# Proposal - Evolution of Exoplanet Atmospheres and their Characterisation

## I. Introduction and scientific rationale of the project

After the successful launch of the CoRoT space observatory (CNES) in December 27, 2006 and the scheduled launch of NASAs Kepler space observatory in 2008, a very large sample of distant stars will be surveyed to detect giant to Earth-size exoplanets in transit. Follow-up observations from ground-based telescopes are needed to constrain the planetary mass. For the first time, CoRoT will detect transiting sub-giant planets, i.e. super-Earths and Neptune-like planets. Knowing the planetary radius and the mass, we can infer the average planetary density. This information will be crucial to understand their composition: gas, rocks, ices, carbon, etc.. Depending on the orbital distance and the stellar spectral type, hot Neptunes might be the evaporation/erosion remnants of gas giants or very massive bodies which formed in the inner system. Super-Earths could be either the evaporation remnants of migrated Neptune's, migrated big icy bodies ("Ocean planets"), or massive terrestrial planets formed in situ. In all three cases the atmospheres should be quite different. Primary atmospheres will strongly depend on the planet-disk interaction: the initial conditions (i.e., where the planets form, how long the nebula interacts with the protoplanet, etc.) will set the scene and influence the planetary environment. In a later stage, the atmospheres are modified by the evaporation and the erosion occurring in the upper part (influenced by atmospheric species in the thermosphere, stellar plasma flow, planetary gravitation, presence of a magnetic field, etc.), but also due to the out-gassing processes. Part of the material from the interior might contaminate the primordial atmospheric composition. Based on findings by the ISSI team "Evolution of Habitable Planets" during the period 2004 - 2006, we propose with the new team to explore the grey zone between terrestrial planets and giants, both from the theoretical and observational point of view. The atmospheres of terrestrial exoplanets are not expected to be exact Earth replicas, and nearby planetary systems will certainly offer a wide diversity of terrestrial planets in terms of age, mass, spectral-type of the parent star, amount of volatiles (especially water), and orbital distances. The planetary spectrum may change dramatically if the planet is inhabited. The search for biosignatures in exoplanetary spectra cannot be considered without a more general characterization of the observed planets. It is thus necessary to study the potential signatures of life in the context of the expected diversity of planets and the evolution or modification of their atmospheres due to the interaction with energetic particles (cosmic rays), thermal and non-thermal loss processes over evolutionary epochs. These precursor studies are important in the context of the next generation of space telescopes, such as Herschel (2008) or the James Webb Space Telescope (2013), which will have the capability of acquiring spectra in the Far-Infrared and Mid-Infrared (MIR) of these extrasolar worlds. Further into the future, the direct imaging of exoplanets (Darwin and TPF missions, as well as SEE-Coast, etc.), will extend our understanding to extrasolar bodies orbiting few AUs from their parent star and expand our knowledge to Earth-size objects, inhabited or not.

## II. Topics addressed by the team

### 1. Interaction between the protoplanetary disk/nebular with planetary atmospheres

Young stellar objects are generally found with disk-like rotating structures surrounding them. These structures predominantly consist of molecular gas and dust and are probably dispersed through the outflow processes occurring either at the surface of the disk or in the immediate vicinity of the accretion shock where matter is falling down onto the protostellar surface. Average densities in observed young disks are quite often higher than $10^6$ cm$^{-3}$, which are typical number densities for planetary exospheres. Although the time scales for their dispersal is quite uncertain, most young stars with ages $> 10^7$ years lack such dense molecular disks. Significant dusty disks, viz. debris disks, occur at higher ages. The nebula's density and conditions play an important role in the more mature stage when the planet detaches from the gas reservoirs and is exposed to the loss processes driven by its host star. The evolution of the planetary mass is thus determined by the pressure gradients, as long as there is a nebula pressure, and by the properties of the exosphere in a later stage. By considering the initial conditions of the nebula and observations of disks our team will study the formation of protoplanetary

exospheres which separate these two eras and the regimes of early mass-gain from the nebula and the onset of thermal and non-thermal atmospheric loss processes as a function of disk life time.

