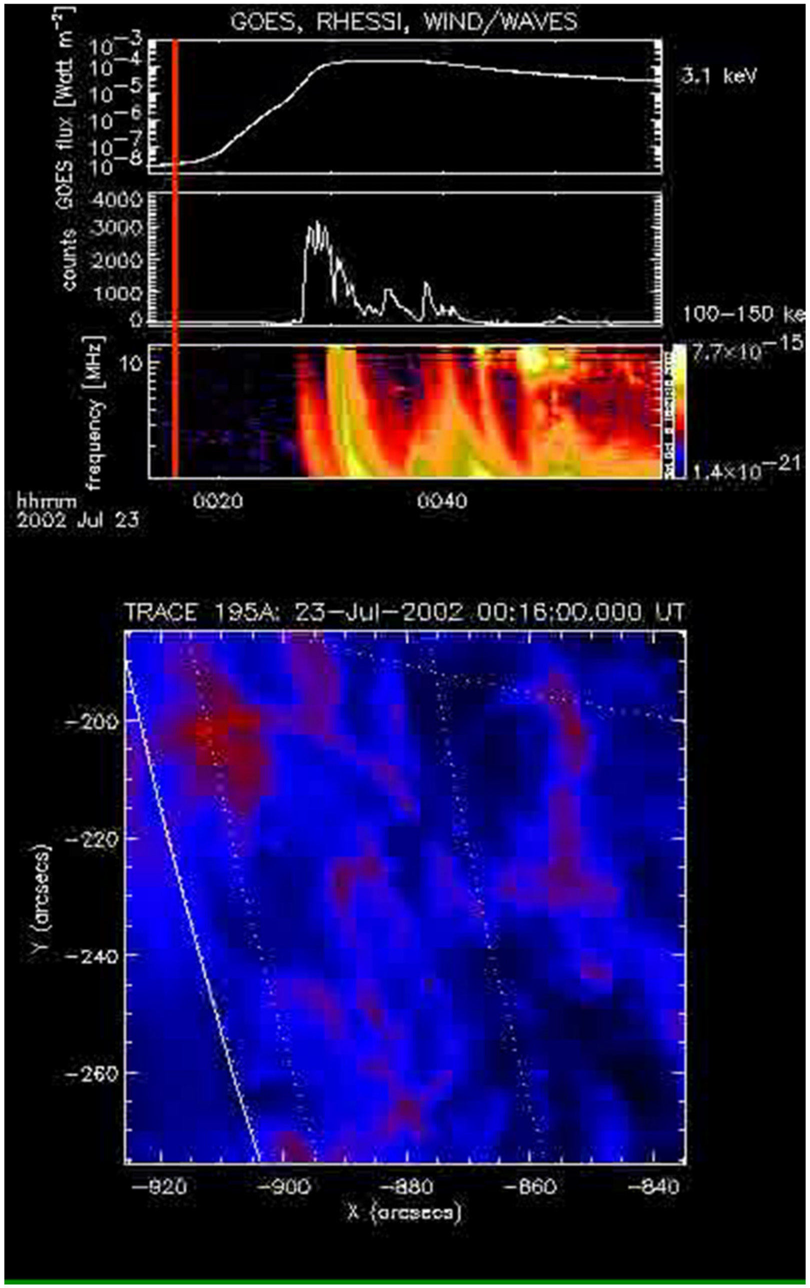


Sept 6, 2017

Magnetic energy storage and release

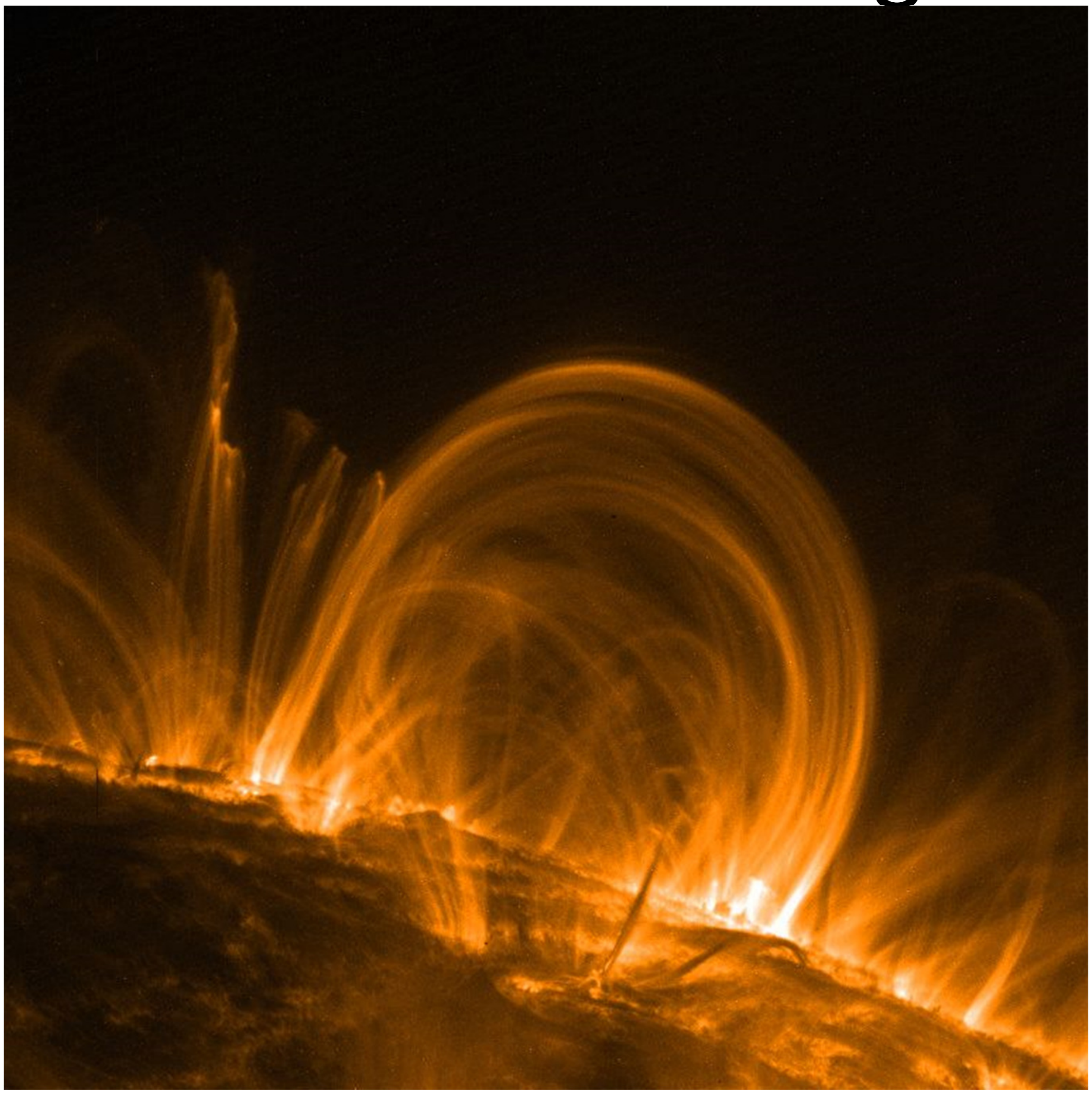


