Measuring and modeling the variability of solar Balmer lines

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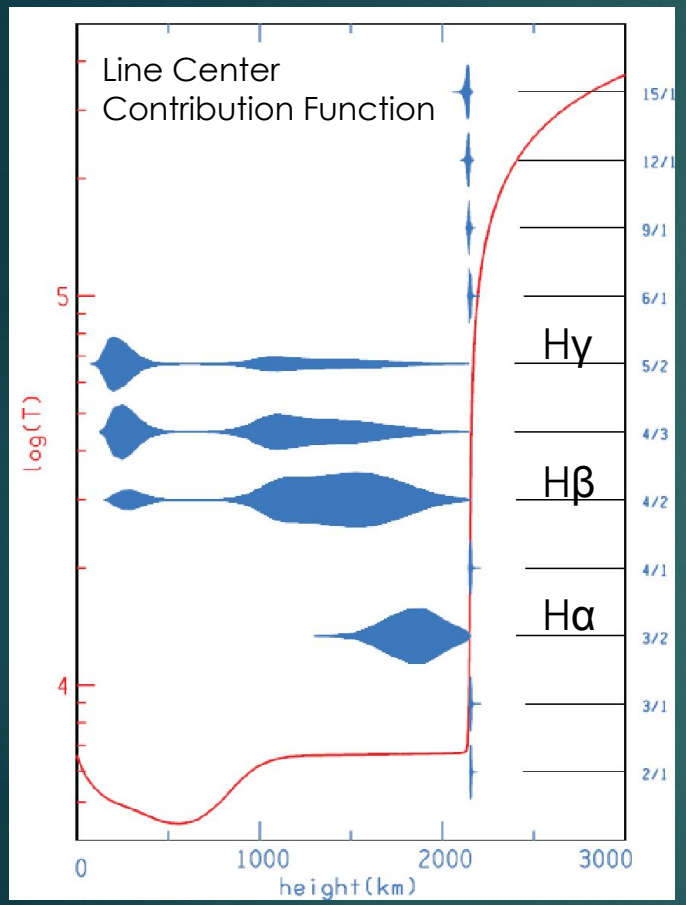
Why Hydrogen Balmer lines?

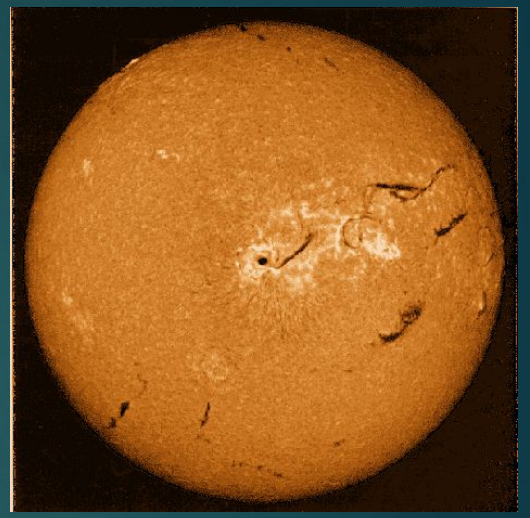


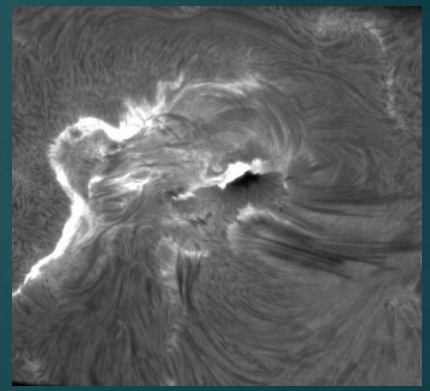
From Avrett&Loeser 2008

Cores of Upper Balmer lines form in the Chromosphere:

➡ Diagnostic of stellar chromospheres and phenomena occurring in it.

