SOLAR ACTIVITY PHENOMENA: 
OPEN QUESTIONS 
AND RECENT MODELLING

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Main Goal

Analysis of available models and data sets relevant to the modelling and prediction of solar activity

Study of phenomena occurring on the Sun which may have consequences on the Earth environment with the ultimate goal of predicting effects on the Earth
Logical scheme

- Description of the main characteristics of solar phenomena relevant to Space Weather
- Open questions relevant to these phenomena
- Model Classification
Solar Phenomena

- 11-Year Activity Cycle
  - Solar irradiance variability
  - IMF variability
- Active regions
  - Sunspots
  - Filaments
  - Loops
- Eruptive Phenomena
  - Flares
  - CME
- Solar Wind
11-Year Activity Cycle

What do observations show?

![Graph showing solar activity cycle](image1)

![Graph showing solar irradiance data](image2)

![Graph showing carbon-14 and sunspots](image3)

COST 724 Meeting
10-13 October 2005
Athens

Solar Activity Phenomena:
open questions and recent modelling

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11-Year Activity Cycle
11-year Activity Cycle

- The modulation of the IMF during the cycle influences the solar wind flux and the cosmic ray flux on Earth.
- The solar activity cycle modulates the TSI (climatic changes: ~30%).
- The variations of EUV flux during the cycle modulate the ozone formation in the Earth atmosphere.
11-year Activity Cycle: open questions

- The requirement of strong fields $O(10^5 \, G)$ near the bottom of the convection zone raises the question: how such strong fields can be generated?
- Why there are differences in the activity level from one solar cycle to another one?
- What causes the different periodicities?
- What causes the long minima periods (i.e. Maunder minimum)?
- Why is the IMF slowly increasing in time?
The connection between the solar interior and the atmosphere

Schussler 2005
Active regions in the solar atmosphere

18 Luglio 2003
What are active regions?
The result of the intersection of magnetic flux tubes with the solar atmosphere.
Active regions: what observations show about their formation and evolution

- The emergence of bundles of magnetic flux tubes in the solar atmosphere is at the basis of active region formation;
- During the first phases of AR formation, many physical processes are at work: magnetic coalescence, AFS formation, plasma downflows in rising flux tubes, decreasing upward velocities of the magnetic flux tubes, magnetic reconnection,.....
Active region formation: open questions

- Why the emergence of some flux tubes causes the formation of a fully evolved (recurrent) active region, while other flux tubes give rise to the formation of short-lived active regions?

- How long do the magnetic flux tubes remain anchored to the low-lying toroidal magnetic field?

- What causes the magnetic disconnection?

- What causes the different complexity of active regions?

- Why some active regions are more flare-productive than others?
Sunspots: observational evidences

- Sunspots are always located within active regions which, typically, have a bipolar magnetic structure.
- They follow the Hale polarity rule, the latitude belt rule (butterfly diagram) and the Joy’s law.
- The leading polarity often hosts the dominant sunspot.
- The time scale for the formation of a large sunspot is between a few hours and several days.
- When the diameter of a pore exceeds 3.5 Mm, it starts exhibiting a penumbral structure, but if it grows too rapidly, it remains a pore (but than it decays within one day).
- The penumbra grows in bursts, sector after sector.
Sunspots: open questions

- What is the subsurface structure of sunspots: monolithic or composed by smaller flux tubes?
- Which fraction of the heat flux blocked by sunspots is stored in the CZ and which fraction is immediately radiated elsewhere in the solar atmosphere?
- Why do sunspots have penumbra?
- Is there field-free material in sunspots?
- What drives the flow which produces the Evershed effect?
- How do sunspots decay? Do moving magnetic features carry off all the lost flux?
- What places an upper limit to the sunspot size?
- Why are leading polarity spots often larger than following polarity spots?
- How common is magnetic reconnection between sunspots and their canopies?
Sunspots: modelling and limits to modelling

- A realistic simulation of the complete evolution of a magnetic flux tube,
- starting from an instability at the bottom of the convection zone,
- covering the rise through the CZ,
- including the emergence at the surface,
- the further evolution of the emerged flux,
- is not feasible with present-day computational facilities (Schlusser, 2005).
Filaments: observational evidences

- Filaments are one hundred times denser and one hundred times cooler than the surrounding atmosphere
- They are located on the magnetic neutral line
- The magnetic configuration can be direct or inverse
- During their eruption they often show a helicoidal shape
Filaments: open questions

- How do they form?
- How can they be stable for days?
- What mechanism allows the formation of “magnetic islands” separated from the surrounding plasma (density and temperature difference)?
- What is the most efficient mechanism causing their destabilization?
- What is the role of magnetic helicity in their destabilization and eruption?
Coronal loops

