INTRODUCTION TO HELIOPHYSICS

Course Description

This course is intended to provide master's students from the Faculty of Physics of the University of Bucharest with a comprehensive introduction into the physics of the Sun and the heliosphere (the space permeated by the solar wind), which is also known as *heliophysics*. Over time, solar physics has evolved over three distinctly different phases using progressively more sophisticated observing tools. The first phase of naked–eye observations that dates back over several thousands of years has been mainly concerned with observations and reports of solar eclipses and the role of the Sun in celestial mechanics. In the second phase, which lasted about a century before the beginning of the space era, ground-based solar–dedicated telescopes, spectrometers, coronagraphs, and radio telescopes were built and quantitative measurements of solar phenomena were made to probe the basic geometric and physical parameters of the Sun. During the third phase, which started with the beginning of the space age around 1950s, we launched dedicated spacecraft to explore the Sun and interplanetary space in all possible wavelengths and particle energies. These missions conveyed to us high-resolution images and spectral measurements that allowed us to conduct quantitative physical modeling of solar and heliospheric phenomena, supported by numerical simulations using the theories of magnetohydrodynamics and plasma particle physics. This was the time when the omnipresent solar wind was discovered — in 1959 by Soviet satellite Luna 1 — which marked the beginning of heliophysics. Ever since, *heliophysics has been focused on understanding the phenomena occurring in interplanetary space — driven by processes at the Sun — as the solar wind slows down and terminates at the boundary of the solar system, the termination shock*.

This course focuses on the new physical insights in solar and heliospheric physics that have mostly been obtained from the last decade of ground and space missions, such as from soft X–ray observations with Yohkoh, extreme–ultraviolet (EUV) observations with SoHO, TRACE and SDO, hard X–ray observations with Compton and RHESSI, a great variety of radio observations, in–situ observations with Ulysses, ACE, Wind, etc. These various remote sensing and in–situ observations have been inspiring frontier efforts in theoretical and numerical modeling of the observed phenomena by solar and heliospheric researchers worldwide. The course will also put emphasis on newly emerged sub–fields of solar physics, such as helioseismology and high–energy solar physics, which further our knowledge of the solar interior and dynamic processes in the solar atmosphere, respectively.

The last 16 years (1995–2011) have been the most exciting era in the exploration of the solar interior, solar atmosphere, and solar wind in a wide range of wavelengths and particle energies, thus producing unprecedented stunning pictures, movies, and high–precision spectral and temporal data. It has gradually become clear to solar scientists that much of the observed structure owes its existence to the Sun's magnetic field. This major discovery brought new insights into the detailed structure of the solar interior, solar atmosphere, solar wind and their coupling. These physical insights further our basic understanding of how (i) solar magnetic fields are generated and evolve in the solar atmosphere and interplanetary space, (ii) solar corona is heated, (iii) solar wind is powered, (iv) magnetic instabilities lead to flares, (v) coronal mass ejections are triggered, (vi) charged particles are accelerated at the Sun and its vicinity, among other important physical processes. Furthermore, the course discusses in length the solar and heliospheric impact on the terrestrial magnetosphere dynamics. Last but not least, the course also makes the solar–stellar connection, thus enabling students to apply the gained knowledge in solar and heliospheric physics to studies of other Sun–like stars and their winds.

The principal philosophy and approach of this introductory course in heliophysics is to convey a physics introduction course to a selected topic of astrophysics, rather than to provide a review of observational material. The material is therefore not described in historical, phenomenological, or morphological order, but rather structured by physical principles. In each lecture, I will outline the basic physics of relevant models that explain particular solar-heliospheric phenomenon. I will include in each lecture analytical and numerical model calculations that have been applied to the observed phenomena, and I will show comprehensive data material that illustrate the relevant models and physical interpretations. I will provide students with basic introduction to magnetohydrodynamics, plasma physics, and physics of charged particle motion that is needed to understand the basic solar-heliospheric phenomena. This course is intended to be an up–to–date journey into the physics of the Sun and the heliosphere suitable for master or graduate students majoring in physics or astrophysics.

Contents of the Course

(Note: each lecture is 75 minutes)

1. Introduction (1 lecture)
    - Sun as a star
    - Solar observations: past, present, and future
    - Historic evidence for solar variability
    - Overview of structure of Sun and heliosphere
2. Solar Interior I (1 lecture)
    - Nuclear energy generation in solar interior
    - Solar neutrino: theories and experiments
    - Equation of state and opacity
    - Standard hydrostatic models of solar interior
    - Mixing in radiative zone
3. Solar Interior II (1 lecture)
    - Convection zone
    - Element separation by atomic diffusion
    - Solar dynamo
4. Helioseismology (1 lecture)
    - Observations of surface oscillations
    - Theory of oscillation mode excitation: the inversion problem
    - Internal rotation and magnetism of the Sun inferred from its oscillations
5. Photosphere (1 lecture)
    - Surface radiation and its relation to solar interior
    - Granulation pattern
    - Magnetic fields
    - Physical models
6. Chromosphere (1 lecture)
    - Basic morphology
    - Physical models
    - Spicules: are they the footprints of the solar wind?
7. Corona (1 lecture)
    - Observations from ground and space
    - Basic properties: plasma state, radiation, and magnetic fields
    - Structure and dynamics of "quiet" and active Sun
    - Outstanding problems
8. Transient Features (1 lecture)
    - Active regions: development, structure, and internal motions
    - Sunspots: development and structure
    - Prominences: development, structure, and destabilization
    - Solar flares: basic description, ground- and space-based observations
    - Coronal mass ejections (CMEs): relation to flares and prominence destabilization
9. Basic Principles of Solar Magnetohydrodynamics (MHD) (1 lecture)
    - Electromagnetic equations: Maxwell's laws, Ohm's law, & induction equation

