Cross-scale phase relationship of solar activity with solar wind parameters: a Space Climate focus

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ABSTRACT

Understanding the relationship between solar activity and solar wind is crucial for exploring the interactions among different solar atmospheric layers and the dynamics within the heliosphere. In this work, we used data from five solar cycles to examine the phase relationship between a proxy of solar activity, namely the Ca II K index, and solar wind parameters at 1 AU, such as dynamic pressure and speed. By taking advantage of a powerful tool, the Hilbert-Huang Transform, we decomposed the signals into their intrinsic modes of oscillation and analyzed their phase differences. Despite preserving a certain degree of phase coherence, both solar wind parameters exhibit delayed variations relative to the Ca II K index on space climate scales, showing an anti-phase relationship until 1985, followed by quadrature phase differences. Additionally, we explored how the relationship between the Ca II K index and solar wind parameters varies across different time scales. Our results indicate the presence of a potential bifurcation in the phase-space of the Ca II K index and solar wind speed (dynamic pressure), with the time scale acting as a bifurcation parameter. This suggests that including longer time-scale components enhances the discernibility of their connection. This discovery could be pivotal for understanding the complex interactions between solar activity and solar wind, offering important implications for prediction and interpretation in space climate studies.

1. DATA

We use five solar cycles (20-24) monthly averages data of:

- Ca II K index (Ca II K; Jul. 1965 - Oct. 2017), *Bertello+2016 composite*;
- Ca II K index reconstructed via Mg II index (Nov. 2017 - Apr. 2021), *Reda+2023a*;
- Solar wind (SW) speed and dynamic pressure (Jul. 1965 - Apr. 2021).

