Physics of Exoplanets: syllabus

Only nine planets were known before 1995, the ones orbiting our favourite star, the Sun, which then included Pluto. Twenty years later, we have «lost» Pluto but we have gained two thousands planets in orbit around other stars. Current statistical estimates indicate that, on average, every star in our Galaxy hosts at least one planetary companion, i.e. our Milky Way is crowded with one hundred billion planets!
The most revolutionary aspect of this young field is the discovery that the Solar System does not appear to be the paradigm in our Galaxy, but rather one of the many possible configurations we are seeing out there. These include planets completing a revolution in less than one day, as well as planets orbiting two stars or moving on trajectories so eccentric as to resemble comets. Some of them are freezing cold, some are so hot that their surface is molten. How do we progress from here?

This course is aimed at providing a comprehensive view of the nature of exoplanets, through an integrated approach covering observations, data analysis and interpretation. Finding out why are these new worlds as they are is one of the key challenges of modern astrophysics.

Lectures notes and suggested reading material will be provided during the course. The lectures will be audio-recorded. I have taught this course at UCL in the spring 2017 and in the spring 2018, during 30 hours of teaching and hands-on tutorials.

Introduction to Extrasolar Planets

- General information about the course – teaching hours, planned courseworks, course overview.
- First discoveries, statistics, current knowledge of the field.

Techniques to discover new exoplanets

- Radial velocity
  - Hands-on tutorial with analysis of real data (including multiple planets systems, Rossiter–McLaughlin effect)
- Transit and TTV
  - Hands-on tutorial with analysis of real data
- Astrometry
- Microlensing
  - Hands-on tutorial with analysis of real data
- Direct imaging
  - Hands-on tutorial with analysis of real data
- Pulsar timing
- Current and future observatories to discover new planets with various techniques

Planet interior

- Bulk composition derived from mass-radius diagrams, degeneracies and open questions (e.g. hot-Jupiters' radius anomaly)
- Current models for different planetary types (Earths, super-Earths, sub-Neptunes, Neptunes & gas giants)

Planet formation & disk-planet interaction

- Current understanding of star and disk formation
  - Initial mass function, understanding of filaments from Herschel, accretion from disks to stars, T-tauri stars, jets...
- Disk structure and chemistry
  - Observational evidence from ALMA and VLT-SPHERE: gaps and spirals.
- Current theories for the formation of giant planets and observational evidence
  - Core accretion and gravitational instability models, pebble accretion.
- Current theories for the formation of smaller planets (Earths, super-Earths, sub-Neptunes) and observational evidence
- Planetary migration: basic mechanisms and types (Type I, Type II)
- Orbital stability, resonances, tidal locking
- Formation and history of the Solar System: observational evidence

Exoplanetary atmospheres

Current theories about atmospheric composition and dynamics of exoplanets

- Primordial and evolved atmospheres (impact of escape processes, volcanic activity, collisions with other bodies, life)
- Condensates at different temperatures, sequestration.
- Equilibrium and non-equilibrium chemistry (role of dynamics, stellar radiation, temperature, elemental composition)
- Similarities and differences with brown dwarfs and Solar System planets

Techniques to observe the chemical composition and thermal structure of exoplanet atmospheres

- Transit and eclipse spectroscopy
  - Hands-on tutorial with analysis of real data
- Eclipse mapping, orbital phase curves and high-dispersion spectroscopy
- Direct imaging spectroscopy
  - Hands-on tutorial with analysis of real data
- Brief introduction to advanced signal processing techniques to remove instrument systematics and stellar activity
  - Tutorial on machine learning techniques
- Current and future observatories: expected experiments and discoveries.

Remote sensing techniques using emitted, transmitted and reflected light at multiple wavelengths

- Radiative Transfer Equations for three-dimensional inhomogeneous media and approximated solutions for Plane-Parallel atmospheres
- Infrared remote sensing of vertical thermal structure and molecular abundances. Weighting functions.
- Light scattering by particulates (Lorenz-Mie approximation, Geometric Optics) and their impact in emitted, transmitted and reflected spectra
- The importance of opacities (line-lists, cross sections)
  - Tutorial on molecular spectroscopy for students who did not attend any previous course on this topic (optional)
- Degeneracies embedded in transit, eclipse/direct imaging spectra

- State of the art spectral retrieval models to interpret exoplanet spectra based on Bayesian techniques.
    - Tutorial on Baysian techniques for students who did not attend any previous course on this topic (optional)

Biosignatures and habitability

Current knowledge and speculations, future plans.