

# Evolution of Solar-Type Activity: An Observational and Theoretical Perspective

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## Abstract

When stars depart from the main-sequence, various changes occur including the loss of angular momentum owing to changes in the stellar interior and the impact of stellar winds. These processes affect the amount of outer atmospheric heating and emission as revealed by observations in the UV and X-ray spectral regimes. From a theoretical perspective, both magnetic and acoustic energy generation are affected as indicated by detailed theoretical simulations. Here, I will summarize selected observational and theoretical results, including recent work for  $\beta$  Hydri (G2 IV), a star constituting a prime example and proxy for the future Sun.

**Keywords:** stars: activity, stars: individual:  $\beta$  Hydri, stars: magnetic fields, stars: chromospheres, stars: coronae, Sun: evolution

## 1. Introduction

The study of the evolution of stellar activity is a central theme of astronomy and astrophysics. It is also of particular relevance to the Sun. Important contributions have been made about the relationships between the stellar age, mass loss, magnetic field coverage, change in angular momentum, and outer atmospheric heating and emission regarding the various spectral regimes. Selected results will be highlighted in this paper (see Sect. 2 for examples).

Aspects about solar-type evolution (sometimes also referred to as “Sun in Time”) have been described in the living review by Güdel (2007) and related studies. The findings include that (1) the Sun’s magnetic activity has steadily declined during its main-sequence life, associated with an increase in luminosity, (2) the young Sun exhibited significantly faster rotation generating enhanced magnetic activity, (3) associated magnetic heating processes occurred in the chromosphere, the transition region, and the corona; induced ultraviolet, extreme-ultraviolet, and X-ray emission has been about 10, 100, and 1000 times, respectively, higher compared to the present-day levels, (4) drastic consequences happened regarding the Solar System (especially for close-in planets and moons) due to high-energy particles and significant solar flares, and (5) important notable processes occurred such as photoionization, photochemical evolution,

and possible erosion of the planetary atmospheres; the latter were highly relevant for the origin or non-origin of life.

Some of these topics can be explored through the examination of solar analogs. In the following, we will give special consideration to  $\beta$  Hydri ( $\beta$  Hyi; HD 2151, HR 98, HIP 2021), a well-studied star in the Southern Hemisphere (see, e.g., Fawzy and Cuntz (2023) for compiled information and references). Previous work by Brandão et al. (2011) confirmed  $\beta$  Hyi's spectral type as G2 IV, among other properties. The stellar parameters of  $\beta$  Hyi read as follows:  $T_{\text{eff}} = 5872$  K,  $M_{\star} = 1.08 M_{\odot}$ ,  $R_{\star} = 1.81 R_{\odot}$ ,  $L_{\star} = 3.49 L_{\odot}$ , and  $\log g_{\star} = 4.02$  (cgs) – see da Silva et al. (2006), North et al. (2007), Bruntt et al. (2010), and Brandão et al. (2011), with all symbols having their usual meaning. The stellar age is given as  $6.40 \pm 0.56$  Gyr; hence,  $\beta$  Hyi represents the medium-distant future of the Sun.

A highly comprehensive approach has been applied by Bruntt et al. (2010), who combined results from interferometry, asteroseismology, and spectroscopy to derive fundamental parameters of many stars, including  $\beta$  Hyi. Thus, the stellar mass and effective temperature could be determined within an uncertainty of  $\pm 0.05$  and  $\pm 59$ , respectively. The method of Brandão et al. (2011) relied on asteroseismic modelling, including the consideration of seismic and non-seismic data in conjunction with detailed evolutionary models.

Consequently,  $\beta$  Hyi is of extraordinary interest to both theoretical and observational studies, including the propagation and dissipation of acoustic and magnetic energy in its outer atmosphere, as well as associated chromospheric and coronal emission. Previous observational studies allowing to verify the status of  $\beta$  Hyi employ the analysis of solar-like oscillations (Carrier et al., 2001; Bedding et al., 2007). Hence,  $\beta$  Hyi is a valuable example for solar studies in a broader context. This paper is organized as follows: in Sect. 2, we present selected previous results on the evolution of solar-type activity; in Sect. 3, we discuss aspects of  $\beta$  Hyi. Concluding remarks are given in Sect. 4.

