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Stellar activity and winds shaping the atmospheres of Earth-like planets

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Abstract. Planets orbiting young, active stars are embedded in an environment that is far from being as calm as the present solar neighbourhood. They experience the extreme environments of their host stars, which cannot have been without consequences for young stellar systems and the evolution of Earth-like planets to habitable worlds. Stellar magnetism and the related stellar activity are crucial drivers of ionization, photodissociation, and chemistry. Stellar winds can compress planetary magnetospheres and even strip away the outer layers of their atmospheres, thus having an enormous impact on the atmospheres and the magnetospheres of surrounding exoplanets. Modelling of stellar magnetic fields and their winds is extremely challenging, both from the observational and the theoretical points of view, and only ground breaking advances in observational instrumentation and a deeper theoretical understanding of magnetohydrodynamic processes in stars enable us to model stellar magnetic fields and their winds – and the resulting influence on the atmospheres of surrounding exoplanets – in more and more detail. We have initiated a national and international research network (NFN): 'Pathways to Habitability – From Disks to Active Stars, Planets to Life', to address questions on the formation and habitability of environments in young, active stellar/planetary systems. We discuss the work we are carrying out within this project and focus on how stellar evolutionary aspects in relation to activity, magnetic fields and winds influence the erosion of planetary atmospheres in the habitable zone. We present recent results of our theoretical and observational studies based on Zeeman Doppler Imaging (ZDI), field extrapolation methods, wind simulations, and the modeling of planetary upper atmospheres.

Keywords. Stars, magnetic fields, activity, habitability, planetary atmospheres

1. Stellar magnetic field-, activity- and wind evolution

The activity output (radiation, winds, stellar flares and high-energy particles) that is triggered by the magnetic field of the central star is largely responsible for the erosion of planetary upper atmospheres, whereby the star's X-ray and ultraviolet radiation (XUV) play the most significant role here. This radiation declines in time, whereby the precise evolutionary path crucially depends on the stellar rotational evolution (Tu *et al.* 2015, Fig. 1). A broad, general picture is described by simple, unique decay laws (Güdel *et al.* 1997; Ribas *et al.* 2005; Claire *et al.* 2012) but especially at ages less than a few 100 Myr, these may not apply to individual stars. This age range is crucial, though, for setting

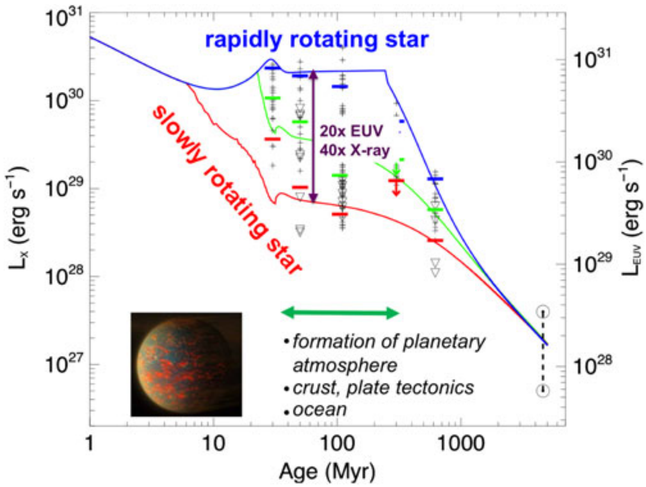

Figure 1. High-energy Sun in time (Tu *et al.* 2015).

the boundary conditions (astrophysically and geophysically) for the co-evolution of star-planetary systems into habitable ones. Stellar wind estimates are confronted with similar issues: although indirect estimations are available (Wood *et al.* 2005), little systematics can be inferred for stars at young ages (Johnstone *et al.* 2015a; Johnstone *et al.* 2015b). It highly depends on the initial conditions of stellar rotation at very young ages, how it changes with time: it can evolve along completely different tracks for many 100 million years. As a result, evolutionary tracks for stellar magnetic activity, short-wavelength radiation and ionized winds can be very different, which implies very different evolutionary scenarios for the erosion of planetary atmospheres.