- Plasma equations: mass continuity, equation of motion, and perfect gas law
- Energy equations: forms of heat equation, radiation, heating, and energetics
- Consequences of induction equation: diffusive limit versus perfect conducting limit

10. Magnetohydrostatics (1 lecture)
    - Plasma structure in prescribed magnetic field
    - Structure of magnetic flux tubes: axial fields, azimuthal fields, and force-free fields.
    - Current sheets: formation and stability properties
    - Potential fields: description and properties
    - Force-free fields: description and properties
11. Sun's Magnetic Fields (1 lecture)
    - Observations from ground and space
    - Magnetic field in active region corona
    - Magnetic helicity: description, properties, and evolution
    - Basic features of magnetic topology: (quasi–)separatrix surfaces, nullpoints, spines, fan surfaces, separators, etc.
12. Magnetic Reconnection (1 lecture)
    - Overview of magnetic reconnection as universal physical process
    - Steady two-dimensional reconnection: Sweet–Parker and Petschek models
    - Unsteady/bursty two–dimensional reconnection
    - Magnetic reconnection in three–dimensional geometry
    - Examples of reconnection on the Sun: flares and CMEs
    - Examples of reconnection in the Earth's magnetosphere
    - Laboratory experiments of magnetic reconnection
13. MHD Oscillations (1 lecture)
    - Dispersion relation of MHD waves
    - Fast kink–mode and sausage–mode oscillations
    - Slow–mode (acoustic) oscillations
    - Damping of MHD oscillations: key to derive transport coefficients in solar atmosphere
14. Propagating MHD Waves (1 lecture)
    - MHD waves in closed coronal loops
    - MHD waves in open field lines of solar corona
    - Global waves
    - Damping of MHD waves: relation to coronal heating
15. Shock Waves (1 lecture)
    - Shock formation and its effect on magnetic field
    - Properties of hydrodynamic and MHD shocks: Rankine–Hugoniot relations
    - Perpendicular versus parallel shocks
    - Oblique shocks: switch–off shock, switch–on shock, and intermediate (Alfvén) wave
    - Implications for acceleration of charged particles
16. Heating of the Solar Atmosphere (1 lecture)
    - Heating energy requirements and overview of coronal heating models
    - DC heating models
    - AC heating models
    - Observations of heating events
    - Scaling laws and statistics of heating events
17. Solar Flares (1 lecture)
    - Coronal flare plasma heating
    - Chromospheric flare plasma heating
    - Chromospheric evaporation
    - Flare loop cooling
18. Coronal Mass Ejections (CMEs) I (1 lecture)
    - Summary of CME observations
    - Pre–CME conditions and magnetic geometries

- Theoretical concepts of CMEs
- Numerical MHD models

19. Coronal Mass Ejections (CMEs) II (1 lecture)
    - Density and temperature structure of CMEs
    - Dynamics of CMEs in low corona
    - Energetics
    - Interplanetary propagation: shock waves, radio bursts, particle acceleration at propagating CME shocks
20. Particle Acceleration (1 lecture)
    - Overview of particle acceleration mechanisms
    - Electric DC–field acceleration
    - Stochastic acceleration
    - Diffusive shock acceleration
    - Observations of charged particle acceleration near the Sun and in the heliosphere
21. High–Energy Solar Physics (1 lecture)
    - Overview of observations: SMM, Yohkoh, Hinode, RHESSI
    - Solar corona in soft and hard X–rays
    - Gamma–ray observations
    - Implications for coronal heating and solar flare models
22. Solar Wind and Its Coronal Origins (1 lecture)
    - Observations of bimodal nature: fast (steady) solar wind and slow (turbulent) solar wind
    - Models of solar wind acceleration
    - Helmet streamers and coronal holes
    - Interplanetary magnetic field: Parker spiral
    - Solar wind impact on the terrestrial magnetosphere
    - Corotating interacting regions (CIRs)
23. Heliosphere (1 lecture)
    - Basic structure of the heliosphere
    - Interaction of solar wind with local interstellar medium (LISM)
    - Physical processes at the termination shock: origin of anomalous cosmic rays (ACRs)
    - Study of LISM from within the heliosphere: pick–up ions and energetic neutral atoms
24. Our Sun, Other Suns, Other Stars (1 lecture)
    - Sun–as–a–star spectrum variability
    - What can other stars tell us about the Sun?
    - Magnetic variability of Sun–like stars
    - Post–main–sequence solar evolution

References

1. M. Aschwanden (2004), *“Physics of the Solar Corona: An Introduction”,* Ed. P. Blondel, Springer–Verlag (Berlin, Germany).
2. A. N. Cox, W. C. Livingston, and M. S. Matthews (1991), *“Solar Interior and Atmosphere”,* University of Arizona Press (Tucson, AZ, USA).
3. N. Gopalswamy, R. Mewaldt, and J. Torsti (2006), *“Solar Eruptions and Energetic Particles”,* Geophysical Monograph 165, AGU Books (Washington, DC, USA).
4. E. R. Priest (1982), *“Solar Magnetohydrodynamics”,* Ed. B. M. McCormac, Reidel Publishing Co (Dordrecht, Holand).
5. E. R. Priest and T. G. Forbes (2000), *“Magnetic Reconnection: MHD Theory and Applications”,* Cambridge University Press (Cambridge, UK).