## 2. Selected Previous Results

In the following, we present tidbits about the evolution of solar-type activity pertaining to both observational and theoretical aspects.

- A seminal paper was given by Noyes et al. (1984). They examined the relation between rotation, convection, and activity in low-mass main-sequence stars. Noyes et al. (1984) found that the mean levels of Ca II H and K chromospheric emission is well-correlated with the stellar rotational period, in alignment with predictions from dynamo theory. The authors also noted a dependency of Ca II H and K on the stellar spectral type that inspired many future theoretical and observational studies.
- Schrijver (1987) and Rutten et al. (1991) studied sets of main-sequence stars of different activity levels as well as giant stars while focusing on Ca II H + K and Mg II  $h + k$  chromospheric emission. The authors argue that the results indicate the presence of two-component chromospheric emission, consisting of basal-flux emission (presumably of

non-magnetic, i.e., acoustic origin) and another type of emission that distinctly depends on the stellar activity level. The latter component is expected to be magnetic in nature. On the other hand, Judge and Carpenter (1998) argued in a subsequent study that the basal component is at least in part of magnetic origin as well.

- Another important contribution was made by Baliunas et al. (1995), who studied the Ca II H + K emission cores in 111 stars of spectral type F2–M2 on or near the main-sequence. The results indicate a pattern of change in rotation and chromospheric activity on an evolutionary timescale, in which (1) young stars exhibit high average levels of activity and rapid rotation rates; (2) stars of intermediate age have moderate levels of activity and rotation rates, and (3) stars as old as the Sun and older have slower rotation rates and lower activity levels; the authors also commented on possible stellar Maunder minima. More recent work by Wright et al. (2011) derived the stellar activity – rotation relationship for a sample of 824 solar and late-type stars, thus offering information on the evolution of stellar dynamos.
- Charbonneau et al. (1997) studied various processes closely related to the evolution of angular momentum based on detailed stellar structure models including the change in inertia and the loss of angular momentum through the stellar winds; moreover, the change of chromospheric emission on stellar evolutionary time scales has been discussed as well. Follow-up work has also been pursued, including studies by Keppens et al. (1995), who explored the evolution of the rotational velocity distribution for solar-type stars. Furthermore, Saar and Osten (1997) studied the rotation, turbulence, and surface magnetic fields in Southern dwarfs.
- Another relevant contribution was provided by Pérez Martínez et al. (2011). They examined the Mg II *h + k* line emission associated with the extended chromospheres of a set of 177 cool G, K, and M giants and supergiants. These fluxes represent the chromospheric radiative energy losses presumably related to basal heating by the dissipation of acoustic waves, plus a highly variable contribution due to magnetic activity. The statistical analysis of the data provide evidence for a well-defined Mg II basal flux limit.
- Previous examples for two-component (acoustic and magnetic) for stellar chromosphere models allowing a detailed comparison with the work by Schrijver (1987) and Rutten et al. (1991) have been given by Cuntz et al. (1999). They consider K2V stars of different magnetic activity. The magnetic filling factor (MFF) is set via an observational relationship between the measured magnetic area coverage and the stellar rotation period. It is found that the heating and chromospheric emission is significantly increased in the magnetic component and is strongest for flux tubes that spread the least with height, expected to occur on rapidly rotating stars with high magnetic filling factors. For stars with very slow rotation, the authors were able to reproduce the basal flux limit previously identified with nonmagnetic regions. The empirical relationship between the Ca II H + K emission and the stellar rotation rate could be reproduced as well. Additional results for stars of other spectral types were given by Fawzy et al. (2002a) and Fawzy et al. (2002b). Previ-