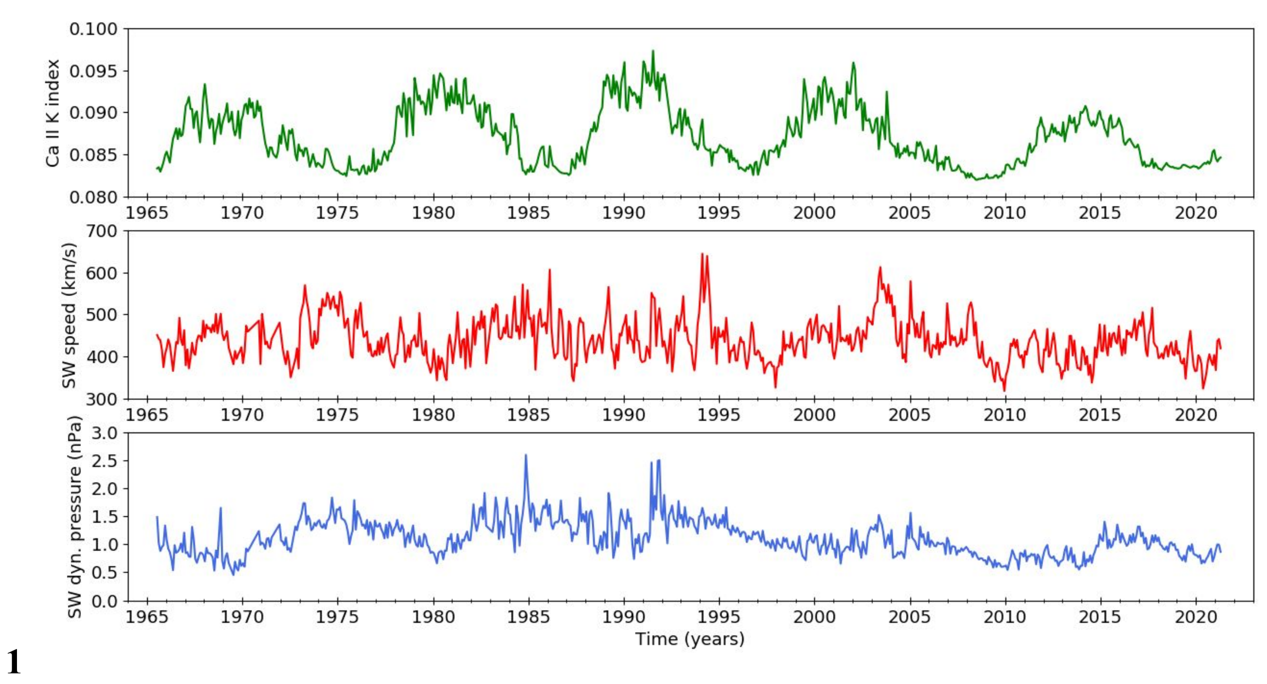

Fig. 1
Monthly averages of Ca II K index (top), SW speed (middle) and SW dynamic pressure (bottom).

2. HILBERT-HUANG TRANSFORM

The Hilbert-Huang Transform is a powerful two-step method for analyzing nonstationary and nonlinear signals.

- **Empirical Mode Decomposition (EMD)**

  EMD is a data-driven method for decomposing a signal *x(t)* into a finite set of Intrinsic Mode Functions (IMFs), representing local stationary modes of the signal. The decomposition is such that the starting signal *x(t)* can be written as:

$$x(t) = \sum_{i=1}^{n} IMF_i(t) + r(t)$$

  where *r(t)* is a residual term.

- **Hilbert Spectral Analysis**

  Once derived the set of empirical modes (i.e., the IMFs), by means of the Hilbert Transform (*H*), it is possible to extract for each of them the instantaneous phase, amplitude and frequency. This goal is achieved by introducing the complex signal $\xi_i(t)$.

$$\xi_i(t) = IMF_i(t) + iH[IMF_i(t)] = A_i(t)e^{i\phi_i(t)}$$

$A_i(t)$ ⇒ Instantaneous amplitude

$\phi_i(t)$ ⇒ Instantaneous phase

$\nu_j(t) = \frac{1}{2\pi}\frac{d\phi_j(t)}{dt}$ ⇒ Instantaneous frequency

The characteristic time scale of each IMF can be obtained as:

$$<\tau_j> = <\nu_j^{-1}>$$

IMF number	Ca II K index $<\tau>$ (yr)	SW speed $<\tau>$ (yr)	SW dyn. pressure $<\tau>$ (yr)
1	0.3 ± 0.2	0.3 ± 0.2	0.3 ± 0.2
2	0.7 ± 0.3	0.6 ± 0.3	0.5 ± 0.3
3	1.4 ± 0.8	1.1 ± 0.4	1.2 ± 0.9
4	3.6 ± 2.7	2.1 ± 1.1	2.3 ± 1.5
5	12.4 ± 4.7	4.8 ± 2.6	5.2 ± 4.0
6	51.4 ± 14.5	11.2 ± 3.3	13.9 ± 5.1
7		19.8 ± 5.6	51.5 ± 15.6

Table 1
Characteristic time sales of the IMFs (or modes) of the signals analyzed.

3. PHASE ANALYSIS

Exploiting the phase values of each IMF, we compute the unwrapped phase difference between the IMFs of Ca II K and those of SW speed and dyn. pressure. Following the approach by *Donner & Thiel (2007)*, the resulting values were normalized to the interval [-π,π]. The standard deviation of the phase difference σ(Δϕ) is then considered, since it is a statistical feature useful to quantify the phase coherence between time series.

Fixing an upper threshold of 0.09, phase coherence is found at similar scales up to QBOs. Moving to larger scales, also adjacent modes seem to maintain a significant phase coherence.

