Sun-as-a-star variability of Solar Balmer lines

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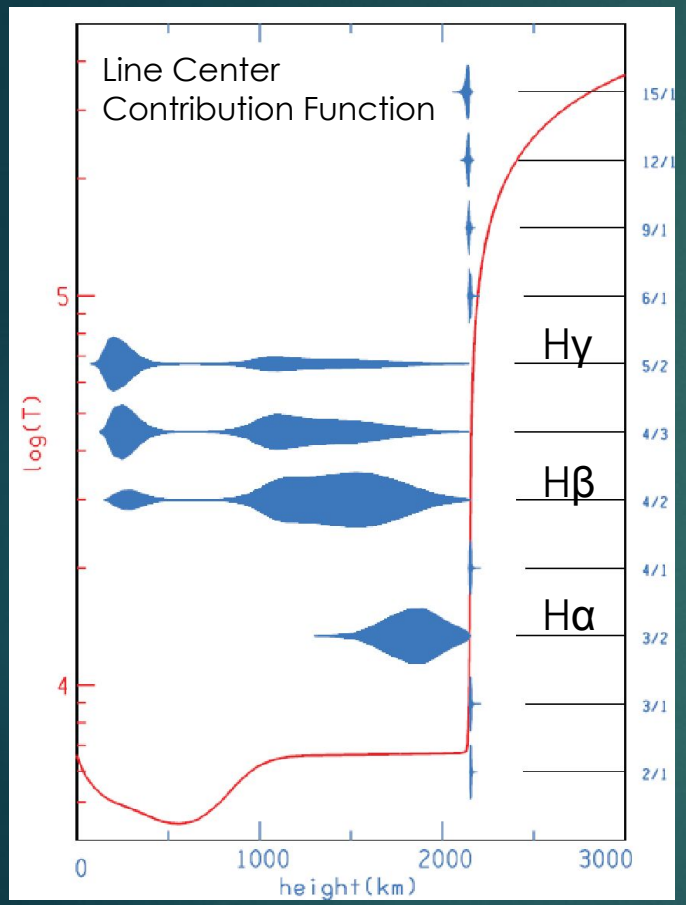
Why Hydrogen Balmer lines?

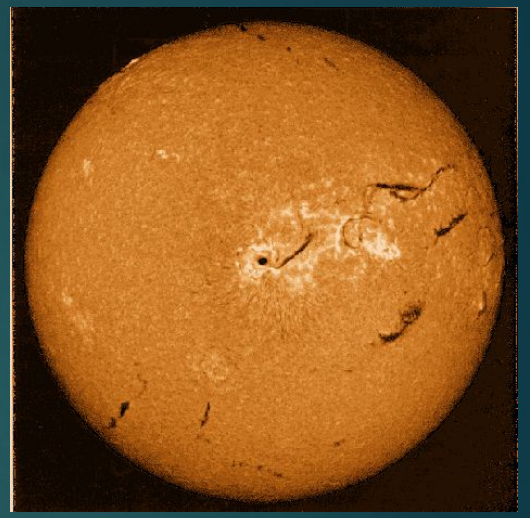


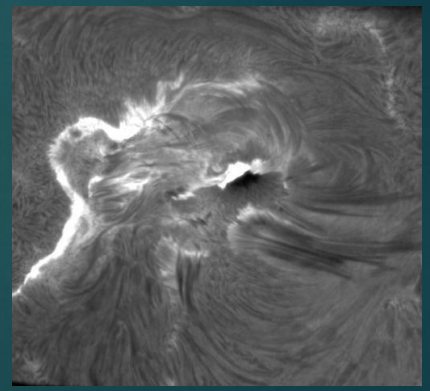
From Avrett&Loeser 2008

Cores of Upper Balmer lines form in the Chromosphere:

➡ Diagnostic of stellar chromospheres and phenomena occurring in it.

➡ Proxy of Stellar Magnetic Activity



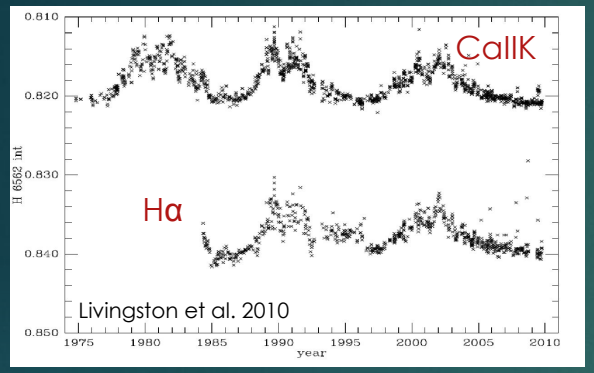


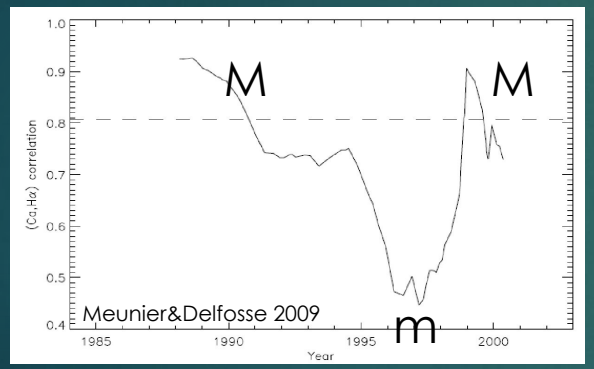
Balmer lines probe higher layers of Exo-planet atmospheres.