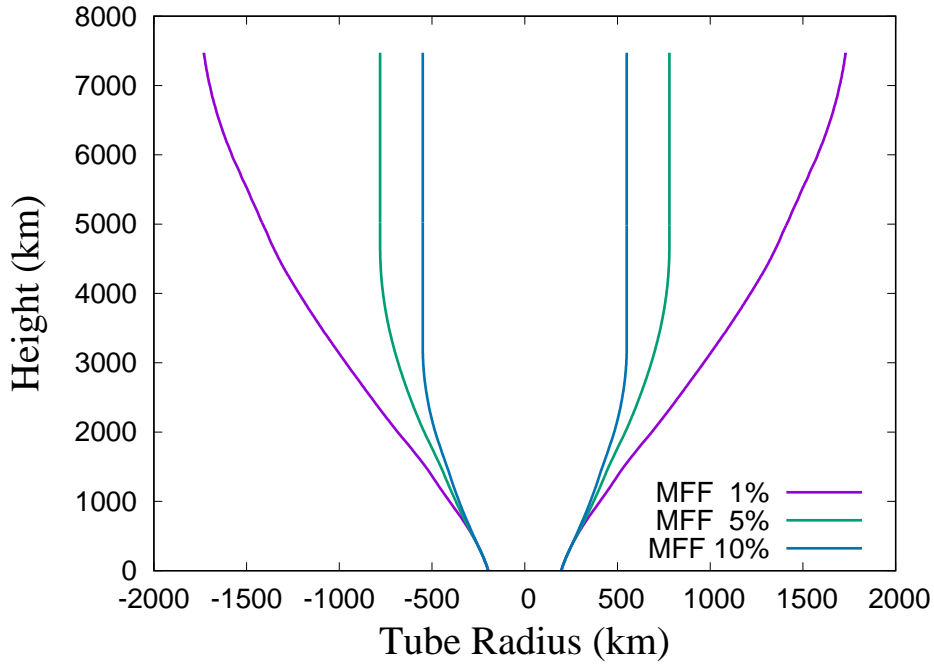
ously, Buchholz et al. (1998) reproduced the basal flux limit for both main-sequence stars and giants based on pure acoustic hearing.

- More recently, additional papers have been published for solar-type stars pertaining to the relationships between stellar evolution, loss of angular momentum, atmospheric heating and spectral emission, including associated effects on exoplanets. Examples include work by Johnstone et al. (2015), Tu et al. (2015), and Linsky et al. (2020). Johnstone et al. (2015) and Tu et al. (2015) focused on the evolution of solar-type winds as well as the UV and X-ray behaviors of solar-type stars on evolutionary time scales. Linsky et al. (2020) pointed out, in alignment with previous studies, that EUV and X-ray emission from stellar coronae drives mass loss from exoplanet atmospheres, whereas emission from stellar chromospheres drives photochemistry in exoplanet atmospheres. This is a pivotal inspiration for further work, including the study of the spectral energy distributions of host stars – noting that the latter is essential for understanding the evolution and habitability of terrestrial exoplanets. The authors concluded that as stars age on the main-sequence, the emissions from their chromospheres and coronae follow a pattern in response to the amount of magnetic heating in these atmospheric layers.

### 3. Case Study: Beta Hydri

A key example for assessing the evolution of solar-type activity is  $\beta$  Hyi. It has a surface temperature, metallicity, and mass akin to the Sun; however, it is  $\sim 2$  Gyr older than the Sun (Dravins et al., 1998; Brandão et al., 2011). Hence,  $\beta$  Hyi constitutes a striking example of future solar activity and properties. Previous results have been given by, e.g., Dravins et al. (1993c), Dravins et al. (1993b), and Dravins et al. (1993a). These studies indicate that  $\beta$  Hyi is at an early subgiant stage, when lithium that once diffused to beneath the main-sequence convection zone is dredged up to the surface as the convection zone deepens. Other findings include that (1) according to 3-D photospheric hydrodynamic simulations, typical granules are about a factor of five larger than solar ones, (2) there is reduced photospheric pressure initiating higher granular velocities, (3) high-resolution Ca II H and K profiles show the emission to be about half that for the Sun, but with the same sense of violet-red asymmetry, (4) weak UV and X-ray emission if compared to the Sun, and (5) stellar wind conditions shaped by post-main-sequence thermodynamics.