## 2. Formation and classification of primordial atmospheres

Planetary atmospheres in the solar system are well separated in two categories: those of terrestrial planets and those of giant planets. For extrasolar planets and in particular very large terrestrial planets (e.g. "Super Earth's", Ocean planets, "Hot Neptunes", etc.) a richer collection of types is expected, depending on the planetary (core)-mass and distance from the host star. To classify possible planetary atmospheres and explain the key processes that shape giants and terrestrials, we will use an isothermal self-gravitating core-envelope model to simulate the different protoplanetary equilibria and examine the role of the so-called critical mass, necessary to attract the gas of the protoplanetary nebula to a heavy core, so that primordial atmospheres may form. Our team will study the early atmospheres of moons and planets in a general framework, including the definition of planethood.

## 3. Advanced MHD simulations of dynamics of stellar plasma flows and their interaction with planetary environments in close orbital distances

Strongly dependent on the character of the stellar activity, the flow of dense stellar wind/Coronal Mass Ejections (CME) plasma affects significantly planetary magnetospheres, atmospheres and surfaces and can be an important factor for habitability and atmospheric stability of exoplanets within orbits close to their host stars. Of special importance are stellar Coronal Mass Ejections (CMEs) which propagate in the stellar winds of active flaring stars. Besides of the density and velocity disturbances created by CMEs in the stellar plasma flow, are interplanetary shocks, energetic particles accelerated in the shock regions, and the magnetic field disturbances which create magnetic storms yielding atmospheric effects. Being well documented and described in the case of the Sun, the parameters of CME activity on other stars cannot be directly measured by the existing remote observational techniques. This makes very actual the development of specific numeric simulations of stellar CMEs, which are based on the existing knowledge about this phenomenon on the Sun and use an assumption on a general similarity of the physical nature of the solar and stellar CMEs. For modelling the propagation of dense CME plasma features from the stellar surface up to planetary orbits our team will apply the advanced magnetohydrodynamic (MHD) Versatile Advection Code (VAC). Further we will study the generation and role of energetic neutral atoms (ENAs) for supplying energy for thermal escape or deposition in the thermosphere after they are produced by charge exchange between exospheric atoms and stellar wind or CME protons, a fraction of which intercepts the exobase and heats by collision the upper layers of the planetary corona. We will study the role of possible magnetospheres influence on XUV and ENA-heated and expanded upper atmospheres and coronae.

## 4. Stellar X-ray and EUV heating of thermospheres and elemental fractionation due to thermal escape

The evolution of planetary atmospheres can only be understood within the context of the evolving stellar radiation environment. Therefore, we will study the thermospheric plasma kinetics of redistribution of the stellar X-ray and EUV radiation energy deposited in thermospheres between different electronic and vibrational energy states of the neutral and ionized atmospheric constituents. It is planned to identify and model the main sources and sinks of energy, including neutral and ion chemical heating, radiative cooling and heating in the Infra-Red (IR) vibration-rotational bands of molecular gases and ions, heating and cooling due to atmospheric turbulence in the region between the homopause and the heterosphere of the Earth- or Venus-like planets and more massive and larger

hydrogen-rich exoplanets at various solar/stellar evolution phases. To simulate temperature and density profiles we will build new models of the thermospheric heat budget, which will include the identified main sources and sinks of energy, combined with photochemical-diffusion models of the thermospheric neutral species and ions. For the composition of early stages of the planetary atmospheres our team will apply a photo-chemical code, called *PHOtochemistry for Exo-Biology and Exoplanets* (*PHOEBE*), which produces from initial atmospheric conditions and a given stellar spectrum the abundances and mixing ratios ($H_2O$, $O_3$, $NO_x$, etc.) for each chemical species as a function of altitude and time. The thermospheric chemical composition and thermal budget models will also be used to define the parameter space needed to study the thermal atmospheric escape processes (Jeans and hydrodynamic) and the fractionation of atmospheric species over evolutionary time scales.