Hα in particular:

1) Diagnostic of heating processes
2) Diagnostic for interaction of UV radiation of hosting star with exo-planet atmospheres
3) Diagnostic of upper atmospheres of exoplanets

Balmer lines show complex relation with other chromospheric indices - Ha



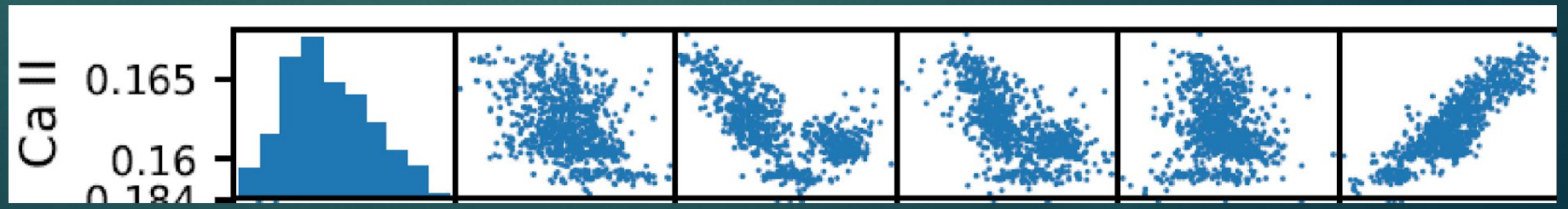


Large sample of solar-like stars Ha-index uncorrelated, no-correlation, correlated with Ca II index (Meunier et al. 2022).

For the Sun, Hα-CaII index correlations show very wide range of values, depending on temporal scales considered and phase of the cycle!

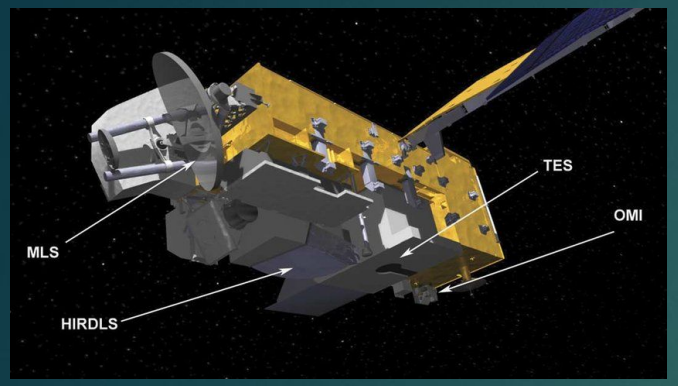
Previous results have been recently challenged by HARPS-N solar measurements

Hα Hβ Hγ Hδ Hε



Anti-correlated!!!

Maldonado et al. 2019



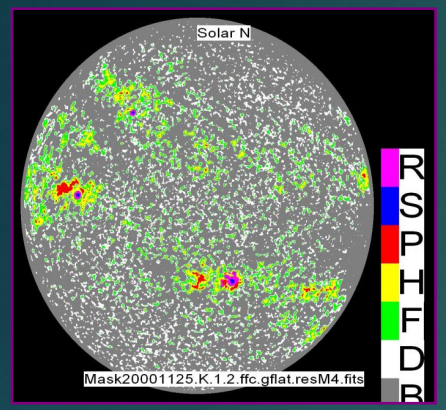
MEASUREMENTS

Instrument	Observable	Resolving Power	Temporal scale
OMI	H-β, γ, δ indices	~850	Solar rotation
SCIAMACHY+GOME-2	H-a index	~2000	Solar rotation
OSIRIS	H-a index	~850	Decadal
ISS	H-a index	~300000	Decadal

- Scarcity of observations, especially for upper Balmer lines, both disk integrated and spatially resolved.
- First attempt to study variability of Balmer lines on the solar rotational scale (to the best of our knowledge).

More data expected in the near future from planet hunters!

Model: semi-empirical irradiance reconstruction

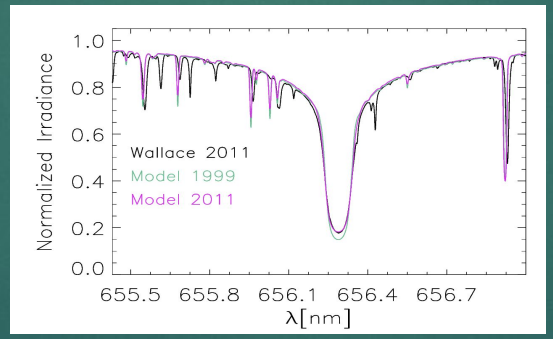


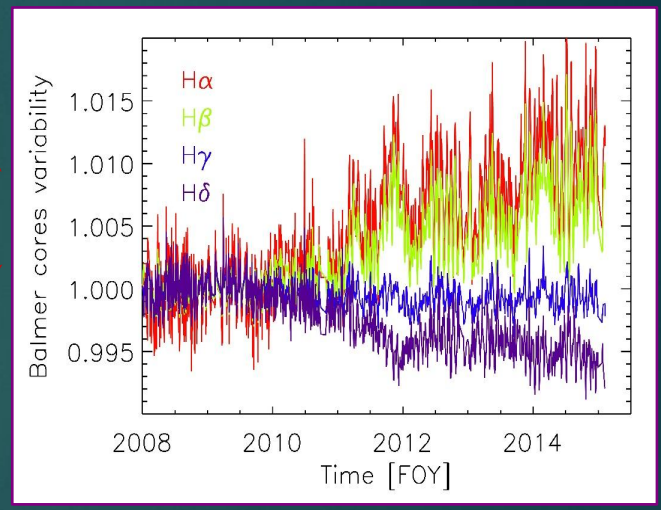
Daily observations acquired with the Precision Solar Photometric Telescope (**PSPT**) from **2005 to 2015**.
CaIIK + red cont.
Masks derived using the **SRPM** (Fontenla&Harder 2005) segmentation algorithm

Feature masks + Synthetic Spectra → Irradiance variability

Set of Atmosphere Models (1D static):

