Multi-physics interaction between exoplanet atmospheres and their host stars

Keywords

Exoplanet atmospheres, atmospheric escape, stellar irradiation/wind, magnetism

Profile and skills required

The candidate must have a Masters in Astrophysics or a related field and a strong interest in theoretical/numerical work and in the comparison of observations with model simulations.

Project description

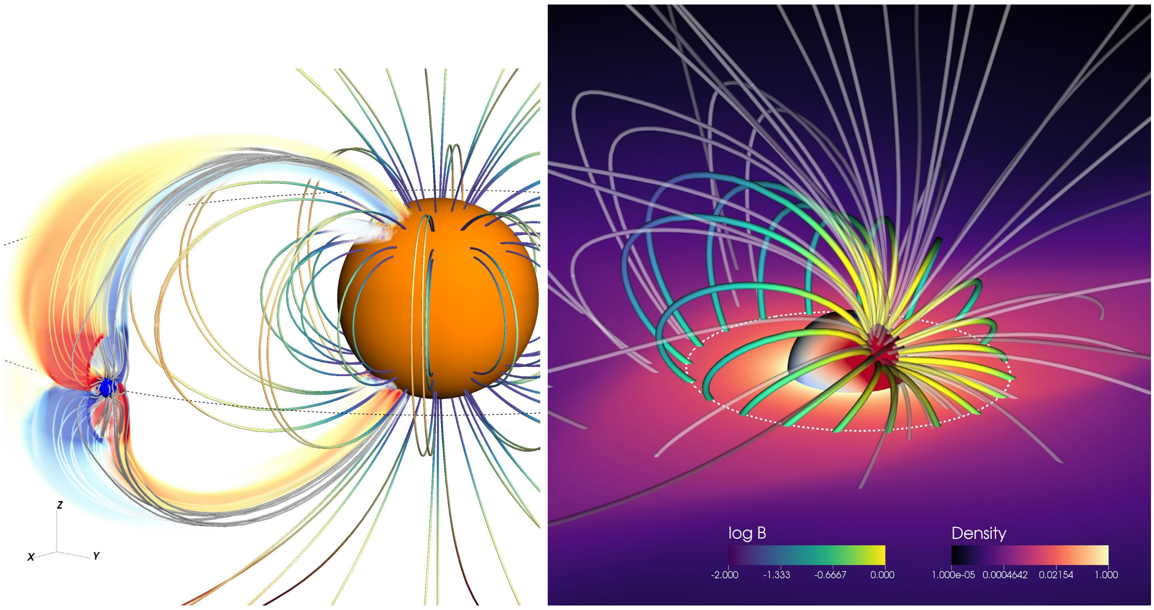
The census of known exoplanets includes >4,000 planets in >3,000 systems. The current exoplanet demographics show that exoplanets exhibit a large diversity in their mass, radius (and thus density and composition) and orbital arrangements. As the field moves from exoplanet detection to characterization of their atmospheres (which provide insight into the planet history), it becomes increasingly important to understand the physical mechanisms in the exoplanet-host star interaction that potentially shape exoplanet demographics. This can be achieved by comparing synthetic populations with empirical demographics, and by attempting to explain specific atmospheric observables for a reduced number of planetary systems.

The focus of this project is to study numerically the physical mechanisms (3D dynamics, photochemistry, magnetic interactions) that drive the escape of strongly irradiated atmospheres, thereby producing a so-called planetary wind, and how such planetary wind interacts with the stellar wind. The project will provide insight into exoplanet systems for which upper atmospheric in-transit observations of e.g. Lyman-alpha, C II, H-alpha, He I at 1083 nm exist but that remain without a proper theoretical interpretation (e.g. Allart et al., 2018; Bourrier et al., 2018; Spake et al., 2018). By building on specific planetary systems, we will infer population-wise conclusions applicable to the close-in population of exoplanets. Our priority is thus to develop physically-motivated models that embrace the complexity of these interactions and help place in context the available observables. We see this project as a first step into the development of a versatile and powerful 3D multi-physics model that can become the international reference for exoplanet-host star interactions.

