A Stellar high-energy luminosity evolutionary model

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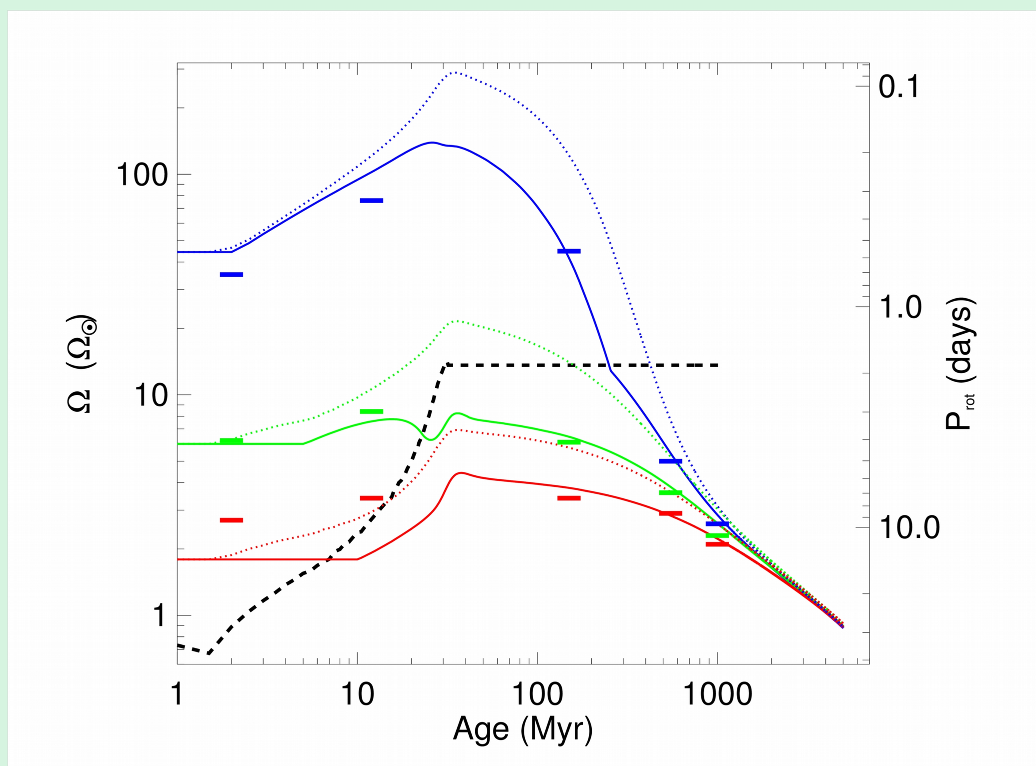
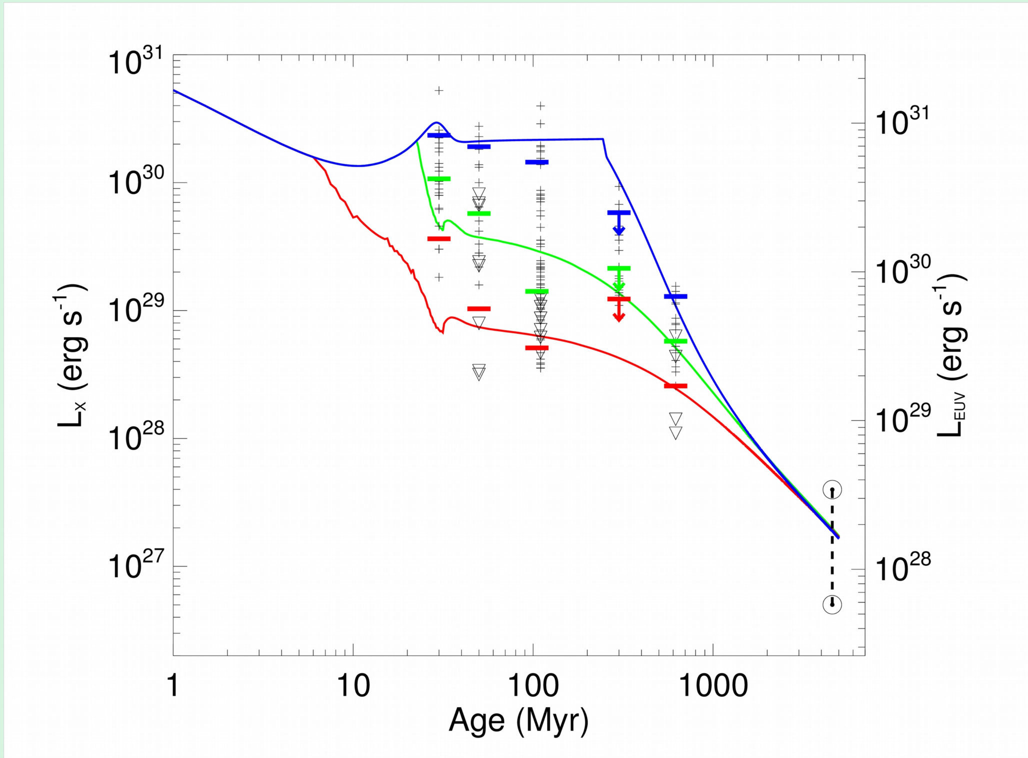
For solar-like main-sequence stars, high-energy radiation decays in time owing to stellar spin-down. The early Sun's X-ray (≈ 1 − 100 Å) and extreme-ultraviolet (≈ 100 − 900 Å) emissions could thus have exceeded the present-day Sun's level by orders of magnitude (Ribas et al. 2005), which drives atmospheric erosion. Such extreme radiation levels were critically important for both the primordial hydrogen atmospheres (e.g., Lammer et al. 2014) and the secondary nitrogen atmospheres (Lichtenegger et al. 2010) of solar system planets. We use a rotational evolution model to predict such luminosity distributions as a function of age, and we show that these predictions agree with the observed time-dependent scatter of X-ray luminosity. We also extend this evolutionary model to stars of lower mass.