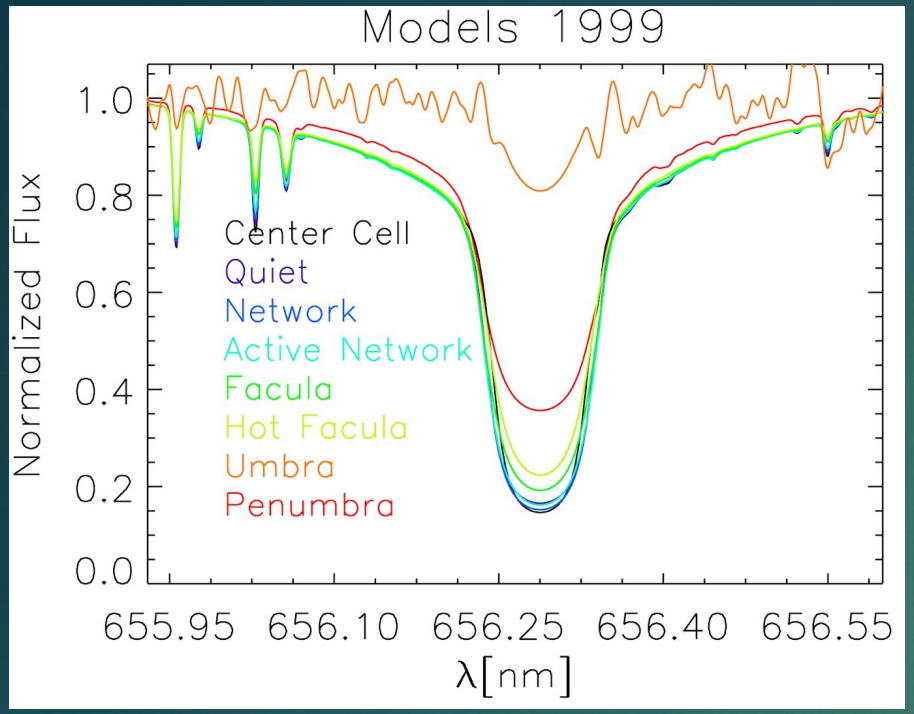
- Fontenla et al. 1999 (FAL99)
- Fontenla et al. 2011 (FAL2011)





Variability of reconstructed Balmer core Intensities obtained from FAL1999 models

RH radiative Transfer code (Uitenbroek 2001, Kowalski et al. 2017)
NLTE synthesis of Balmer lines (not only Hα!)
Syntheses at 21 different lines-of-sight



