Final report of the ISSI Team on "Charactizing stellar- and exoplanetary environments"

by ***Doz. Dr. Helmut Lammer – ISSI team leader***

The main science cases and aims as proposed in the team proposal have been successfully finished, after 3 ISSI team meetings with many fruitful scientific discussions (see Fig. 1), cooperations have been stimulated and finally several team-related peer reviewed articles came out from these meetings. Finally our team decided to publish a book by Springer, with several article contributions by the various team-members (not related with the official ISSI-Springer publications). The book will be edited by *H. Lammer and M. L. Khodachenko*, because the publisher showed a great interest. Currently our team finishes this book on the team subjects and science cases that will be submitted to the publisher during April 2014.

Below is a summary of the studies and findings of our team related to the exoplanet host star and plasma environment:

Radiation from host stars controls the planetary energy budget, photochemistry in planetary atmospheres, and mass loss from the outer layers of these atmospheres. Stellar optical and infrared radiation, the major source of energy for the lower atmosphere and planetary surfaces, increases slowly as stars evolve from the zero-age main sequence. Ultraviolet radiation, including the Lyman-α emission line that dominates the UV spectrum of M dwarf stars, controls photochemical reactions of important molecules, including H_2O, CO_2, and CH_4. Extreme ultraviolet and X-radiation from host stars ionizes and heats the outer layers of planetary atmospheres driving mass loss that is rapid for close-in Jupiter-like planets. The strength of the stellar UV, EUV, and X-radiation depends on stellar activity, which decays with time as stellar rotation decreases. As a result, the evolution of an exoplanet's atmosphere depends on the evolution of its host star.

Exposure to stellar winds can have significant long term consequences for planetary atmospheres. Estimating the effects of these winds requires knowledge of how they evolve with time. For determining this empirically, within the ISSI team meetings we studied the winds of stars of various ages and activity levels, but this is not easy to do as the coronal winds of solar-like stars are very hard to detect. Relevant observations will be reviewed in the forthcoming team book. For the wind and plasma discussions our team also invited *Alien Vidotto* and *Colin Johnstone* within ISSIs young scientist program.

Stellar magnetism as a crucial driver of activity, ionization, photodissoziation, chemistry and winds in stellar environments has also been discussed during our ISSI team meetings. They therefore have an important impact on the atmospheres and the magnetospheres of surrounding planets. Modelling of magnetic fields and their winds is extremely challenging, both from the observational and the theoretical points of view, and only recent groundbreaking advances in observational instrumentation, as well as a deeper theoretical understanding of magnetohydrodynamic processes enable us to model stellar fields and winds - and the resulting influence on surrounding planets - in more and more detail. In the forthcoming book our team members review what is known about the magnetic fields of cool stars, covering relevant techniques such as Zeeman Doppler imaging (ZDI), field extrapolation and wind simulations, as well as relevant observational results.

Exoplanet upper atmosphere observations and modelling have also been studied in detail by our team members. The detections of atomic hydrogen, heavy atoms and ions surrounding giant exoplanets such as HD 209458b constrain the composition, temperature and density profiles in the planets upper atmosphere. Observations provide guidance for models that have so far predicted a range of possible conditions. Team member *T. Koskinen* presented the first hydrodynamic escape model for the upper atmosphere that includes all of the observed species in order to explain their presence in the upper atmosphere and to further constrain the modeled temperature and velocity profiles. Heating rates and the role of suprathermal hydrogen atoms have been studied too by our team members. It was found that molecules dissociate near the 1 μbar level. Complex molecular chemistry does not need to be included above this level. Diffusive separation of the detected species does not occur because the heavy atoms and ions collide frequently with the rapidly escaping H and H^+. This means that the abundance of the heavy atoms and ions in the thermosphere simply depends on the elemental abundances and ionization rates. For a planet such as HD 209458b it was found that, H and O remain mostly neutral up to at least three planetary radii, whereas both C and Si are mostly ionized at significantly lower altitudes. We also explore the temperature and velocity profiles, and find that the outflow speed and the temperature gradients depend strongly on the assumed heating efficiencies.

Fig. 1.: *Various photos made during active discussions and team member presentations as well as socializing events at ISSI in Bern.*

The near-UV observations of the hot-Jupiter WASP-12b obtained by *Fossati et al.* have revealed the presence of an asymmetric transit light curve that is both more pronounced in the near-UV and starts at an earlier time than the optical light curve. These features of the near-UV transit of WASP-12b have intrigued several modelers and have been discussed and studied in detail within our team.
A summarization of the current knowledge of exoplanet atmospheres and wider environments of known exoplanets will be given in our book.

This work follows previous attempts to explain this asymmetry with an exospheric outflow or a bow shock, induced by a planetary magnetic field, and provides a numerical solution of the early ingress, though we did not perform any radiative transfer calculation. Team members performed pure 3D gas dynamic simulations of the plasma interaction between WASP-12b and its host star so that the plasma flow pattern in the system could be described and the overfilling of the planet's Roche lobe occurred with a noticeable outflow from the upper atmosphere in the direction of the Lagrange points one and two. Due to the conservation of the angular momentum, we found that the flow to the Lagrange point one is deflected in the direction of the planet's orbital motion, while the flow toward the second Lagrange point is deflected in the opposite direction. In such a configuration our team members could show that the supersonic motion of the planet inside the stellar wind leads to the formation of a bow shock with a complex shape that allows us to consider a long-living flow structure that is in the steady state.

Within our team magnetospheres and magnetic dynamos and their role in atmospheric protection has been also studied within our team in detail. Weak intrinsic magnetic dipole moments of tidally locked close-in giant exoplanets have been shown in previous studies to be unable to provide an efficient magnetospheric protection for their expanding upper atmospheres against the stellar plasma flow, which should lead to significant non-thermal atmospheric mass loss. Besides the intrinsic planetary magnetic dipole, our team investigated that a paraboloid magnetospheric model (PMM) considers among the main magnetic field sources also the electric current system of the magnetotail, magnetopause currents, and the ring current of a magnetodisk. Due to the outflow of ionized particles from a XUV heated and hydrodynamically expanding upper atmosphere, hydrogen-dominated upper atmospheres may have extended magnetodisks. The magnetic field produced by magnetodisk ring currents dominates above the contribution of an intrinsic magnetic dipole of a "hot Jupiter" and finally determines the size and shape of the whole magnetosphere. A slower than the dipole-type decrease of the magnetic field with the distance forms the essential specifics of magnetodisk-dominated magnetospheres of "hot Jupiters." These results in their 40 % – 70 % larger scales compared to those traditionally estimated by only the planetary dipole taken into account. Therefore, the formation of magnetodisks has to be included in the studies of the stellar wind plasma interaction with close-in exoplanets, as well as magnetospheric protection for planetary atmospheres against non-thermal escape due to erosion by the stellar plasma flow.

Finally, team members also discussed future space missions and their role to enhance the scientific understanding related to the team science tasks.

The articles that have been published by our team or came out after team discussions are listed separately. It should also be noted that our team members presented the results of the published studies also at various international scientific conferences and meetings in the USA, Europe, Russia and China.