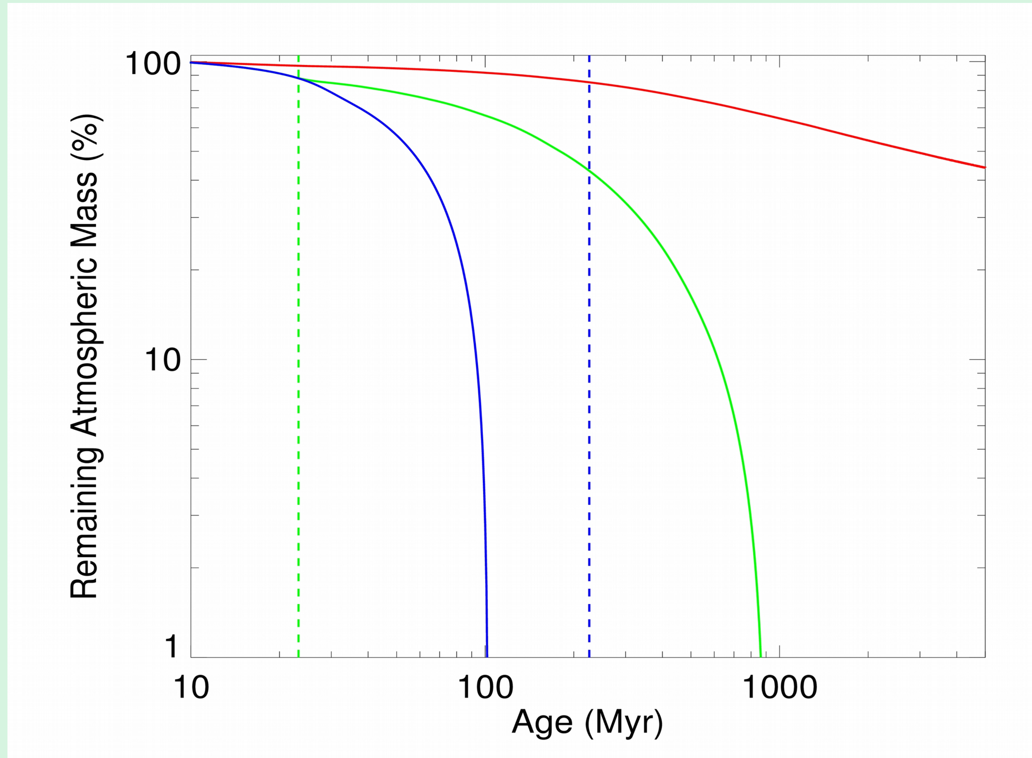
Rotation rate



L_X & L_{EUV}



Atmospheric loss



Rotation Rate Evolution
We use an extension of the rotational evolution model by Johnstone et al. (2015), which is empirical on over 2000 stars in clusters of ages 150, 550, and 1000 Myr.

