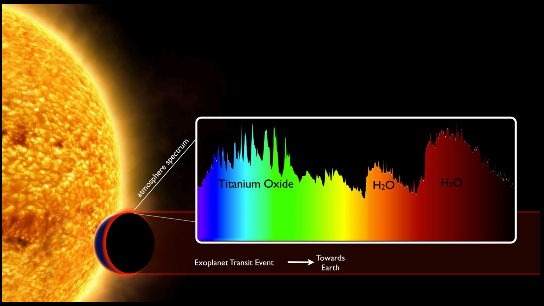
Exoplanet characterization

Atmospheres, Internal Structure and Evolution of Exoplanets and their Parent Stars



SUMMARY.
Exoplanets are new windows into our Universe. We want to know what they are made of, how they were formed and ultimately whether they may harbor life. Characterizing exoplanets i.e., measuring their physical parameters and atmospheric properties to infer their structure and composition is key. They are part of systems including one or several stars and therefore the combined evolution of stars and planets is essential to learn more about these objects. We propose a course that combines expertise on stellar and planetary atmospheres, structure and evolution with the goal to characterize exoplanets and their parent stars.

OBJECTIVES

- The students will learn the physical principles behind the internal structure, atmosphere and evolution of stars and planets. Both standard and modern concepts will be presented.

- Theoretical and numerical approaches are proposed : The first part will be dedicated to the derivation of the fundamental equations and the understanding of the general concepts in the fields of stellar physics and planetology. With this background, the students will have the opportunity to use state-of-the-art numerical codes based on these principles to approach current hot topic problems in exoplanetology and interpret recent observed data.

PREREQUISITES

The only requirement for this course is the S2 Fundamental Course: Stellar Physics.

THEORY

by T. Guillot, O. Creevey, A. Chiavassa, L. Bigot

- **Basics of stellar evolution (O. Creevey, L. Bigot).**

  Classical Stellar Evolution: Main equations of radiative hydrostatic equilibrium, energy transport, equations of state (EOS), opacities to understand the HR diagram. Topics on determining planet-host parameters (radius, mass, age). Exploration of the properties with age.

  Modern developments: Limb darkening, granulation, stellar cycles, rotation, winds. Consequences for the detection and characterization of transiting exoplanets.

- **Basics of planet evolution (T. Guillot)**

  Classical Planetary Evolution: Solid & gas planets, importance of EOSs, atmospheric boundary conditions, importance of stellar irradiation. Evolution, heat transport, an HR diagram for gaseous planets.

  Modern developments: Atmospheric dynamics, tides, Ohmic dissipation.

- **Basics of exoplanet atmospheres (A. Chiavassa)**

  Classical Planetary atmospheres: Analytical solution models of planetary atmosphere: radiative hydrostatic equation, concept of radiative equilibrium, Eddington approximation.

  Modern developments: greenhouse effects, stellar contamination. definition of habitability. Recap of line transfert, molecular formation. Transmission spectroscopy. Line detection by cross-correlation techniques.

APPLICATIONS

by L. Bigot, A. Chiavassa, O. Creevey, T. Guillot, R. Ligi

Hands-on course: The students will learn how to use the stellar and planet evolution codes CESAM and CEPAM. This will give the the ability to predict physical parameters as a function of input mass, composition and age. They will first calculate evolution tracks for the Sun and for Jupiter. They will test how a change in atmospheric boundary condition (e.g., including irradiation for a hot Jupiter) affects the evolution.

The students will then perform individual projects based on recent research in the fields of stellar evolution and exoplanet research. Possible topics are:

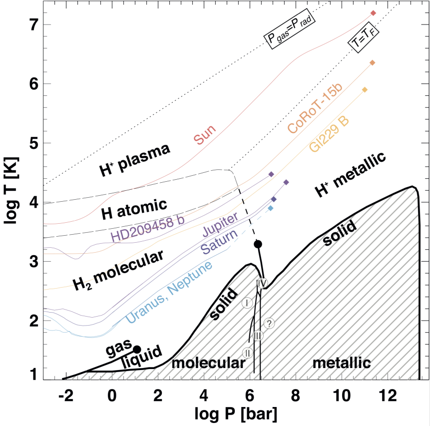
Quantify the inflation of hot Jupiters: Giant exoplanets very close to their parent stars (hot Jupiters) are found to be on average larger than predicted by standard evolution models. Using CEPAM and comparing with existing observations, the student will quantify the effect and test possible solutions (tides, ohmic dissipation, warmer atmosphere...).

Measure planetary core sizes: Some giant exoplanets are denser than average. This may indicate the presence of a dense central core. Using CEPAM and existing observations, the student will calculate possible core mass values for these exoplanets.

Determine an exoplanet's parameters: Given interferometric observations of the host star and the light curve of a transit, the student will use the data analysis tools to extract the stellar radius and the transit depth, hence derive the planetary radius. A deeper analysis of the lightcurve, combined with radial velocity data, should provide the stellar density, hence mass, and the probability density function of the planetary mass and radius. Using the stellar spectral energy distribution and parallax, its luminosity, temperature, and age could be obtained. The nature of this exoplanet can then be discussed.

Combined star and planet fit: Star and planets have properties that change simultaneously with age. To understand the evolution of the system, both stellar (CESAM) and planetary (CEPAM) evolution codes will be used to reproduce multiple observational data relative to the host star and, using existing data analysis tools and hand made procedures, will extract the radius, mass, density, age, temperature of the star and the planet. Special attention will be given to the uncertainties and the correlations among the parameters.

Analysis of exoplanetary atmospheres: The project consists in an analysis of near-infrared high-resolution data of exoplanet atmospheres. The student will compute synthetic molecular spectra, as observed by the CRIRES spectrograph at the Very Large Telescope, and will develop a standard analysis process to remove the instrumental and telluric (i.e., related to the Earth atmosphere) effects while preserving the planet signal. A cross-correlation technique will be used to magnify the planet signal.



Hydrogen phase diagram. Interior temperature-pressure profiles for the Sun, some brown dwarfs and giant planets are shown for comparison.

MAIN PROGRESSION STEPS

- Week 1 – 2: theoretical courses and exercises (homeworks)
- Week 3: Hands-on course using CESAM and CEPAM.
- Week 4 – 6: individual project
- Week 7: preparation for the evaluation.

EVALUATION

- Written exam on the theoretical lectures (30%),
- Oral presentation of homeworks (15%),
- Evaluation of the advancement of the project (15%),
- Final evaluation during the global oral presentation (40%).

BIBLIOGRAPHY & RESSOURCES

Stellar Astrophysics (LeBlanc)

Lecture notes in Stellar Structure and Evolution (Christensen-Dalsgaard)

An introduction to planetary atmospheres (A. Sanchez Lavega)

Useful link on exoplanet (talks, seminars)

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