➡ Proxy of Stellar Magnetic Activity



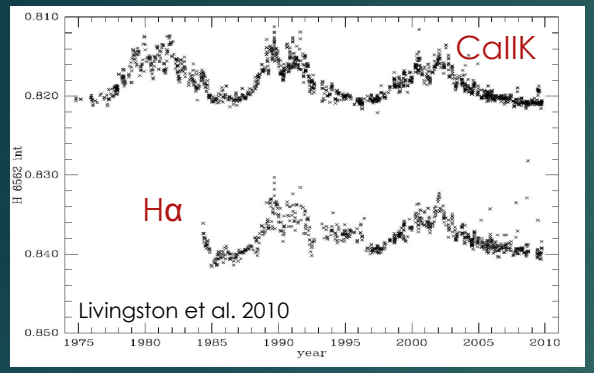


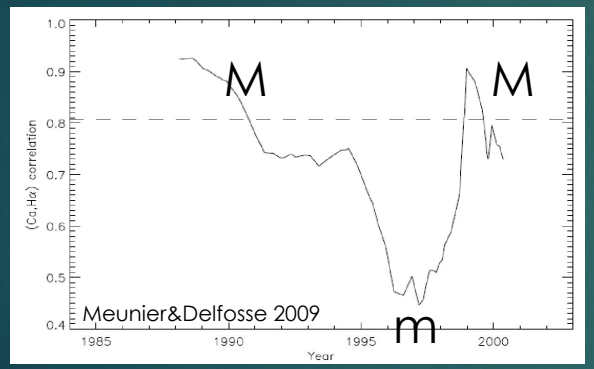
Balmer lines probe higher layers of Exo-planet atmospheres.

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





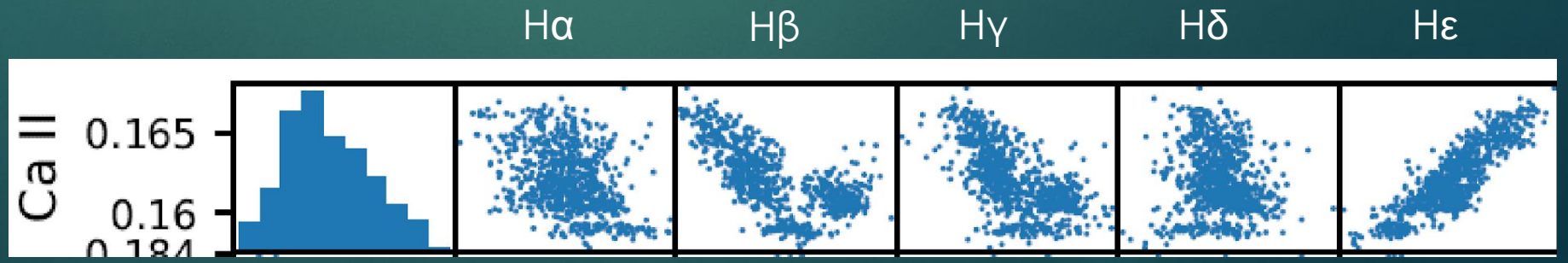
Large sample of solar-like stars Ha-index uncorrelated, no-correlation, correlated with Ca II index (Meunier et al. 2022).

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

Anti-correlated

Maldonado et al. 2019



MEASUREMENTS

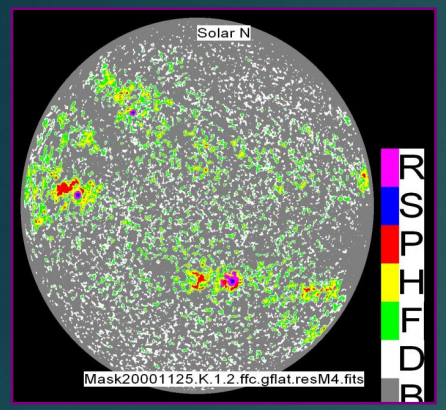
Radiometric Measurements {

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).

OMI+TROPOMI measurements of H-β, γ, δ indices presented by M. DeLand during Sun-Climate 2020 (Marchenko et al. 2021)

Model: semi-empirical irradiance reconstruction

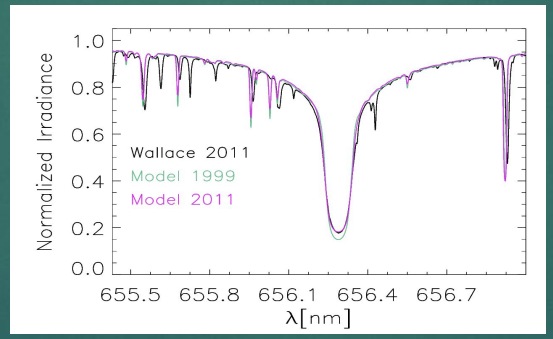


Daily observations acquired with the Precision Solar Photometric Telescope (**PSPT**) from **2005 to 2015**.
CaIIK + red cont.
Masks derived using the **SRPM** (Fontenla&Harder 2005) segmentation algorithm