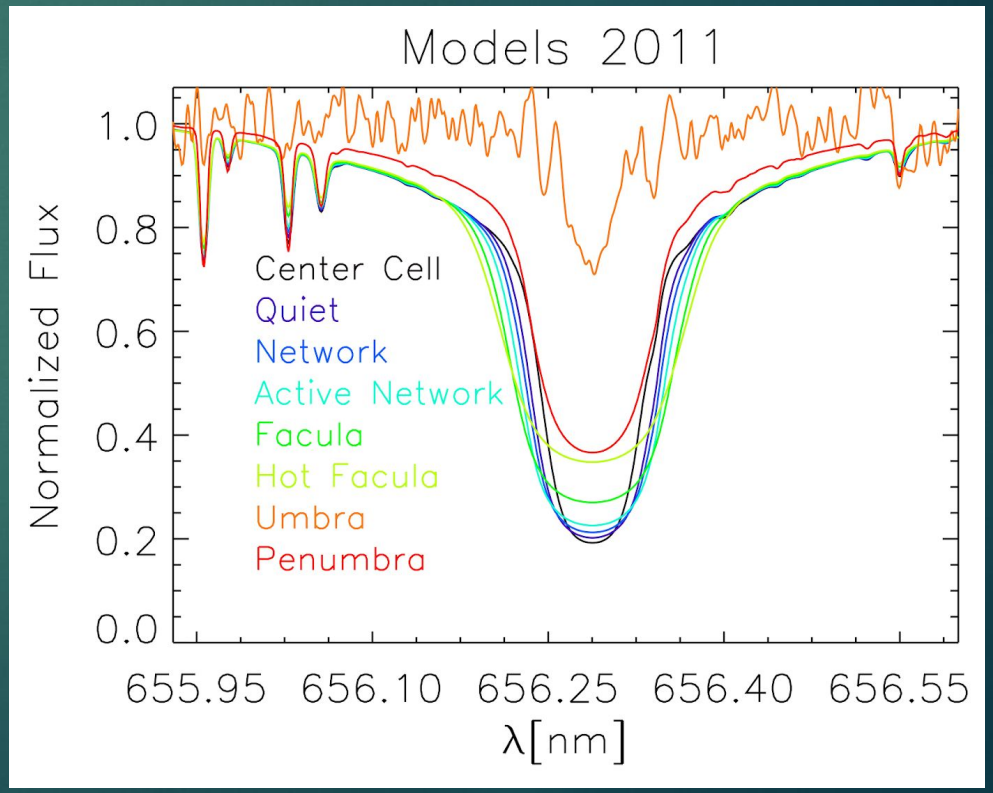
MODELS 1999

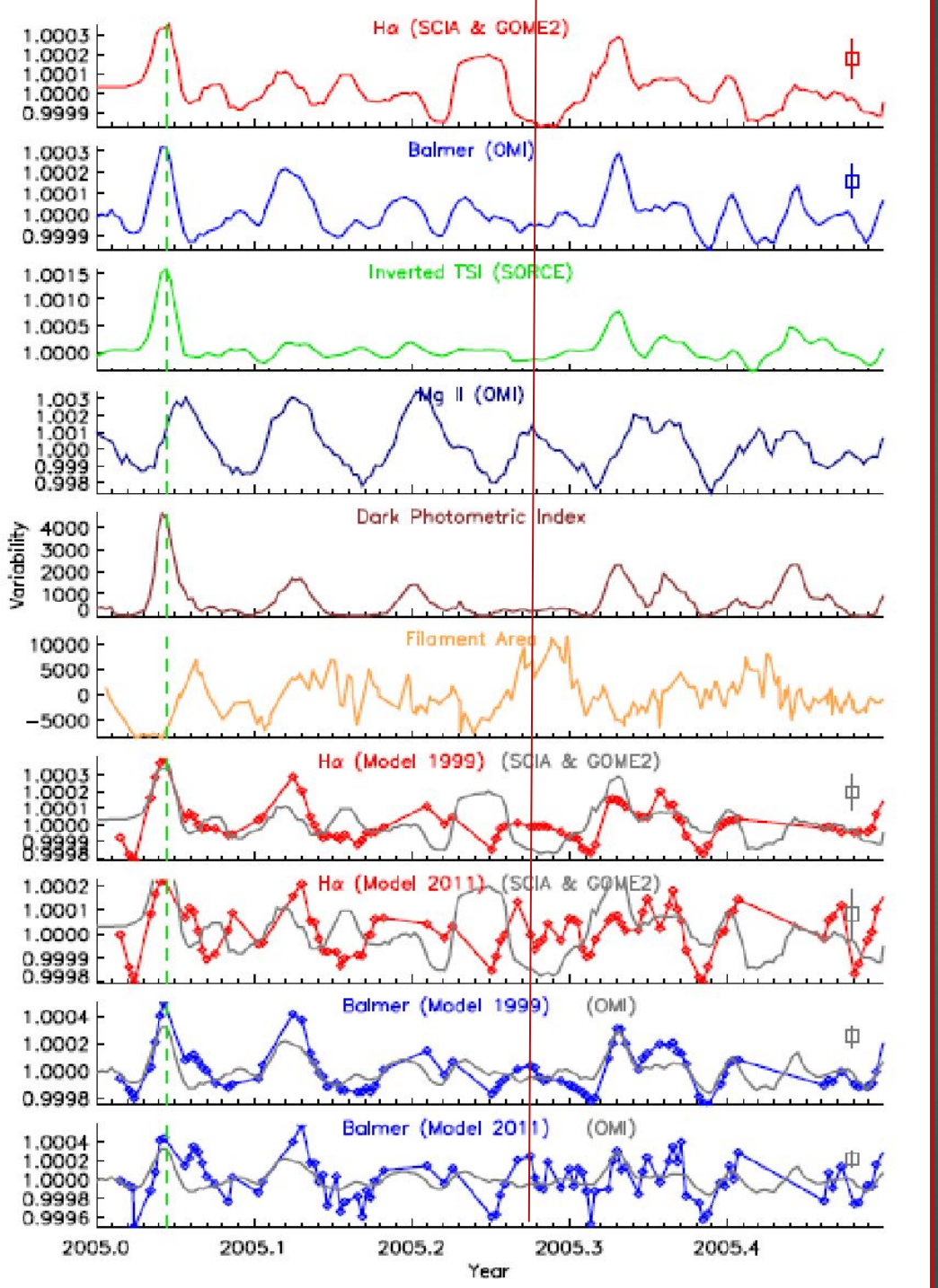
- More commonly used for irradiance reconstructions
- Profiles narrow with the increase of activity (not reproduced by observations)
- Network models produce deeper profiles than the Quiet model
- Better reproduces facular contrast in Ha

MODELS 2011

- Broad profiles, which reproduce better Hig.- Res. observations (Molnar et al. 2019)
- Reproduce better FTS Atlas profiles
- All models produce shallower profiles than the FAL1999
- Network models produce shallower profiles than the Quiet model

Scarcity of spatially resolved observations/studies especially for upper Balmer lines.





Results: Rotational Time Scale

Data and models detrended with a 61-days window

Both Balmer, Ha indices closely follow the inverted-TSI, and often deviate from the variability measured in chromospheric indices.

Models overestimate plage/network contribution

In some rotations the effects of filaments is evident, e.g. 2005.29

Correlation Coefficients detr. Measurements		
	MgII	Inv. TSI
Balmer index	0.25	0.55
Ha index	0.2	0.52

Correlation Coefficients detr. Models		
	MgII	Inv. TSI
Balmer-Model 1999	0.62	0.35
Balmer-Model 2011	0.56	0.2
Ha-Model 1999	0.57	0.3
Ha-Model 2011	0.45	0.3