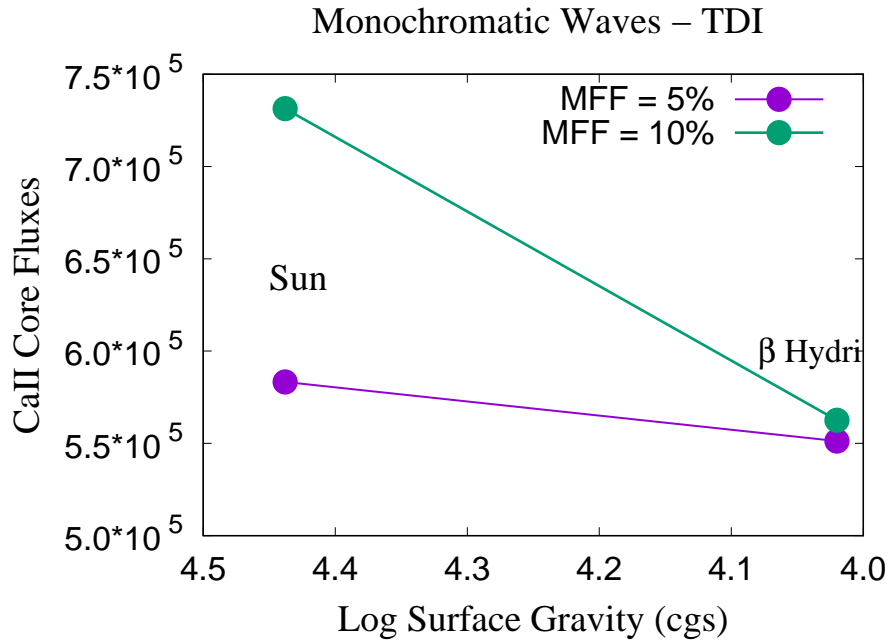
However, most of these results have not yet been compared to detailed ab-initio models; nonetheless, numerous findings about  $\beta$  Hyi's outer atmospheric heating and emission have become available based on theoretical simulations, including recent studies by Cuntz and Fawzy (2022) and Fawzy and Cuntz (2023). These models employ a combination of acoustic and magnetic energy generation and propagation (two-component models), including cases of different magnetic filling factors. Previous theoretical work regarding magnetic and acoustic energy generation with a focus on longitudinal flux-tube waves has been given by Musielak et al. (1994), Musielak et al. (1995), and Ulmschneider et al. (2001). Specifics regarding two-component models have been discussed by Cuntz et al. (1999) and others.



**Figure 1:** Flux tube models for  $\beta$  Hyi based on different magnetic filling factors; see Fawzy and Cuntz (2023) for details. (Reproduced from Fawzy and Cuntz, 2023, originally published by Springer Nature.)

Results obtained by Cuntz and Fawzy include that for acoustic waves the amount of generated energy is notably higher (about a factor of 2.3) in  $\beta$  Hyi compared to the Sun. This behavior is due to the greater photospheric granular velocity of  $\beta$  Hyi owing to its lower surface gravity; see Dravins et al. (1993c). For longitudinal flux-tube waves, the amount of generated energy is reduced (about a factor of 1.1 to 1.3) relative to the solar case, a behavior due to  $\beta$  Hyi's thermodynamic and magnetic field conditions. Figure 1 conveys information about the adopted flux tube models, whereas Fig. 2 gives examples about the emergent Ca II core fluxes, both regarding  $\beta$  Hyi and the Sun (note the impact of  $\log g_*$ !) Smaller magnetic filling factors correspond to flux tubes of more extended spreading accompanied with reduced heating and chromospheric emission as a function of height. The magnetic filling factor in  $\beta$  Hyi is expected to vary across the surface (just like in the solar case); therefore, in the absence of detailed surface information, a set of models with different MFFs should be taken into account.

The height-dependent behavior of the mechanical energy flux for different MFFs regarding  $\beta$  Hyi, as well as different types of models, is presented in Fig. 3; see Cuntz and Fawzy (2022) for background information. This work considers both spectral and monochromatic waves. It is found that a higher MFF entails a somewhat smaller decrease of the magnetic wave energy flux as a function of height, especially in the middle chromosphere, mostly associated with the difference in tube spreading. However, at large heights other effects are also relevant, especially in narrow tubes, including effects associated with strong shocks, which initiate both quasi-adiabatic cooling. The various kinds of models are a stark motivation for more extended studies, including detailed comparisons between theoretical and observational works.