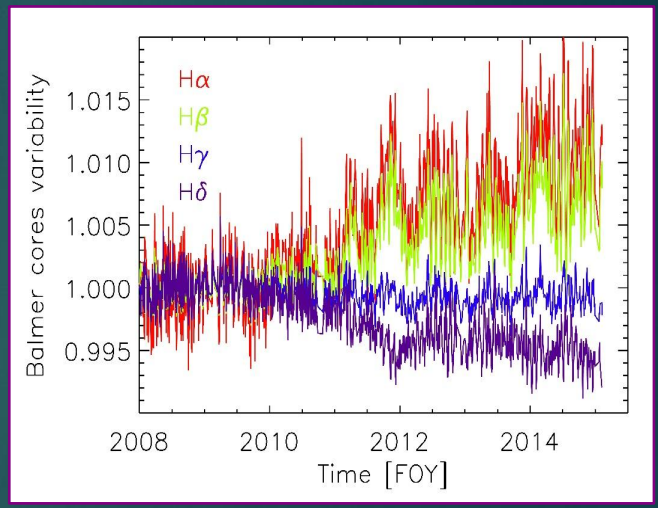
Feature masks + Synthetic Spectra → Irradiance variability

Set of Atmosphere Models (1D static):

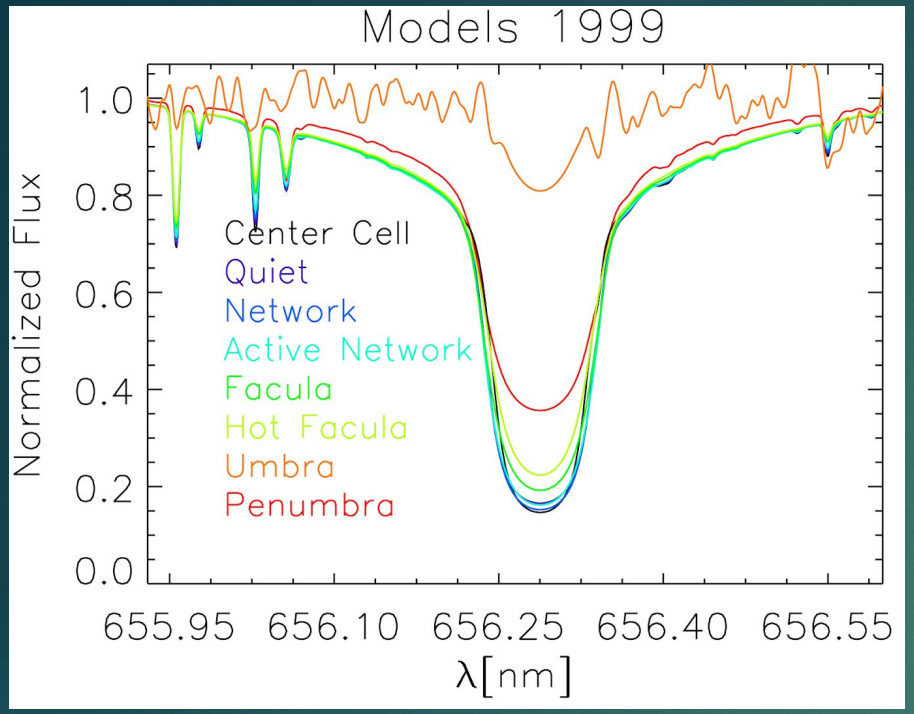
- Fontenla et al. 1999 (FAL99)
- Fontenla et al. 2011 (FAL2011)



RH radiative Transfer code (Uitenbroek 2001)
NLTE synthesis of Balmer lines
Syntheses at 21 different lines-of-sight



Variability of reconstructed Balmer core Intensities obtained from FAL1999 models