Within the research network (NFN): 'Pathways to Habitability – From Disks to Active Stars, Planets to Life' we systematically address the evolution that stellar environments undergo during the PMS and young MS phases, addressing the entire radiative and particle output in the context of stellar rotational evolution with a focus on the study of the magnetic-field and wind evolution, as presented in this talk.

2. Magnetic fields and Zeeman Doppler imaging

Complexity and strength of magnetic fields are believed to be a strong function of the internal stellar structure (Morin *et al.* 2010; Gregory *et al.* 2012; Johnstone *et al.* 2014), which has crucial implications for the properties of the stellar wind, the according mass loss rates and the evolving planetary environment. The structure and strength of magnetic fields can be assessed via the Zeeman Doppler Imaging (ZDI) technique (e.g., Donati *et al.* 2008, Lüftinger *et al.* 2010a; Lüftinger *et al.* 2010b).

Built around complex mathematical procedures ZDI has become one of the most powerful astrophysical remote sensing methods. This technique has meanwhile reached a state of maturity in which we can determine strength, distribution, polarity and even polarity reversals of surface magnetic fields. At the same time temperature- or abundance structures on the surface of stars can be reconstructed by inverting time series of high-resolution spectropolarimetric data.

However, we still have only limited knowledge of statistical and evolutionary systematics. Thus, using the NARVAL spectropolarimeter (attached to the Télescope Bernard Lyot, Pic du Midi, France) we have obtained and/or dearchived spectropolarimetric data of a number of young active stars (e.g. π^1 UMa, Xi Boo A, etc.) determining their magnetic field geometry via ZDI and estimating their wind characteristics using field

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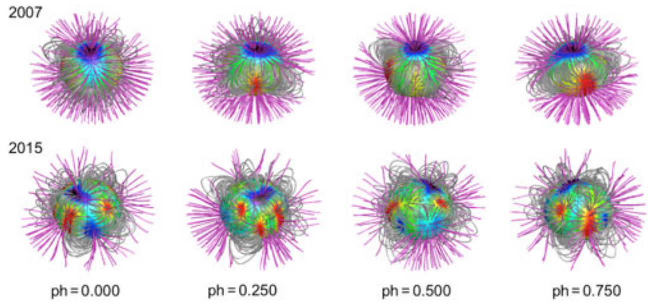

Figure 2. Stellar surface magnetic field distribution of π^1 UMa

extrapolation methods (Lüftinger *et al.*, Kulterer *et al.*, Boro Saikia *et al.* 2019, in prep.). In this context we study systematics in magnetism and winds linked to stellar evolutionary history and relate those to our empirical models predicting wind evolution.

In a collaboration with the Space Sciences Laboratory (Berkeley, USA) and the NASA Goddard Space Flight Center/SEEC (USA) we try to understand, based on our ZDI-maps via data-driven, three-dimensional, magnetohydrodynamic modeling, how eruptive superflares from young solar-like stars (e.g. κ^1 Cet, Lynch *et al.*, submitted) would impact their interplanetary environments.

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Discussion

Linsky: Mass loss rates have been measured for about 15 G and K stars by the astrosphere technique. Observation of mass loss rates at radio wavelengths is difficult to measure because chromospheric emission likely exceeds free-free emission from stellar winds. Do you agree or disagree? Any comments?

Lueftinger: I agree. Getting mass loss rates from radio observations actually only yields upper limits for stellar winds and mass loss rates, which is actually very valuable, as non-detections tell us that there is no stellar wind signature above a certain threshold (obtained by the radio observations). There was a paper published recently by our group in Vienna (Fichtinger *et al.* 2017), where this is described in detail. Via ALMA and VLA radio observations we could determine radio emission and mass loss rate limits of four young solar-type stars.