- Coronal loops are the building blocks of the confined corona.
- They appear in quiet or active areas as bright, arch-shaped structures, connecting regions with intense magnetic fields and opposite polarities.
- They are hot ($10^6$ K) and have a thin transition to the chromosphere ($10^4$ K) near their footpoints.
- Each loop is dynamically and thermally insulated from the other loops and can be described as an independent region.
- Images acquired with increasing angular resolution show a higher number of thinner strands.
Coronal loops: open questions

- What are the detailed profiles of the plasma temperature, density and flow along the magnetic structures, particularly close to the loop footpoints and what is their behaviour as a function of time?
- Can coronal loops be described as single monolithic structures, or are they collections of hundreds or thousands of unresolved strands, each with its own independent dynamics?
- Where and how does the heating deposition occur in the loop plasma?
Heating of coronal loops by AC mechanisms

- AC mechanism (the associated time-scale is shorter than the typical dynamic timescale): dissipation of Alfven waves generated either by global loop oscillations, or by impulsive phenomena;
- The problem is how to move the wave energy to sufficiently small scales to be efficiently dissipated (resonant absorption, phase mixing);
- The presence of chaotic field lines increases the efficiency of this mechanism.
Heating of coronal loops by DC mechanisms

- DC mechanism or microflare heating: the heating is due to the motions of the photospheric footpoints of magnetic field lines which are continuously shuffled around by convective motions.
- These motions may lead to the formation of tangential discontinuities or current sheets in the corona where energy can be dissipated through magnetic reconnection.
- Two phases: a primary energy release at coronal level and a secondary one at chromospheric level (chromospheric evaporation).
Heating of coronal loops: open questions

• Is the heating localized in small parts of the loops or spread on a large part of it?
• Is the heating deposited at the footpoints or higher, in the coronal part of the loop?
• Or both?
• Is the heating transient or continuous?
Eruptive phenomena

• In the solar atmosphere it is possible to observe very rapid (from minutes to tens of minutes) eruptive phenomena:
  
• Flares
  
• Coronal Mass Ejections
SOLAR FLARES

- A solar flare is a sudden ($t_{\text{rise}} \sim$ few minutes), localized ($l \sim 10^6 - 10^8$ m), release of energy (from $10^{23}$ erg in nanoflares to $10^{32}$ erg in large two ribbon flares) during which magnetic energy is converted into radiation across the entire electromagnetic spectrum, heating, particle acceleration and mass motions.
Solar flares

- Solar flares are the most powerful explosions in the solar system
- Despite the remarkable step forwards made in the last decades, there are still many obscure points
- Radiation and particles emitted during flares may strongly interact with Earth ionosphere and magnetosphere
- They represent an optimal tool to understand the (several) physical processes involved in magnetic reconnection
• Compact or simple-loop flares, characterized by $L \sim 10^6 - 10^7$ m, $n_e \sim 10^{17} - 10^{18}$ m$^{-3}$ $E_{\text{tot}} \sim 10^{29} - 10^{31}$ erg. Generally occur in single loops whose shape and volume do not change significantly during the flare and do not present particles emission.

• Two ribbon flares occur in arcades and show two areas of emission on both sides of the magnetic inversion line. The strands separate at 5 –20 km/s while the prominence lying between them rises in the corona.
Solar Flares: open questions

- What is the most likely magnetic configuration in the pre-flare phase (sigmoids, high magnetic helicity, newly emerging flux)?
- Why is the energy released (magnetic reconnection)?
- Where is the energy released (current sheet dimension)?
- What happens after the energy is released?
- What fraction goes into heating, particle acceleration, mass motions?
- Which effects are directly related to the energy release itself and which to subsequent transport effects?
- Is the presence of EIT waves always related to associated CMEs?
CME

- CME are ejections of $10^{15} - 10^{16}$ g of mass from the Sun;
- they are often associated with flares and eruptive prominences;
- the mass is ejected with a speed between 100 - 2700 km/s;
- the occurrence rate varies with the 11-year cycle: 1/day at minimum vs. 6/day at maximum;
- a CME is a three-part structure, with a circular front surrounding a dark region, the cavity, with inside a core due to a bright, erupting prominence.
CME

• A CME can be due to the disruption of balance between the upward pressure of the strongly sheared large-scale magnetic field and the downward force due either to the magnetic tension or to the weight of an overlying mass distribution.