Stellar mass derivation
For MS stars, we use stellar mass evolution model by An et al. (2007) to derive stellar mass from $(B\text{-}V)_0$.
For PMS stars, we use Siess et al. (2000) model to derive stellar mass.

L_x relation with Rossby number (Ro)

L_x can be derived as $R_x = \begin{cases} C Ro^{\beta}, \text{if } R_o \geq R_{o,sat} \\ R_{x,sat}, \text{if } R_o \leq R_{o,sat} \end{cases}$ by $R_x = \frac{L_x}{L_{bol}}$, $R_o = \frac{P_{rot}}{\tau}$

And we take L_{bol} (bolometric luminosity) from Siess et al. (2000) model.

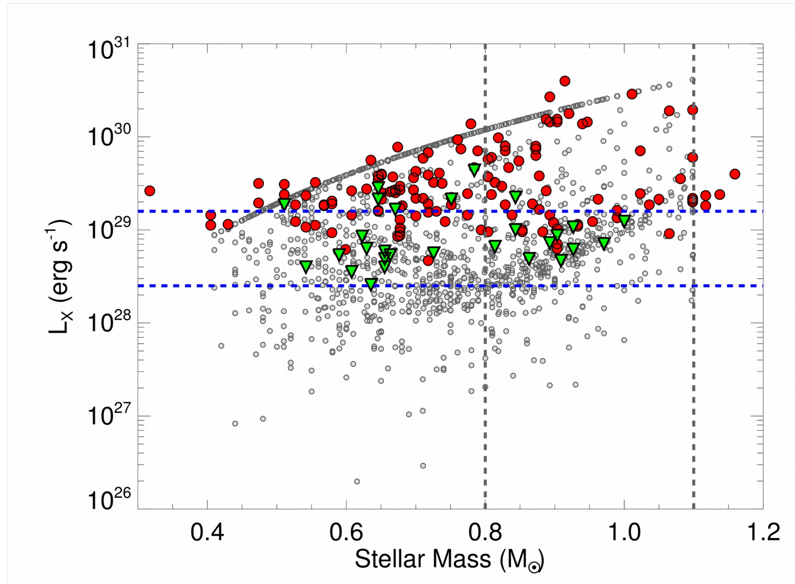
Magnetic convective turnover time scale
We take τ from Spada et al. (2013) model.

EUV Conversion
Sanz-Forcada et al. (2011) derived a power law to convert L_X into L_{EUV}

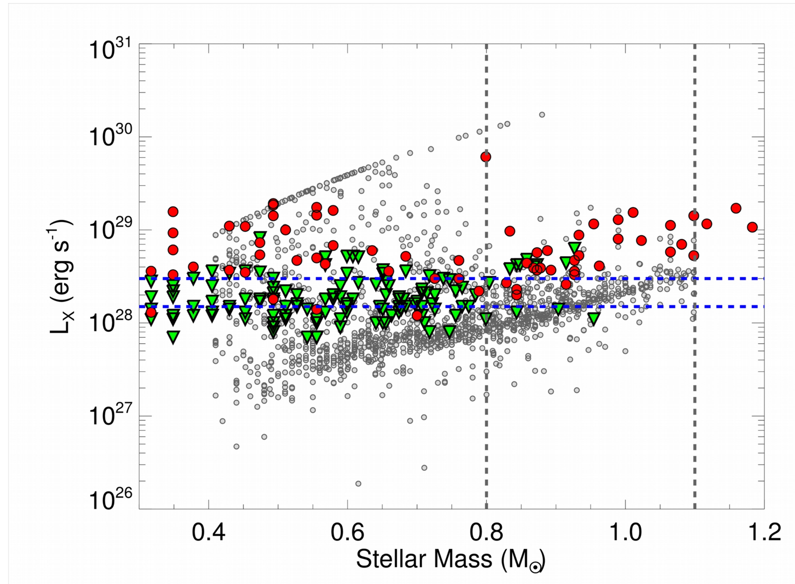
$$\log(L_{EUV}) = 4.8 + 0.86 \log(L_X)$$