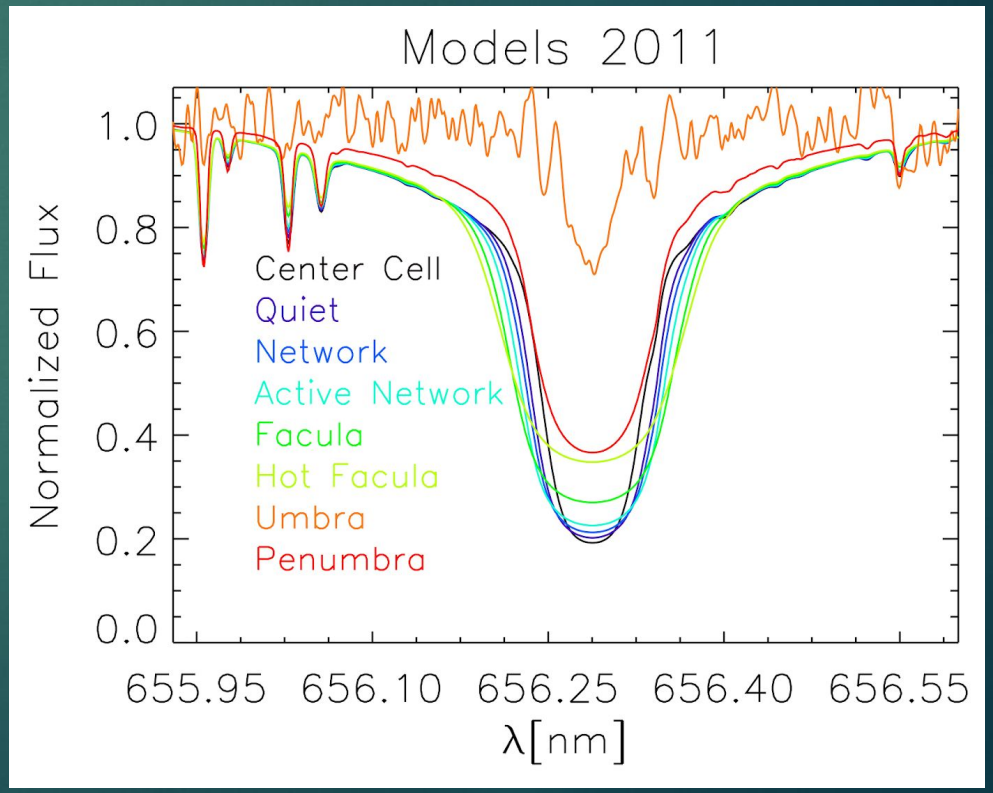
MODELS 1999

- 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

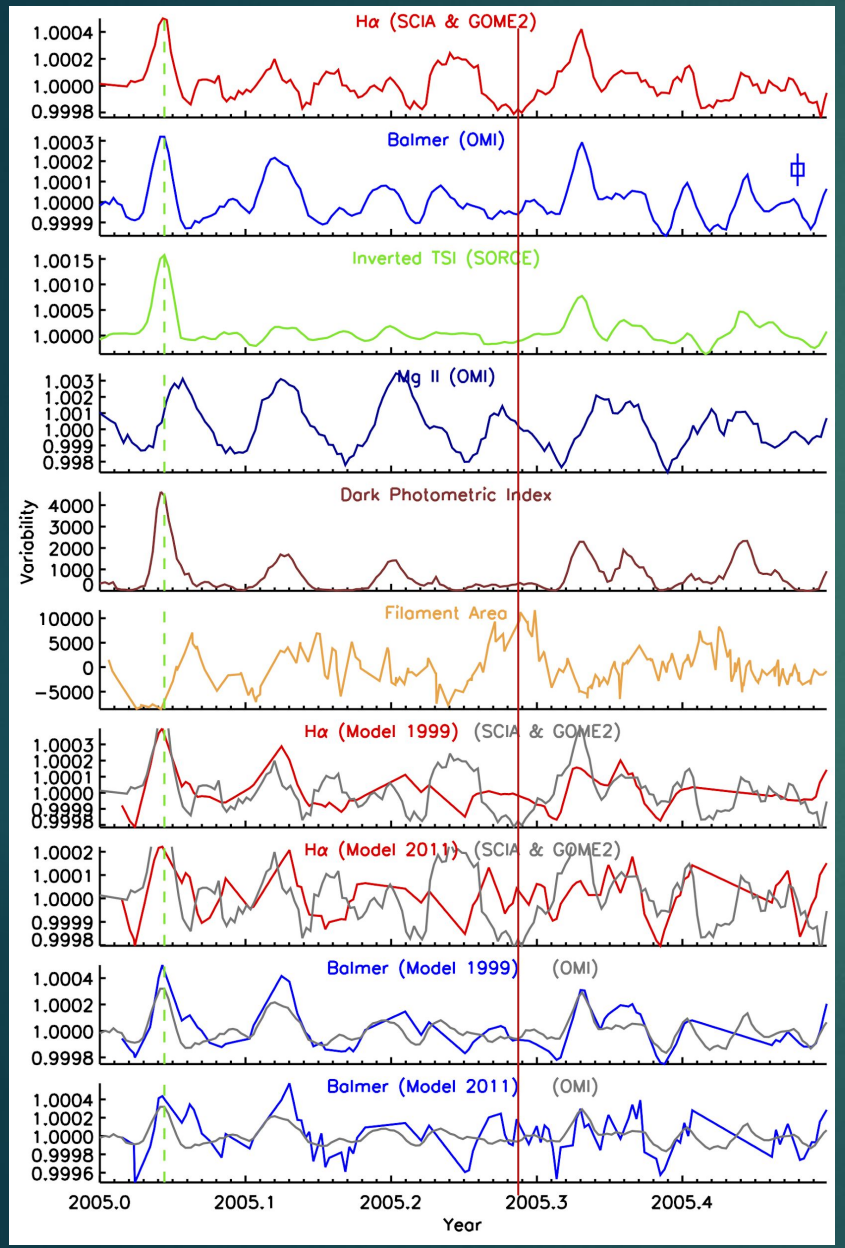
MODELS 2011

- 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: Solar-Rotational Time Scale



- A *Balmer-index* was defined as the sum of the core-to-wing ratio of the H-β,γ,δ as measured by OMI.
- A *Ha-index* was defined as the ratio of the average line intensity (sampled at 5 spectral positions) and the nearby continuum intensity, as derived from the SCIAMACHY+GOME2 composite.

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

See also Marchenko et al. 2021

Correlation Coefficients detr. Measurements		
	MgII	**Inv. TSI**