Results: Solar-Rotational Time Scale

E,F: networks
H,P: plages
S: umbra
Pen.: penumbra
Fil.: filaments

Multivariate Analysis

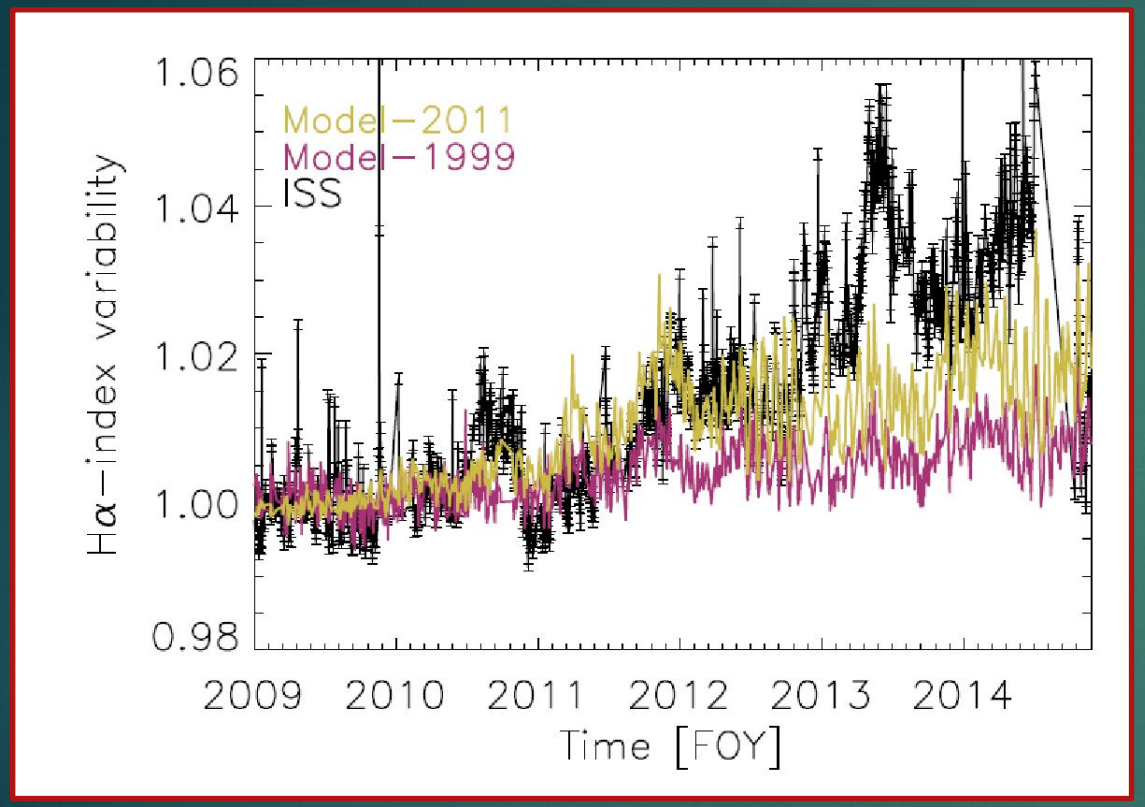
	dof	r_cr (p=0.01)	E	F	Fil.	H	P	Pen.	S
Balmer	203	0.181	–	–	–	–	0.421	0.560	0.544
Model 1999 - Balmer	322	0.145	–	0.446	–	0.856	0.911	0.691	0.660
Model 2011 - Balmer	456	0.121	0.518	0.872	–	0.812	0.702	0.492	–
Hα	401	0.129	-0.089	-0.056	-0.173	0.202	0.427	0.541	0.538
Model 1999 - Hα	983	0.083	0.262	0.656	–	0.796	0.800	0.598	0.575
Model 2011 - Hα	1167	0.075	0.682	0.896	–	0.659	0.528	0.364	–
TSI	485	0.117	-0.043	-0.101	-0.124	–	0.246	0.748	0.746
Mg II index	442	0.122	-0.121	0.459	–	0.763	0.676	0.403	0.390

Measured Balmer indices almost insensitive to network, like the TSI

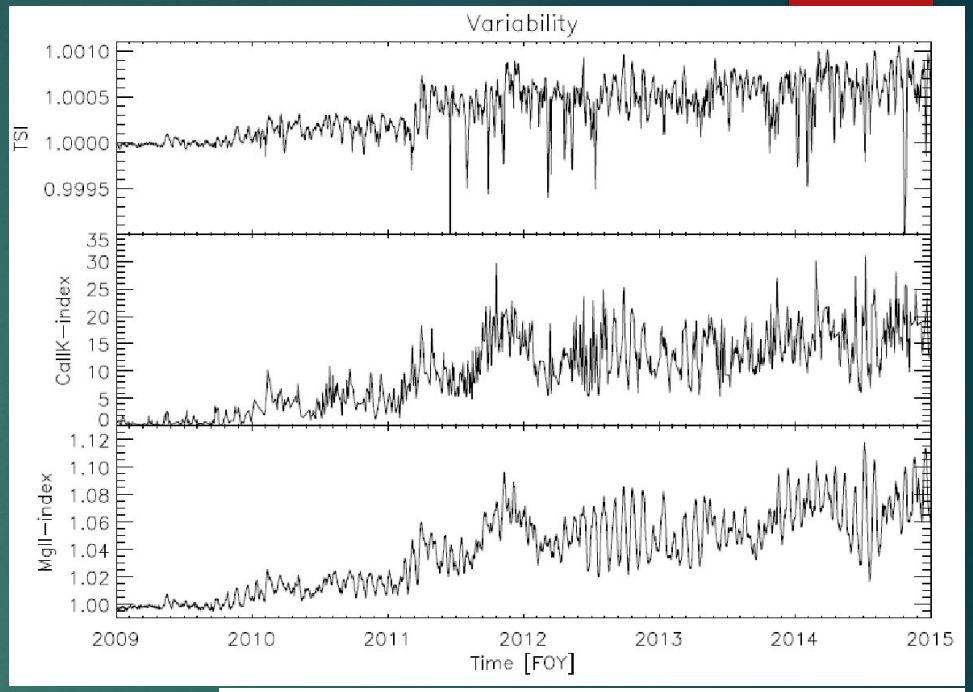
Models overestimate the contribution of networks and plages (Model2011 more so for network)

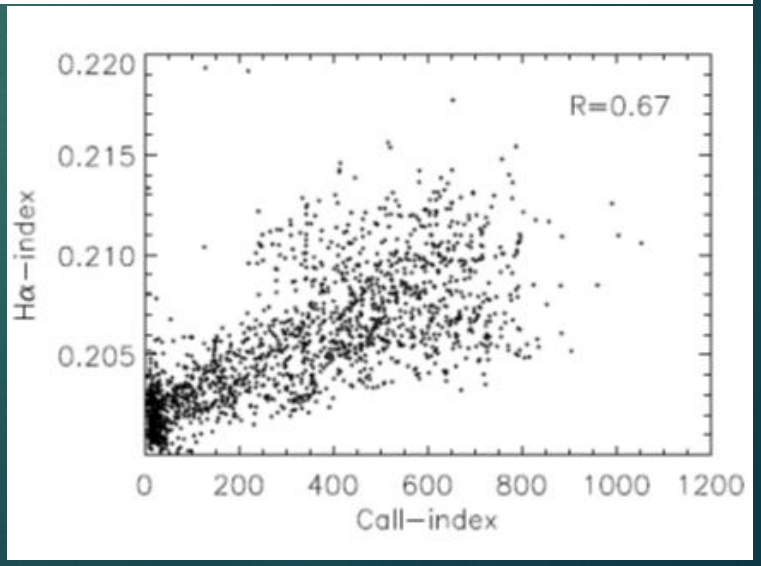
Measured Balmer indices slightly anti-correlated with filaments