Comparison with Observations

L_x at ages of 150 Myr and 620 Myr. The grey symbols show predicted Lx derived from a rotational model. The red circles and green triangles show detections and upper limits for stars in the Pleiades (left) and Hyades (right). The horizontal blue lines show detection thresholds. The upper line of stars in the theoretical distributions is caused by the stars whose rotation rates lie above the mass dependent saturation threshold.



Pleiades (150Myr)

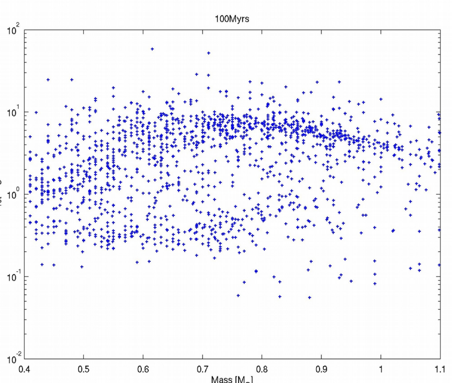


Hyades (620Myr)

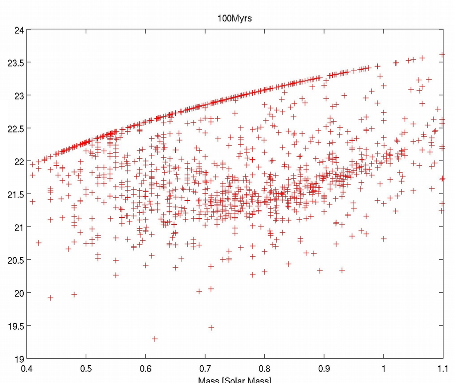
Rotation rate (Ω) & L_x evolution

100 Myr

Ω

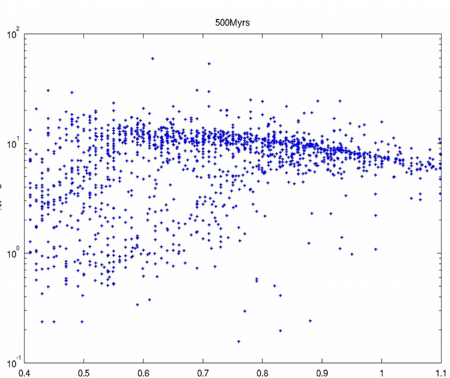


L_x

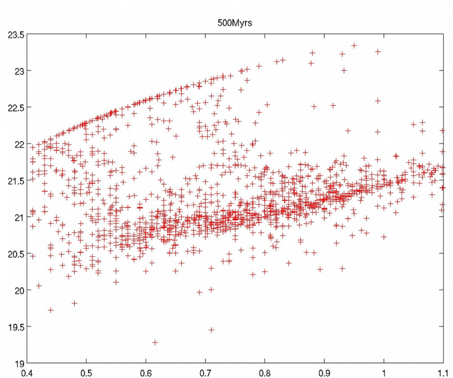


500 Myr

Ω