The project builds upon the expertise and models available at the DRF/IRFU/DAp. In particular, we will utilize the 3D star-wind-magnetosphere interaction model developed by Dr. Strugarek over the past years [Strugarek et al. 2015, 2016, 2019], and based on the open-source 3D MHD code PLUTO (http://plutocode.ph.unito.it). This framework models the magneto-hydrodynamic interaction between a cool star, its corona and wind, and an orbiting magnetized planet. It can furthermore involve dynamical events such as coronal mass ejections [Regnault et al. 2021], and self-consistent ionospheric response of the planet. It will be used to additionally model the atmospheric escape of close-in exoplanets [e.g. Matsakos et al. 2015] in a parametrized way to take into account a mixture of neutral and ionized populations under the influence of stellar irradiation. We will build insight and develop analytical parameterizations with the 1D models built by Dr. García Muñoz [e.g. García Muñoz, 2007; García Muñoz & Schneider, 2019; García Muñoz et al., 2020]. The 1D models include in-detail descriptions of the photochemistry, energy deposition, flow acceleration, and NLTE processes in exoplanet atmospheres that contain H_2/He but also heavy gases such as H_2O/CO_2. These 1D models have been previously utilized in the investigation of the long-term stability of exoplanets and in the interpretation of available upper-atmospheric measurements with the Hubble Space Telescope and other ground-based telescopes.

In particular, the candidate will help transfer the key features of the 1D models to the 3D model. Key questions to address with the resulting 1D-3D model framework include: ***i)*** What's the impact of different stellar types (and corresponding stellar EUV fluxes and wind configurations) on the escape process and the morphology of the planet wind; ***ii)*** What's the connection between the main physical processes in the exoplanet-host star interaction and the in-transit observables? ***iii)*** How sensitive are these processes to the planetary wind composition? ***iv)*** And to magnetic effects?

The above questions are fundamental for the interpretation of the observations to be made with flagship telescopes such as JWST or ARIEL at optical-IR wavelengths, as they will enable us to put in context the current bulk composition of exoplanets with their past evolution. They are also fundamental for the interpretation of exoplanet demographics, a sub-field that is progressing rapidly with e.g. CHEOPS and TESS, and will receive a last boost with PLATO.



Left: Idealized magnetic star-planet interaction for a compact system [Strugarek et al. 2015]. Right: Corona of Kepler-78 derived from an observed spectro-polarimetric magnetic map. The orbit of Kepler-78b is indicated by the white circle [Strugarek et al. 2019].

Themes

The proposed PhD topic is very timely for the characterization of exoplanet atmospheres (including their present and past/future evolution). It requires a variety of skills (analytical, numerical, synthesis) that are highly valuable for the future career (whether in science or not) of the PhD candidate. In particular, the PhD candidate will acquire skills in: atmospheric modeling, MHD/astrophysical fluid dynamics and planet-star interaction physics, parallel computing and big data analysis.

Objectives

To understand the complex physical processes that drive the escape of strongly irradiated atmospheres and the interactions of the planetary and stellar winds.

Supervision team

The PhD candidate will be supervised by Dr. García Muñoz and Dr. Strugarek (both at DRF/IRFU/DAp).

Available resources for the project

The PhD candidate will work with 1D and 3D models developed by the Project PIs and published in the scientific literature. The PIs have significant experience in the development and utilization of these models for the investigation of planetary and stellar winds [e.g. Strugarek 2018]. The project will take place within the Laboratoire Dynamique des Etoiles, des Exoplanètes et de leur Environnement (LDE3 team), which includes experts in various aspects of astrophysical fluid dynamics and exoplanets (e.g. Dr. Sacha Brun, Dr. Pierre-Olivier Lagage). The PhD candidate will interact with Dr. Pascal Tremblin, also at CEA, on exoplanet atmospheres and numerical simulations. Overall, the PhD candidate will benefit from a very rich research environment, with strong connections to space missions and other international teams.

Main objectives of the PhD

Publication of scientific articles, development of numerical simulations, presentations at national/international meetings.

Planned collaborations

For the time being, the project will focus on the interpretation of published observations. Given the state-of-the-art nature of the proposed model, we anticipate that this will produce new collaborations within established space mission consortia.

International connections

The proposed model will become state of the art, and will produce international-level results.

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To go beyond

http://irfu.cea.fr/dap/LDEE/index.php (http://irfu.cea.fr/dap/LDEE/index.php)