Balmer index	0.13	0.45
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

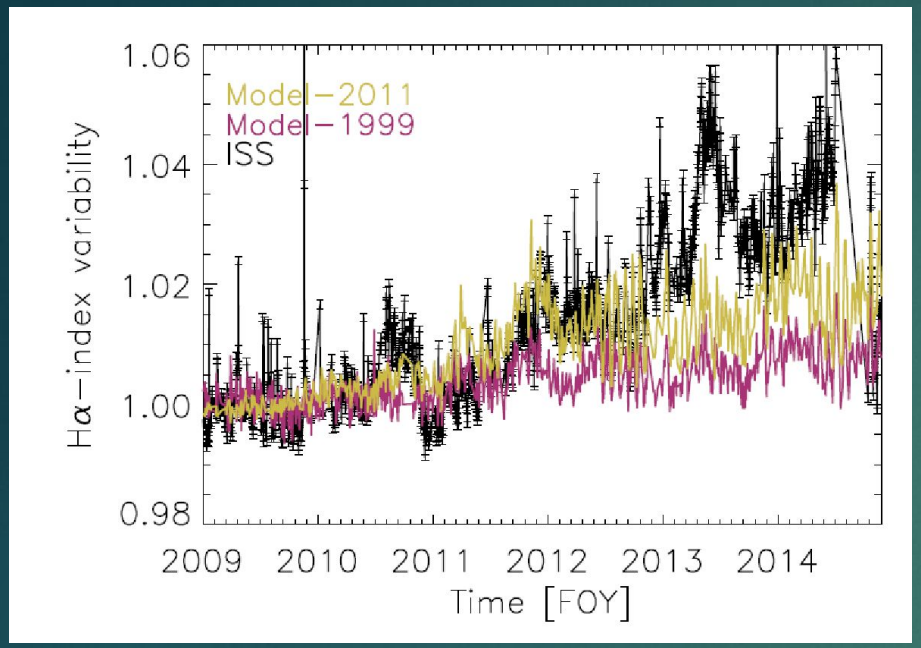
	dof	r_cr (p=0.01)	E	F	Fil.	H	P	Pen.	S	r_multi
Balmer	203	0.181	–	–	–	–	0.421	0.560	0.544	0.568
Model 1999 - Balmer	322	0.145	–	0.446	–	0.856	0.911	0.691	0.660	0.950
Model 2011 - Balmer	456	0.121	0.518	0.872	–	0.812	0.702	0.492	–	0.971
Hα	401	0.129	-0.089	-0.056	-0.173	0.202	0.427	0.541	0.538	0.652
Model 1999 - Hα	983	0.083	0.262	0.656	–	0.796	0.800	0.598	0.575	0.899
Model 2011 - Hα	1167	0.075	0.682	0.896	–	0.659	0.528	0.364	–	0.949
TSI	485	0.117	-0.043	-0.101	-0.124	–	0.246	0.748	0.746	0.862
Mg II index	442	0.122	-0.121	0.459	–	0.763	0.676	0.403	0.390	0.794