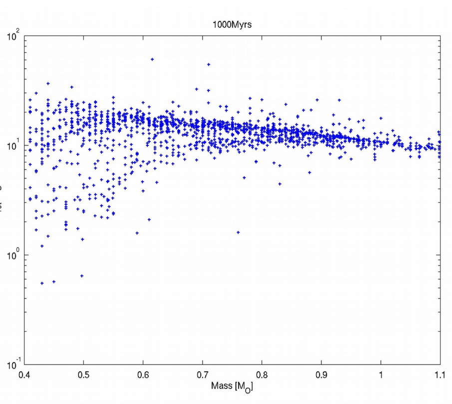


L_x

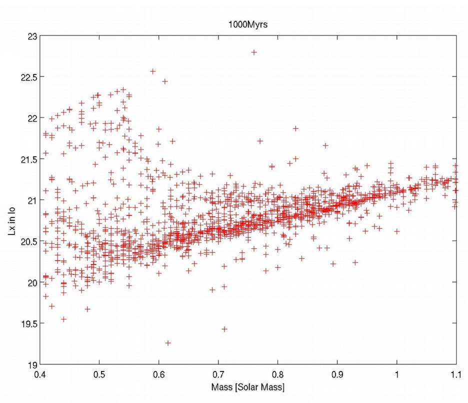


1000 Myr

Ω

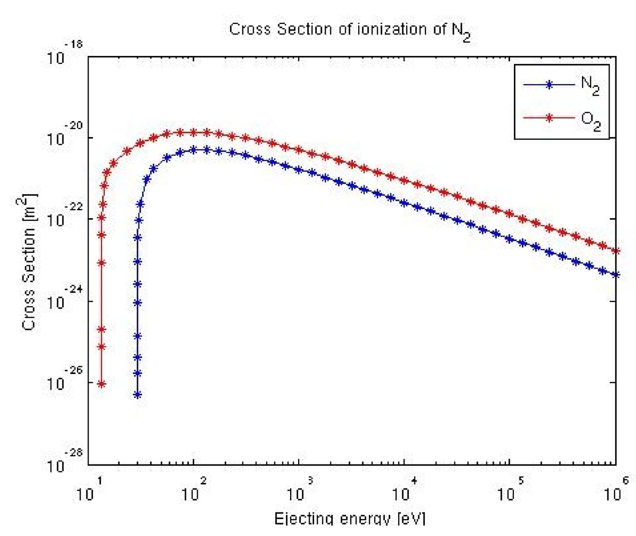


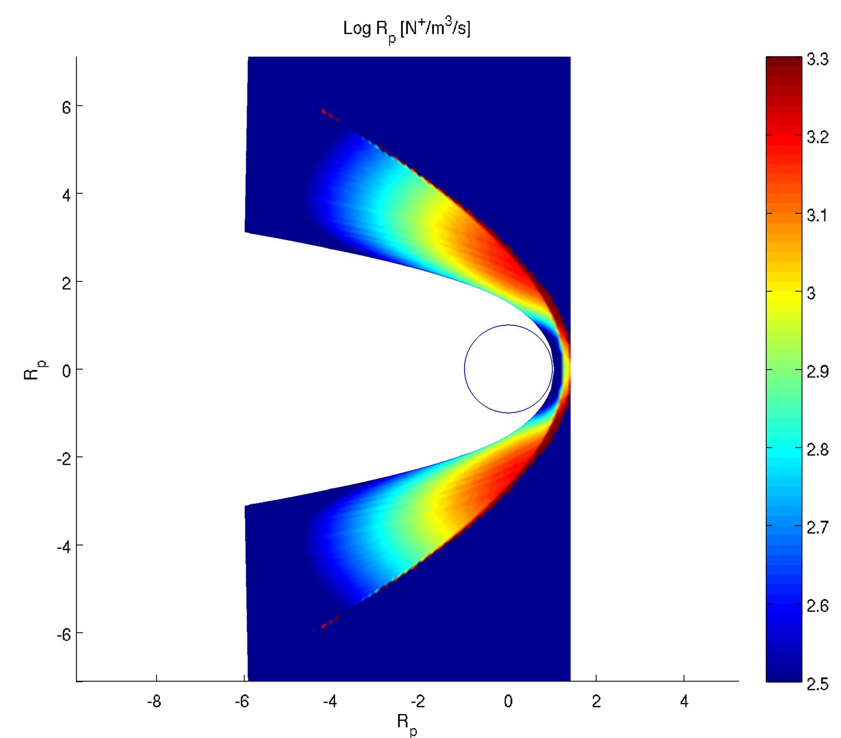
L_x



Application to Atmospheric Loss

Cross section of charge exchange for N_2 and O_2 cases with different energy.





A sketch of charge exchange production rate

Acknowledgements

We acknowledge the support of the FWF NFN project S11601-N16 "Pathways to Habitability: From Disks to Active Stars, Planes to Life" and the related FWF NFN subprojects S11604-N16 and S11607-N16. We acknowledge the support of the "Emerging Fields" grant of the University of Vienna through the faculty of Earth Sciences, Geography, and Astronomy.

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