Results: Solar-Cycle Time scale Ha

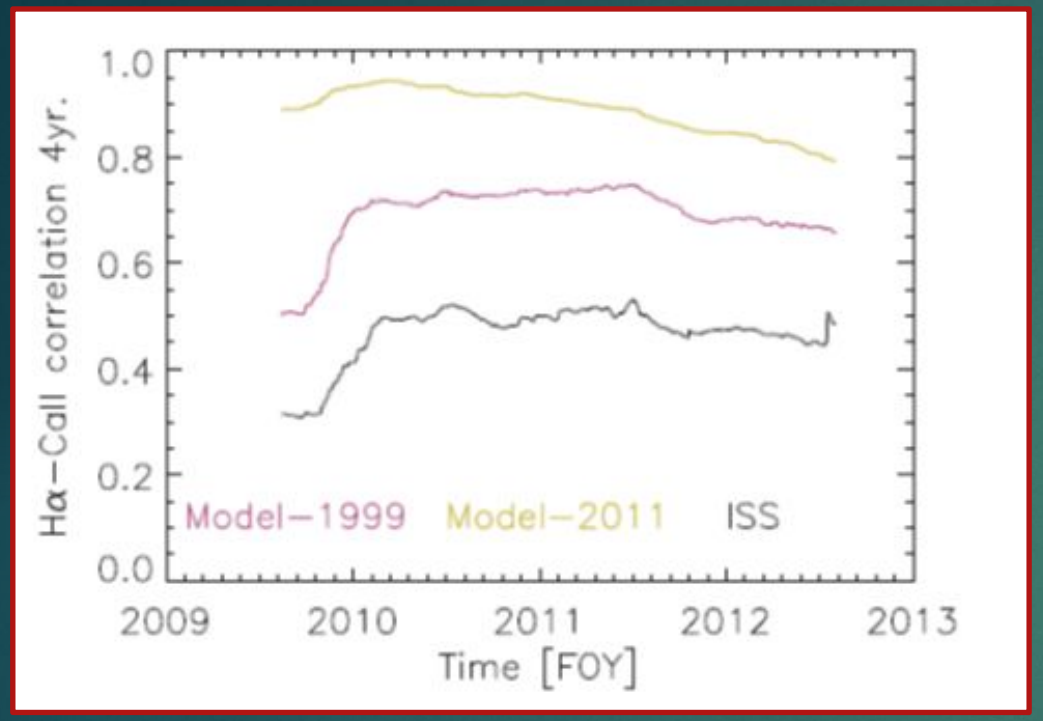


Hα-index increases with the magnetic activity in agreement with Meunier&Delfosse 2009, Livingston 2010





Results: Solar-Cycle Time scale Ha



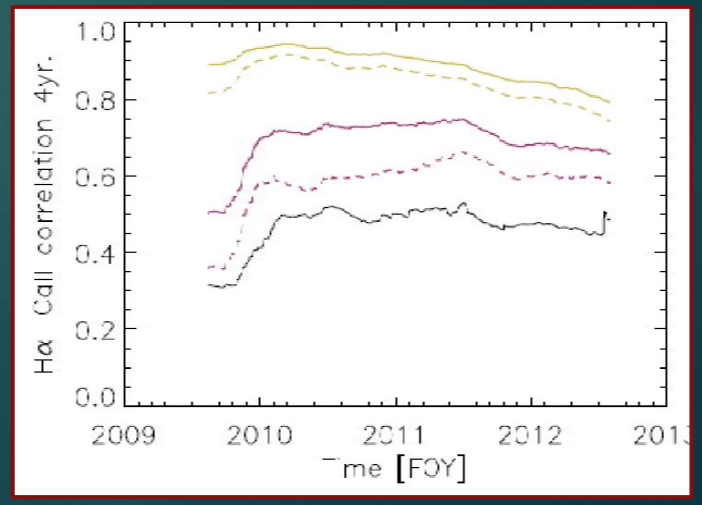
Our reconstructions do not include filaments. Results most likely reflect the low sensitivity of Balmer lines to network, as opposed to other chromospheric indices.

Estimates of filaments contrast in Ha from these curves produce :

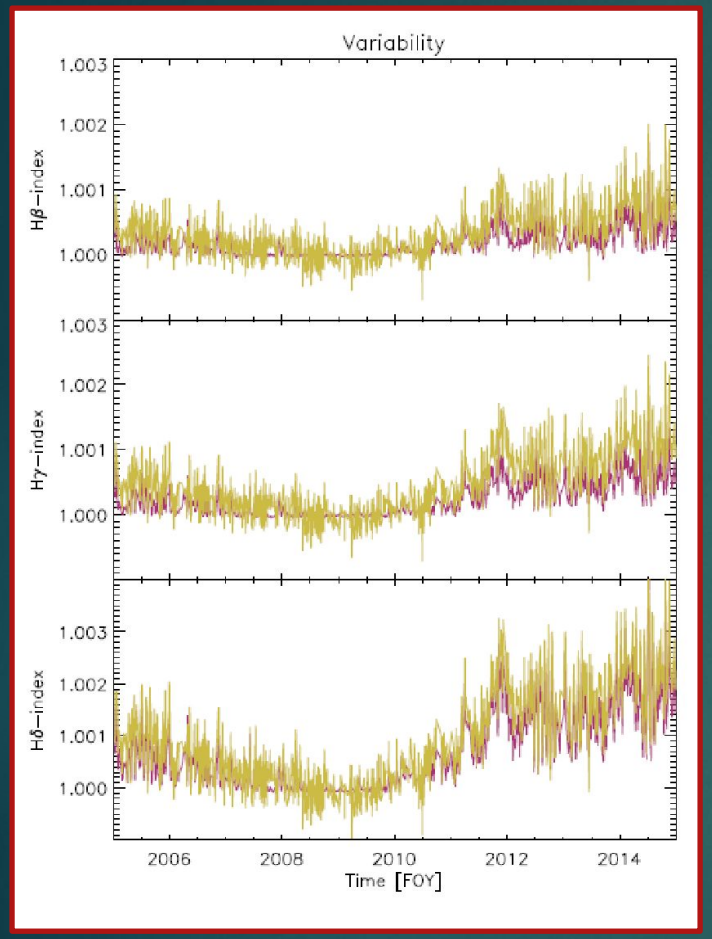
~0.73 for Model 1999. 15% higher than Diercke et al. 2022
~0.1 for Model2011. Unrealistic!