Measured Balmer indices almost insensitive to network, like the TSI

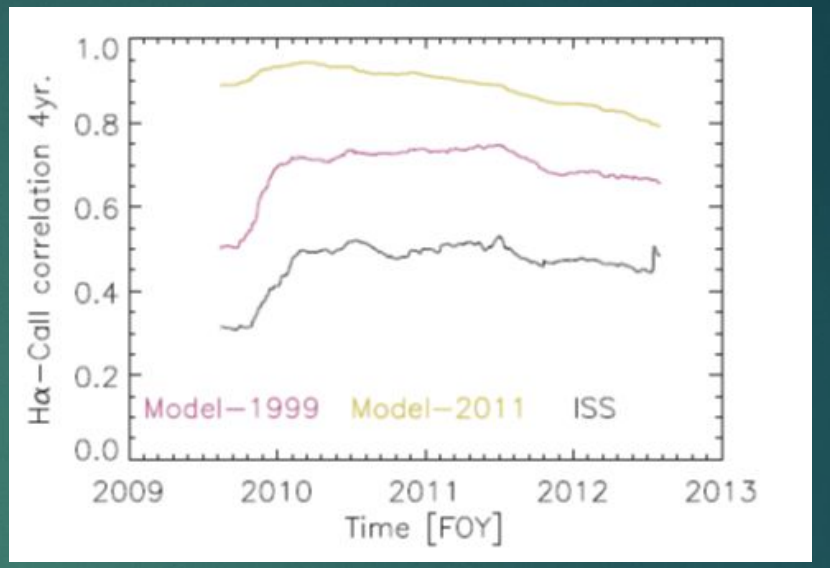
Models overestimate the contribution of networks and plages (Model2011 more so for network)

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



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 (see next talk)
~0.1 for Model2011. Unrealistic!