• Magnetic breakout when the tension is removed by reconnection of overlying and neighboring magnetic field lines

• Flux rope models, when magnetic reconnection occurs below the filament

• Mass loading, magnetic buoyancy leads to the collapse of the overlying mass
CME: open questions

- How are they initiated?
- How do they evolve?
- Different mechanisms accelerate fast (uniform or decelerating speed) and gradual (accelerating speed) CME?
- Are the coronal dimmings due to density depletion or to temperature variations?
- How are coronal EIT waves related to chromospheric Moreton waves?
Solar Wind

- The fast solar wind (800 km/s) presents a 27-day periodicity, indicating the origin in a localized solar source: a coronal hole;
- The interaction of the low latitude fast streams with the Earth magnetosphere causes a recurrent magnetic disturbance.
At solar minimum the fast wind at 800 km/s fills most of the heliosphere, whereas the slow wind at 400 km/s is confined toward the low latitude regions; with increasing solar activity the slow wind becomes predominant and the heliosphere is more symmetric, with a highly variable solar wind speed. The helium abundance varies through the cycle showing a correlation with the wind speed.
At the base of the corona the solar wind is emanating from regions along the boundaries of the magnetic networks;
The highest acceleration of the solar wind emanating from the polar coronal holes at solar minimum occurs between 1.6 and 2 solar radii.
UVCS has shown that heavy ions move faster than protons and are more effectively accelerated across the magnetic field (O VI).
Elements with FIP < 10 eV appear to be more abundant (role of B ?)
Solar wind: open questions

- What are the mechanisms that heat the coronal holes and accelerate the fast wind?
- Where, within the coronal holes, does the solar wind originates? (Plumes or interplumes)
- Where is the slow wind accelerated and what is the mechanism that accelerates it?
Solar Models

- **Zero Order Model:**
  Solar Standard Model

- **First Order Models:**
  1. Models concerning the Solar Interior
  2. Models concerning the Quiet Atmosphere
  3. Models concerning the interaction between the Magnetic Field and the Solar Plasma
Models concerning the Solar Interior

- **Solar Interior**
  - Nuclear reactions (EM emission, solar neutrinos)
  - Oscillations (causality, modality, detectability)
  - Solar Differential Rotation (Interaction between Rotation and Convection)
  - Convection (Giant cells, supergranules, granules)
Models concerning the solar atmosphere

- **Solar Atmosphere**

  - Models of the quiet atmosphere (density and temperature stratification)
  - Granulation
  - Photospheric turbulence
  - Chromospheric and Coronal heating
  - Coronal expansion into the interplanetary space to form the heliosphere
Interaction between Magnetic Field and Solar Plasma

- Solar Dynamo (change in the magnetic field configuration: poloidal ↔ toroidal)
- Active Region Formation and Evolution
- Loop stability and heating
- Eruptive Phenomena (flares, CME)
- Solar Wind modulation and acceleration
Second order models

- Potential, linear force-free, non-linear force-free magnetic field, non force-free magnetic field
- Slender flux tube model (one-dimensional approximation)
- $\Omega$-loop model (two- or three- dimensional approach)
- Loop models (static, stationary, MHD)
- Magnetic reconnection modelling
- Magnetic helicity input
- Magnetic break-out model vs. low reconnection model
- Thick vs. thin target models
- Chromospheric evaporation
- .............
Sunspots: Modelling

- Models of sunspots are of very diverse types and aim to either
  - reproduce observed properties of sunspots,
  - or to understand the physical processes occurring in them.
Sunspots: type of theoretical models

- Numerical codes, usually idealized simulations of some physical process, such as magnetoconvection, presumed to act in the magnetic feature
- Static description of symmetric flux tubes that aim to reproduce the global observed properties of sunspots
- Simplified descriptions of dynamic phenomena in (or around) sunspots
- Full-fledged simulations including time-dependence, compressibility, partial ionization, radiative transfer, 2- or, ideally, 3-dimensionality, a fine spatial and temporal grid and a sufficiently large computational domain
Sunspot models: some examples

- Self-similar models (radial dependence of B is the same at all heights) or Schluter - Temesvary models
- Force-free and potential field models
- Models with current sheet
- Models without current-sheet
Avakyan: Space Solar Patrol → solar activity and flare monitoring (X and EUV);
Hochedez: Flare Nowcast and Forecast
Kretzschmar: Retrieving the Solar X/EUV irradiance from a few line.
Maksimov: Flare forecasting → analysis and interpretation of solar radio data
Messerotti: Analysis of solar radio events and flare radio precursors
Stanislawska: Forecast of Sudden Ionospheric Disturbances by using the spectrum of XUV burst
Steiner: radio observations of solar flares
Zigman: Effects of solar flares on the propagation of VLF radio waves in the ionosphere: data analysis and model
Zuccarello: Solar flare analysis and forecasting (optical and EUV ranges); Active region emergence and evolution