Particle acceleration

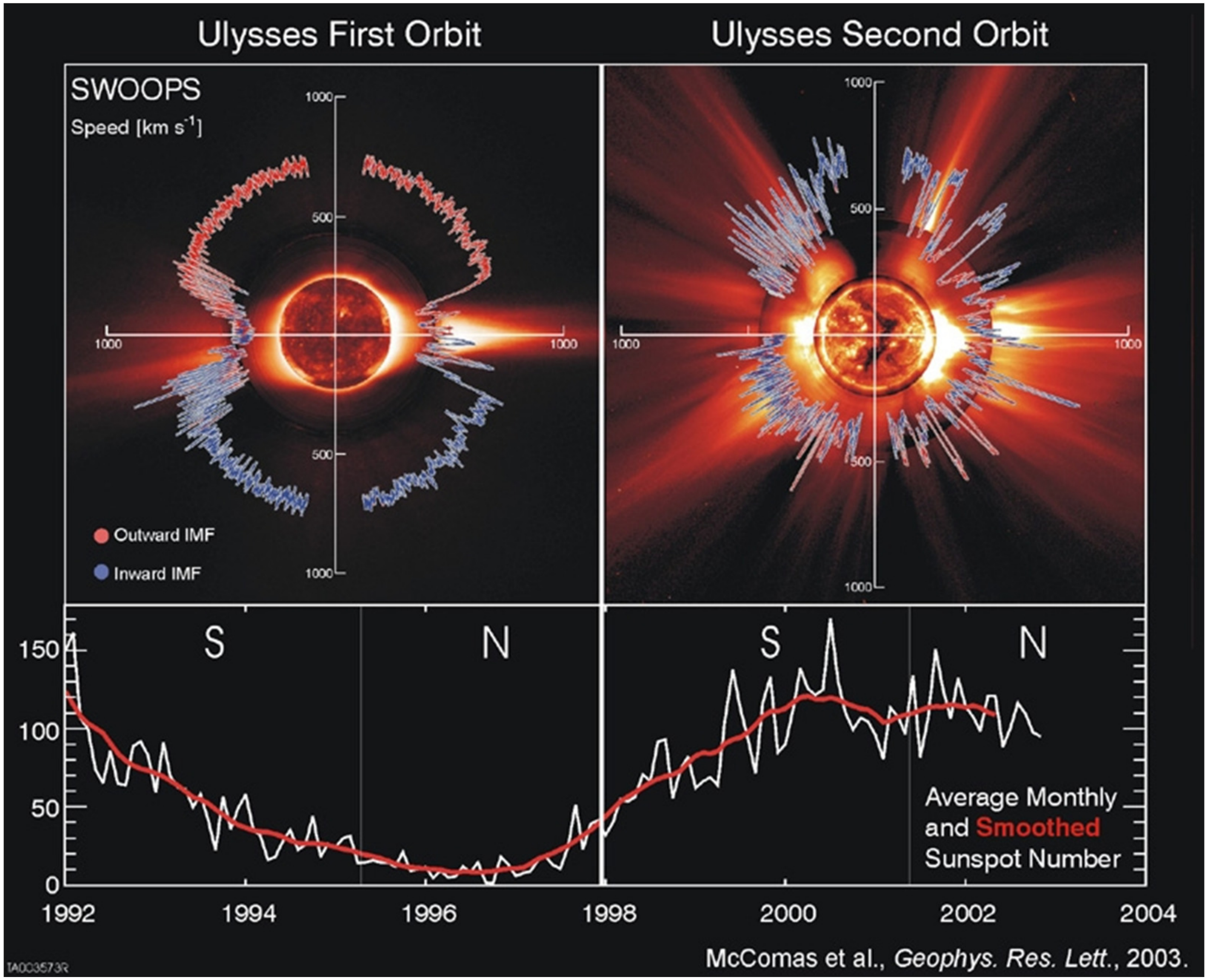


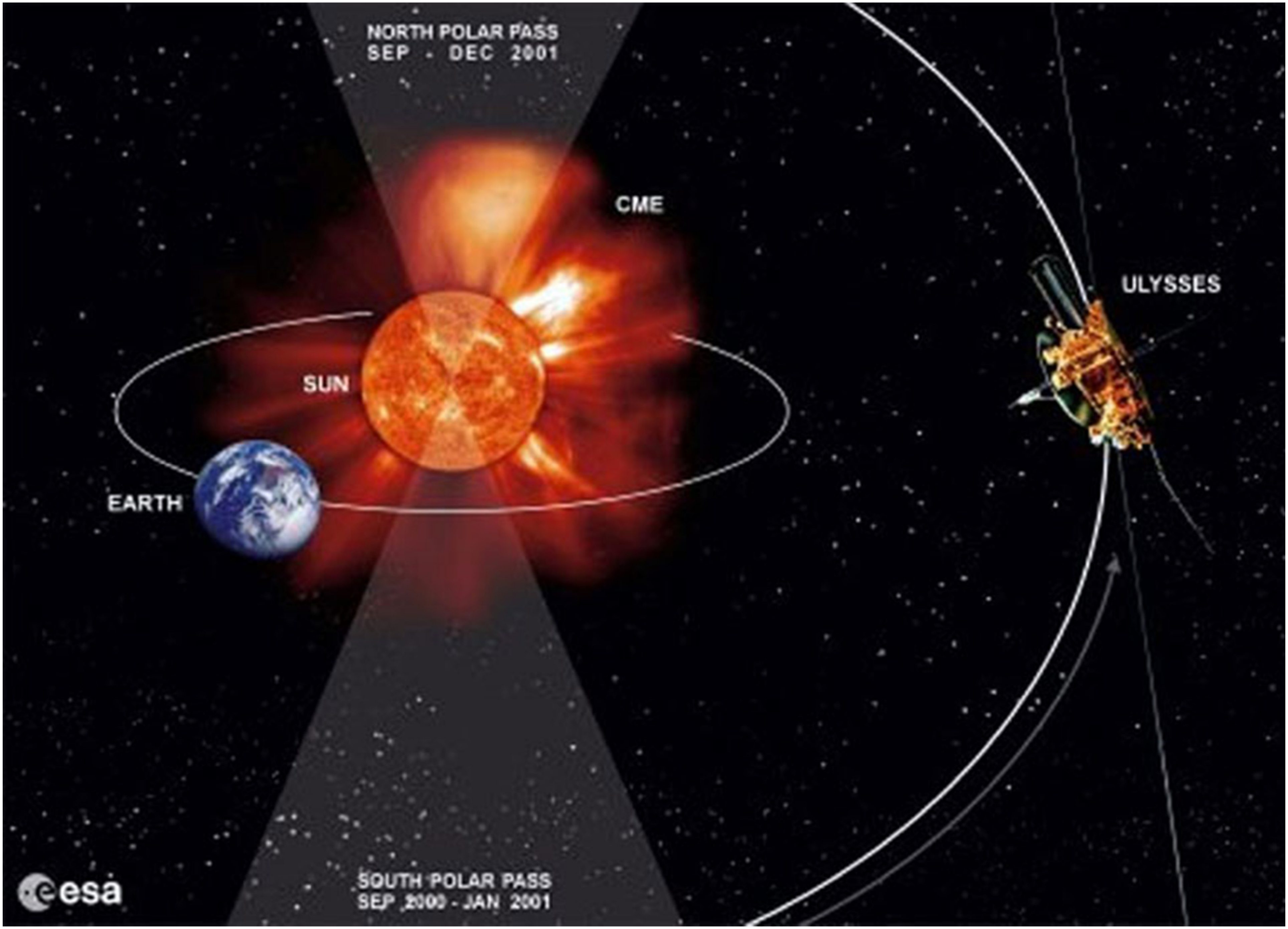
RHESSI observations of
July 23, 2002, flare
00:20-00:40 UT (RED: 12-20 keV,
BLUE: 100-150 keV)

Coronal heating



Source of solar wind




NORTH POLAR PASS
SEP - DEC 2001
CME
ULYSSES
SUN
EARTH
esa
SOUTH POLAR PASS
SEP 2000 - JAN 2001