Model 1999 slightly overestimates the contribution of plage/network

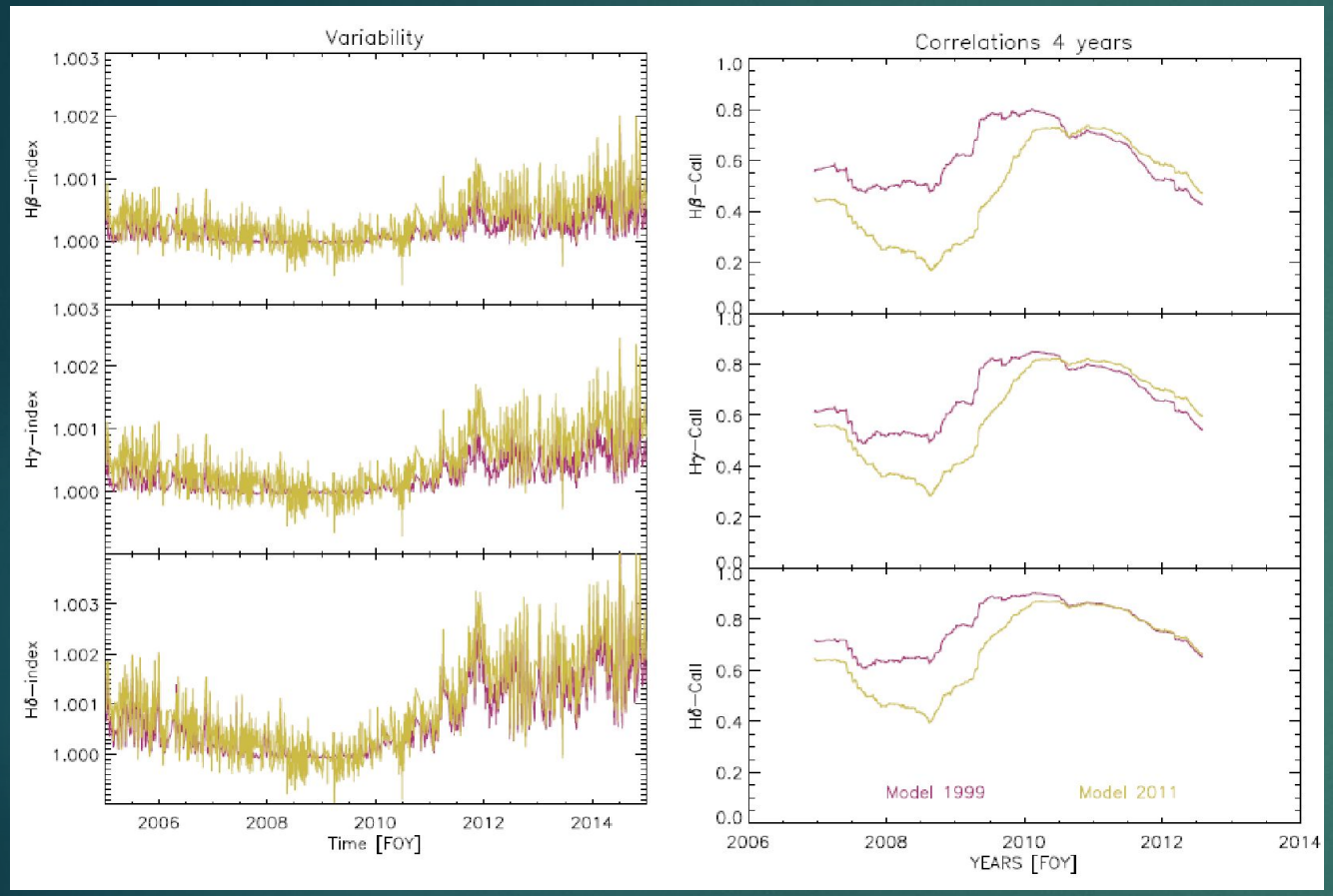
Discussion/Conclusions

- 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.
- The set of FAL 1999 models best reproduces the observations.

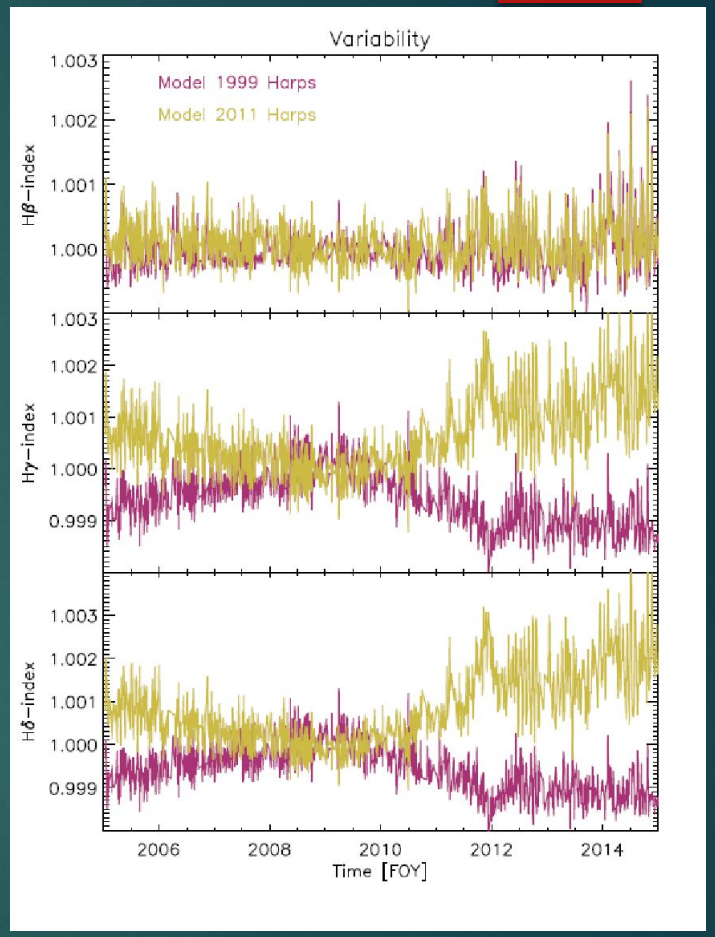
- From a theoretical perspective, it is not so surprising that the core-to-wing ratios of Balmer lines follow photospheric indices. The source function is scattering dominated and more sensitive to photospheric conditions.

