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Stellar Winds and High-Energy Radiation: Evolution and influences on planetary atmospheres

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Abstract

As part of the Austrian research network "Pathways to Habitability: From Disks to Active Stars, Planets and Life" (path.univie.ac.at), we study the evolution of stellar output (e.g. winds, high-energy radiation) over the lifetimes of solar-like stars and the influence of stellar output on the development of habitable planetary environments. We have developed a coupled stellar rotation-wind-radiation model that describes the long term evolution of stellar output over the course of a star's life. We show that the initial rotation rate of a star can significantly influence the evolution of winds and high-energy radiation and therefore the development of planetary atmospheres.

1. Introduction

The atmospheres of planets form and evolve embedded in the environments of their host stars. Stellar output includes winds, radiation, coronal mass ejections, high-energy particles, and magnetic fields. The most significant of these for the evolution of a planetary atmosphere are likely to be extreme ultraviolet (EUV) and X-ray radiation and stellar winds. EUV and X-ray radiation heat the upper atmospheres of planets and can cause significant expansion and, when the input stellar flux is high enough, hydrodynamic flow (Tian et al. 2005). The expansion of the upper atmosphere can lead to a large portion of the gas being exposed to the stellar wind, which can then lead to significant non-thermal erosion of the atmosphere (Kislyakova et al. 2014). These processes are highly sensitive to the properties of the stellar output.

Stellar rotation is the most fundamental parameter that drives magnetic activity (Wright et al. 2011), and therefore winds and radiation evolve on evolutionary timescales due to the evolution of stellar rotation. Stars start out their lives with a range of possible rotation rates spanning almost two orders of magnitude. As they age, they then rotate slower owing to their magnetised winds and this distribution of rotation rates converges: for solar mass stars, this convergence takes less than 1 Gyr.

2. Wind Evolution

A consequence of rotational evolution is the evolution of stellar winds. In Johnstone et al. (2015), we developed a rotation and wind model to predict the time evolution of the winds of stars with a range of masses. We estimated that the solar wind mass loss rate, $\dot{M}_\star$, depends on stellar rotation rate, $\Omega_\star$, radius, $R_\star$, and mass, $M_\star$, as $\dot{M}_\star \propto R_\star^2 \Omega_\star^{1.33} M_\star^{-3.36}$. For the solar wind, this leads to an approximate time dependence of the mass loss rate of $\dot{M}_\star \propto t^{-0.75}$ at ages older than 1 Gyr, and a range of possible evolutionary tracks at younger ages due to the spread in rotation rates (Fig. 1). With our model, we are also able to estimate the wind speeds and densities within a few AU of the star.

3. Radiation Evolution

In Tu et al. (2015), we combined our rotation model with a radiation model to predict the possible evolutionary tracks of solar-mass stars with different initial rotation rates. Stars starting out their lives at the 10th and 90th percentile of the rotational distribution remain highly active for <10 Myr and >200 Myr respectively. For several hundred million years, the differences in the X-ray and EUV luminosities between the two cases is more than an order of magnitude. This is shown in Fig. 2.

4. Summary and Conclusions

The different evolutionary tracks for solar mass stars can lead to differences in the evolution of planetary atmospheres. Tu et al. (2015) demonstrated this for the

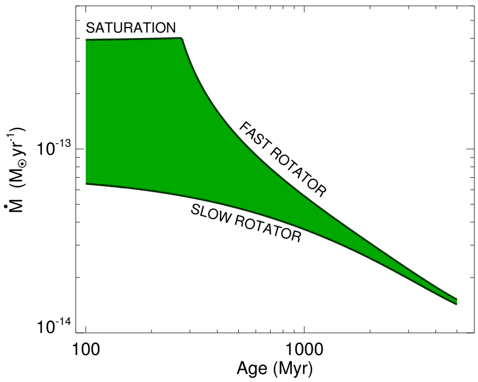

Figure 1: Figure reproduced from Johnstone et al. (2015) showing the predicted evolutionary changes of the solar wind mass loss rate. The slow and fast rotator tracks correspond to stars that are at the 10th and 90th percentiles of the rotational distributions.

simple case of a 0.5 $M_\oplus$ planet with a thick hydrogen envelope at 1 AU around a solar mass star. The atmosphere was assumed to be losing mass due to EUV and X-ray heating of the thermosphere. As we show in Fig. 2, if the planet orbits a rapidly rotating star, the example atmosphere loses its entire mass in 100 Myr. However, if the planet orbits a slowly rotating star, almost half of the initial atmospheric mass remains after 5 Gyr. Clearly, the star's initial rotation rate is an fundamentally important parameter for the development of terrestrial planetary atmospheres.

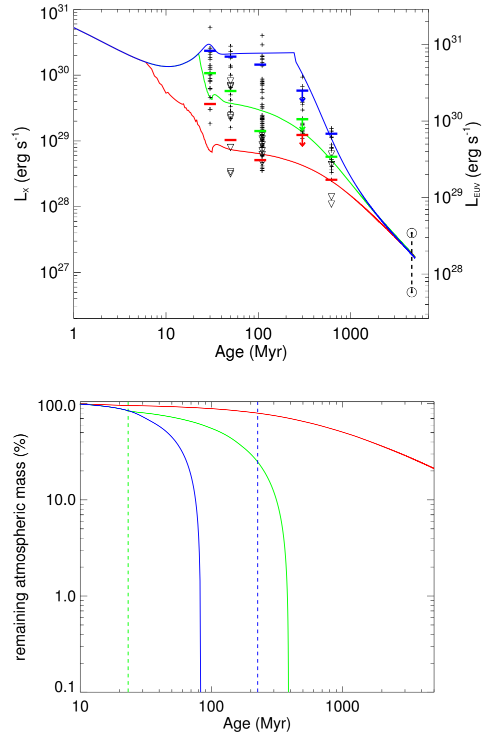

Figure 2: Figures reproduced from Tu et al. (2015). *Upper panel*: evolutionary tracks of the X-ray/EUV luminosities for stars at the 10th (*red*), 50th (*green*), and 90th (*blue*) percentiles of the rotational distribution. *Lower panel*: the corresponding evolutionary tracks for the atmospheric content of an example hydrogen dominated atmosphere of a 0.5 $M_\oplus$ planet.

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