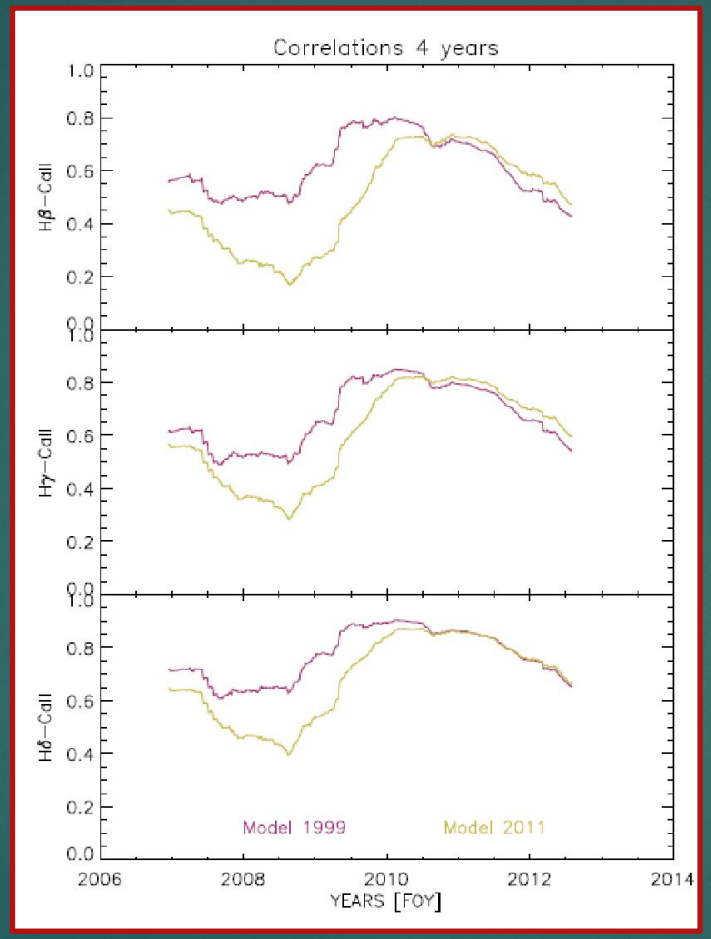
--- Model with filaments:
Core contrast from Kuckein et al. 2016(core contrast -0.3)