## 5. Application of sophisticated 3-D MHD and hybrid-codes for non-thermal atmospheric erosion processes over evolutionary time scales

The extended upper atmospheres are not only irradiated by stellar photons, but also bombarded by fluxes of charged particles coming from their host stars. Stellar plasma may affect the evolution of planetary/exoplanetary atmospheres, by acting both as a sink and source for the atmospheric particles. The flowing plasma pick up electrically charged particles produced from heated and expanded neutral upper atmospheres. The loss rate depends on the properties of the stellar plasma, the strength of the X-ray and EUV flux and the properties of the planet, especially, the strength of its intrinsic magnetic field, the density of the atmosphere and the size of the planet, and the rotation of the planet. The stellar wind/CME - atmosphere interaction is a complicated physical problem, sensitive to many time-dependent parameters like the induced magnetic fields and the planetary obstacles. To understand these problems our team will apply a modified 3-D magnetohydrodynamic (MHD) model based on the Total Variation Diminishing (TVD) model which solves the set of MHD equations and additional continuity equations for ionospheric ion densities. We will simulate the penetration depth and planetary obstacle for the upper atmospheres, and we will apply a global quasineutral hybrid model to study the total ion loss, which has been validated against observations of Martian (at high - Phobos 2 - and low solar activity - Mars Express) and Venus (PVO, Venus Express) conditions. We will also study the atmospheric stability and ion loss, due to the stellar plasma interaction with the upper atmosphere of Earth-like exoplanets, "Hot Neptunes" and "Hot Jupiters".

## 6. Atmospheric characterisation by studying spectral signatures (biomarkers, etc.)

New modelling tools developed by the members of this team will allow us to simulate self-consistently the photochemistry and radiative transfer processes occurring in planetary atmospheres and to generate the corresponding spectra. Our simulations will include in some cases the production of biological gases such as $O_2$, $CH_4$, $NH_3$, and $N_2O$: we will study their detectability as a function of selected parameters, including the nature of the biological activity (photosynthesis, methanogenesis, nitrogen fixation), the mass and orbital distance of the planet, or the type and age and activity of the star. We will also evaluate the efficiency of abiotic mechanisms that can produce false positive. Furthermore, our team will focus on the spectral signatures (biomarkers, etc.) due to specific atmospheric processes, such as the interaction with high energy particles (galactic and stellar), thermal and non-thermal loss of selected atmospheric species and the modulation of the stellar flux at different time scales. By convolving the generated high-resolution spectra, we will also provide the

instrumental performances (signal to noise, spectral resolution) necessary to detect a list of biomarkers.

**7. Data-bases for planetary spectra and stellar plasma-atmosphere interaction**

Our team will develop future tools for the retrieval of planetary and atmospheric properties from observed planetary spectra. Concerning the non-thermal atmospheric loss processes, we will contribute to an exoplanet data-base, including stellar plasma-atmosphere interaction, currently located at the FMI in Helsinki, Finland. These efforts represent an important starting point for the emerging disciplines of exoplanet characterisation and comparative exo-planetology.

*II. Synergies of models and benefits for exoplanet and solar system missions*
The subjects addressed in the proposal are all connected:

- Disk-nebulae life time, onset of atmospheric escape;
- Primordial atmospheres, nebula-protoplanet-exosphere interaction;
- Upper atmosphere energy budget, expansion, thermal escape (Jeans, hydrodynamic);
- Stellar plasma (winds, CMEs) atmosphere/magnetosphere interaction, non-thermal loss, interaction with high energy particles;
- Fractionation of planetary atmospheres;
- Atmospheric stability, atmospheric evolution, habitability;
- Modification of spectral signatures, including biomarkers.

Our proposed team is very interdisciplinary and consists of scientists who can provide a broad expertise and comprehensive modelling tools to study the evolution and characterisation of the exoplanetary atmospheres. The task proposed here was never attempted before. The results of our project are important for discovery missions such as CoRoT, which may detect remnants of "Hot Jupiters", "Hot Neptunes", and Super Earths", and Kepler and SIM, hunting for Earth-sized planets. Moreover the proposed results are crucial for understanding the evolution of planetary atmospheres within the habitable zones and their spectroscopic signatures, in preparation for Darwin/TPF but also applicable to JWST. Finally, by studying the initial conditions of the planetary atmospheres under extreme stellar environments, we will improve our knowledge on the early atmospheres of Venus, Earth, Mars and Titan, and how they evolved during the first hundred Myrs, after the active young Sun reached the Zero-Age-Main-Sequence. Our work will thus have implications for planetary missions like VEX, MEX and Cassini/Huygens, as well as future solar system projects.