THANK YOU VERY MUCH

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



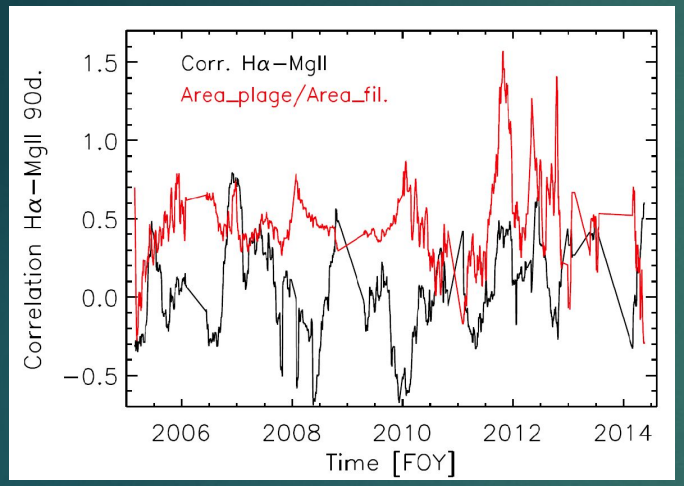
Modelled variability, mimicking OMI measurements



Modelled variability, mimicking HARPS-N measurements

On the contribution of filaments

Solar-rotational time scale

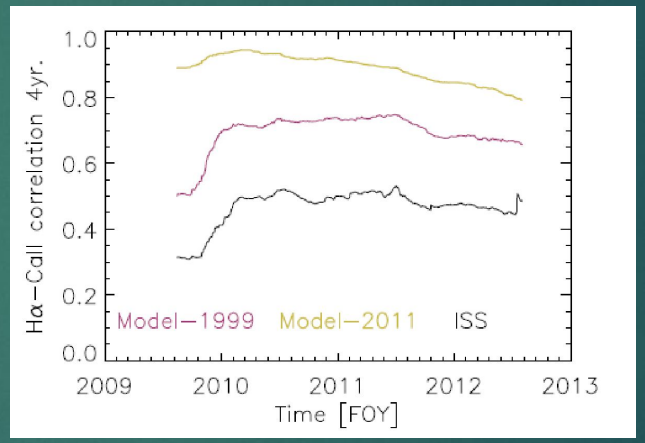


If filaments played a role, then the correlation between Ha and MgII indices would decrease when the A_plage/A_fil. decreases, i.e. the two curves should be correlated.
However, the correlation coefficient is not larger than 0.3

Solar-cycle time scale

$$NewModel = ModelXXX+(C_{fil.}-C_q) \times f_{fil.}$$

$C_{fil.}$ = core-to-wing ratio of filaments. Is a free parameter estimated by fitting the new model to fit the 4-years correlation curve.



The value of $C_{fil.}$ changes with time.

$I_{fil.}$ (core) /I_q (core)= [0.68,0.78] for Model1999

$I_{fil.}$ (core) /I_q (core) > 0.9 for Model2011

Filament contrast from Model 1999 consistent with Diercke et al. 2022, ~0.85 (see next talk)

Filament contrast unrealistically high!

➡ Model 1999 better reproduces measurements