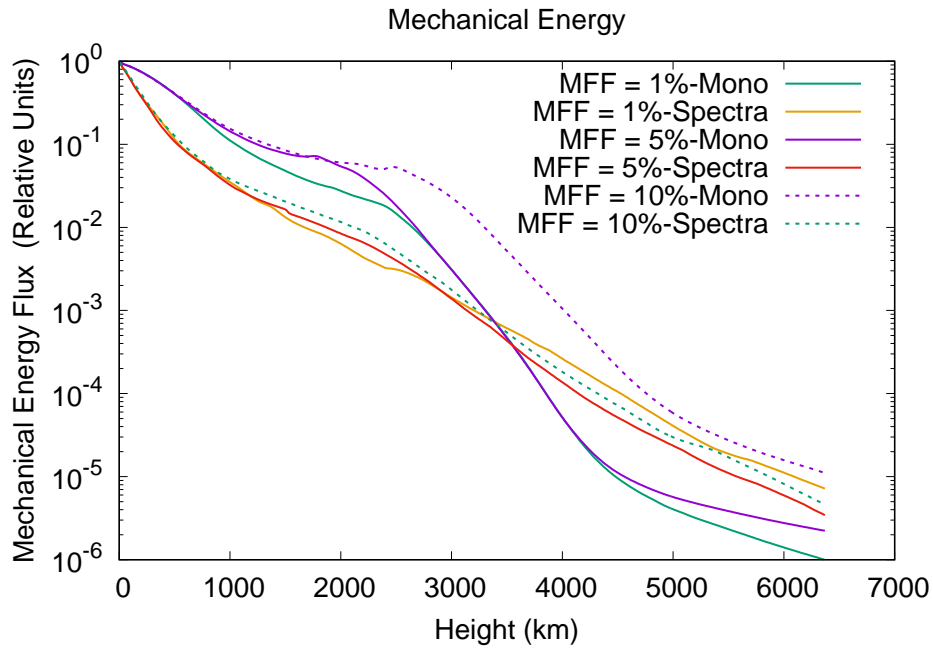


**Figure 2:** Emergent Ca II core fluxes for two-component chromosphere models (acoustic and magnetic) pertaining to the Sun and  $\beta$  Hyi with photospheric magnetic filling factors given as 5% and 10%. (Reproduced from Cuntz and Fawzy (2022) – CC BY 4.0.)

#### 4. Concluding Remarks

Future work is expected to provide more detailed comparisons between the outcomes of theoretical models and observations in order to assess the modes of outer atmospheric heating as well as the photospheric/chromospheric magnetic filling factors. The latter are a distinct testimony of stellar evolution, which is closely connected to the loss of angular momentum resulting in a reduction in magnetic activity. In case of the Sun, its activity varies on different timescales, including very short and super-long timescales, with the latter being associated with stellar and planetary evolution (e.g., Nandy et al., 2021, and references therein). Clearly, those latter changes are closely related to the Sun’s nuclear evolution, thus affecting the solar interior structure, which continues to result in the loss of angular momentum as well as changes in the solar rotation rate, magnetic surface structure, and the magnitude of magnetic and nonmagnetic surface heating and outer atmospheric emission.

For example, the environment of the early, young Sun was relatively extreme, with more energetic storms, winds, and radiative output creating harsh conditions for (especially) the inner Solar System planets, including Earth. These conditions will continue to abate, which will favorably affect the habitability prospects of other Solar System objects, including the terrestrial satellites of Jupiter and Saturn. Reviews on stellar activity and its role(s) on space weather have been given by Lammer et al. (2009) and others; see also white paper by Airapetian et al. (2018) and subsequent contributions. This type of work is highly relevant to a large array of topics including (but not limited to) the future of life on Earth, general prospects of planetary habitability concerning different types of stars, and the search for life in the Universe.



**Figure 3:** Height-dependent behavior of the mechanical energy flux in magnetic wave models (relative units) for  $\beta$  Hyi. Both monochromatic waves and spectral waves have been considered based on magnetic filling factors of 1%, 5%, and 10%, respectively; see Fawzy and Cuntz (2023) for background information and details. (Reproduced from Fawzy and Cuntz, 2023, originally published by Springer Nature.)

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## Further Information

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### Conflicts of interest

The author declares no conflict of interest.

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