Fil. Area from Meudon database

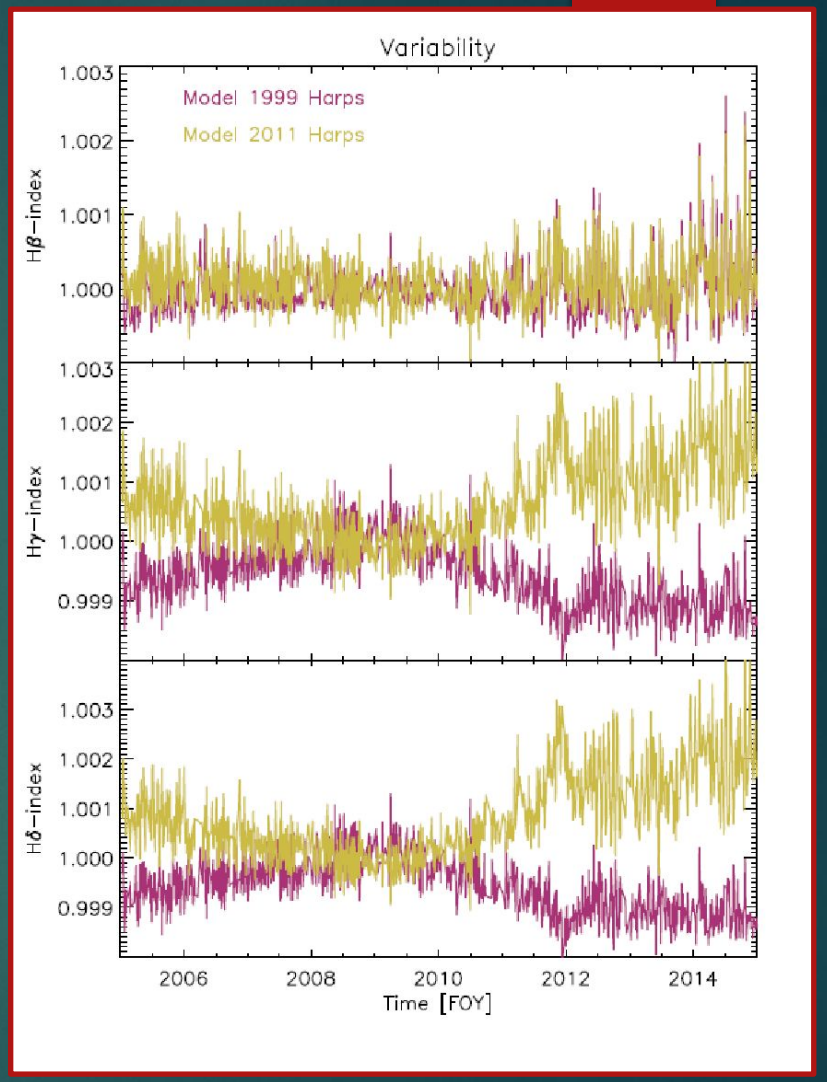


Results: Solar-Cycle Time scale H-β,γ,δ



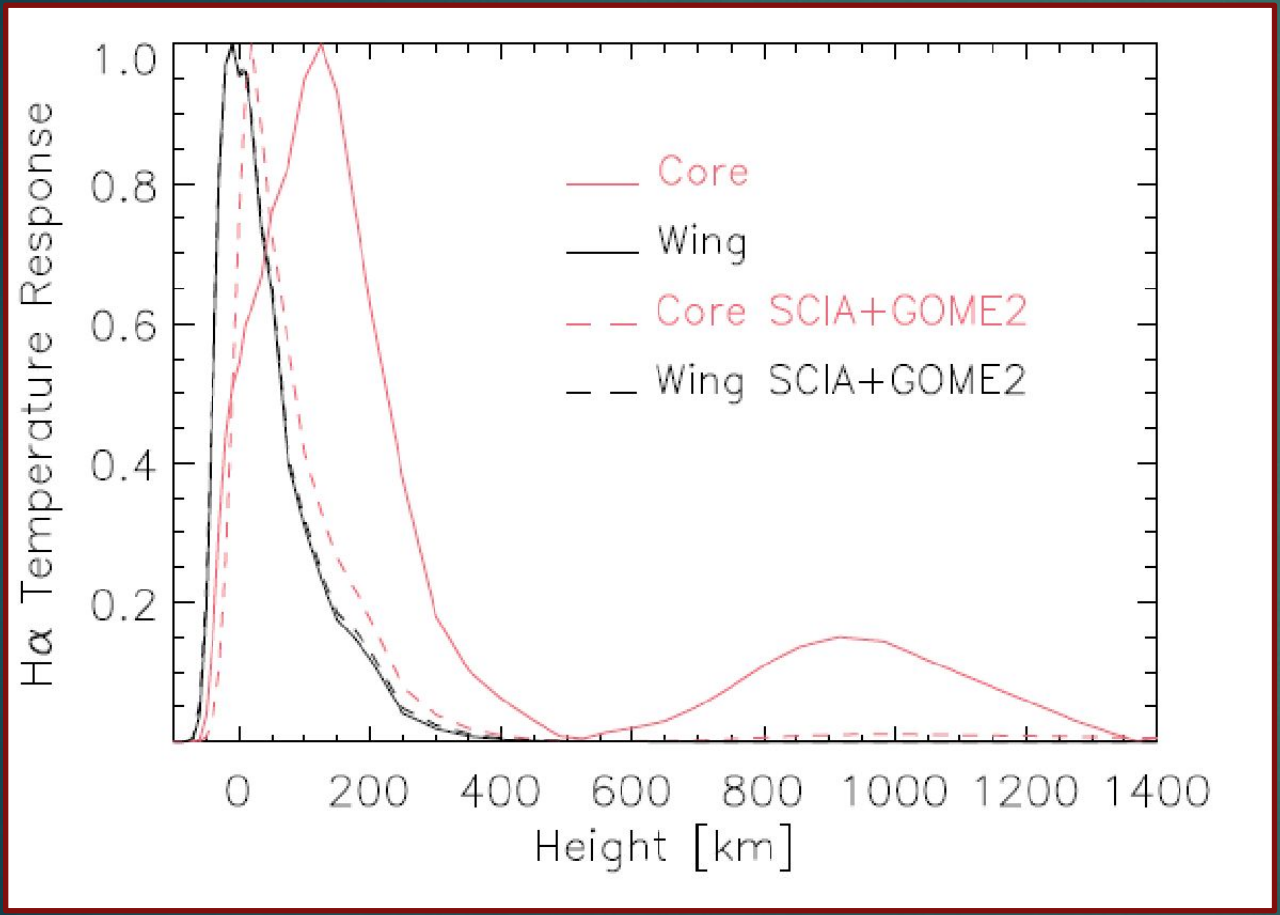


Modelled variability, mimicking OMI measurements
Indices defined as in Marchenko et al. 2021



Modelled variability, mimicking HARPS-N measurements. Indices defined as in Maldonado et al. 2019

Is the Ha core-to-wing ratio a photospheric or a chromospheric index?



Measurements and models indicate that Balmer indices behave like photospheric indices, mostly because of the small/null sensitivity of network.

Cauzzi et al. 2009 found that network brightness in Ha has no correlation with the underlying photospheric magnetic field.

Ha is well known to **respond to photospheric temperature variations rather than chromospheric ones** Socas Navarro & Uitenbroek 2004; Przibylla and Butler 2004; Cauzzi et al. 2009).

Conclusions

- On solar rotation timescales, both models and measurements indicate that the **Balmer indices closely follow the inverted TSI and thus often deviate from the behavior of chromospheric indices.**
- On the longer temporal scales, both model and measurements indicate **that the correlation between the Ha-index and the CaII-index increases, and both the indices vary in phase with the activity cycle.**
- Balmer line profiles of network models are similar to those of quiet-Sun models, thus indicating that the **Balmer indices are almost insensitive to the network**. This result most likely explains the low-/anti-correlation with the chromospheric indices (which are sensitive to the network) found at low levels of activity.
- **Balmer indices are less sensitive to filaments than what had been previous suggested.**
- The set of FAL 1999 models best reproduces the observations, although both models overestimate the variability. **The contribution of faculae is most likely overestimated.**
- **Spectral resolution does not affect Hα variability**, but affects the variability of upper Balmer lines.

- From a theoretical perspective, it is not so surprising that the core-to-wing ratios of Balmer lines follow photospheric indices. The source function is scattering dominated and more sensitive to photospheric conditions.

THANK YOU VERY MUCH