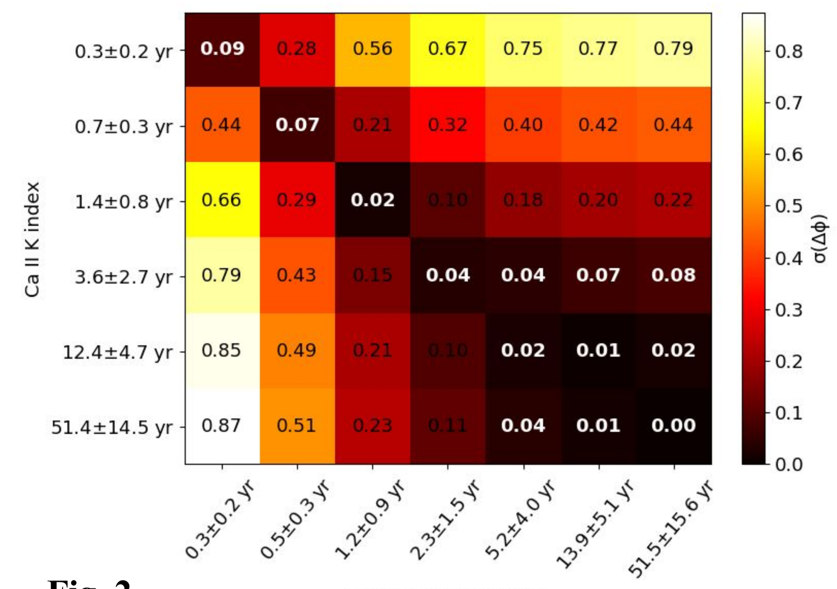

Fig. 2
Phase coherence colormap of Ca II K with SW dyn. pressure across the different time scales.

Focusing on the solar cycle time scales (IMFs 4-5 for Ca II K and IMFs 5-6 for SW speed and dyn. pressure), we examine how the solar wind phase evolves over time with respect that of solar cycle. Two phase states are identified:

- SW dyn. pressure is nearly in antiphase to Ca II K up to 1987 (Δϕ= -0.9π), after which it shifts to a more in-phase state (Δϕ= -π/2);
- SW speed is nearly in antiphase to Ca II K up to 1990 (Δϕ= -0.8π), after which it transitions toward a more in-phase state (Δϕ= -0.9π/2).

These results confirm previous findings by *Samsonov+2019* and *Reda+2023b*.

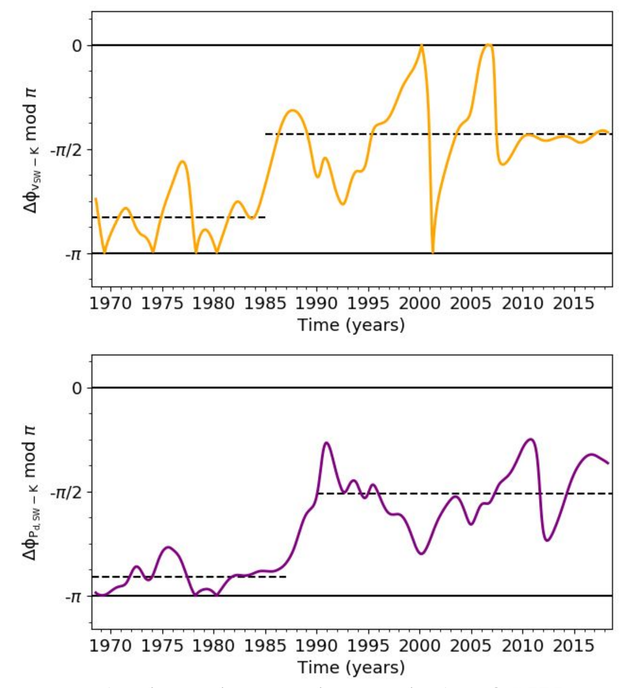

Fig. 3
Phase difference (only solar cycle modes) of SW speed (top) and SW dyn. pressure (bottom) with Ca II K.

4. CROSS-SCALE RELATIONSHIP

Having the different time scale components allows to investigate how the relationship between Ca II K and SW properties evolves across the time scales. After having considered a mean phase difference, we find that adding the contribution of increasing (decreasing) time scale components enhances (reduces) the discernibility of the connection between solar activity and solar wind. This suggests the presence of a bifurcation in the phase space of Ca II K versus solar wind parameters, with the time scale acting as the bifurcation parameter.

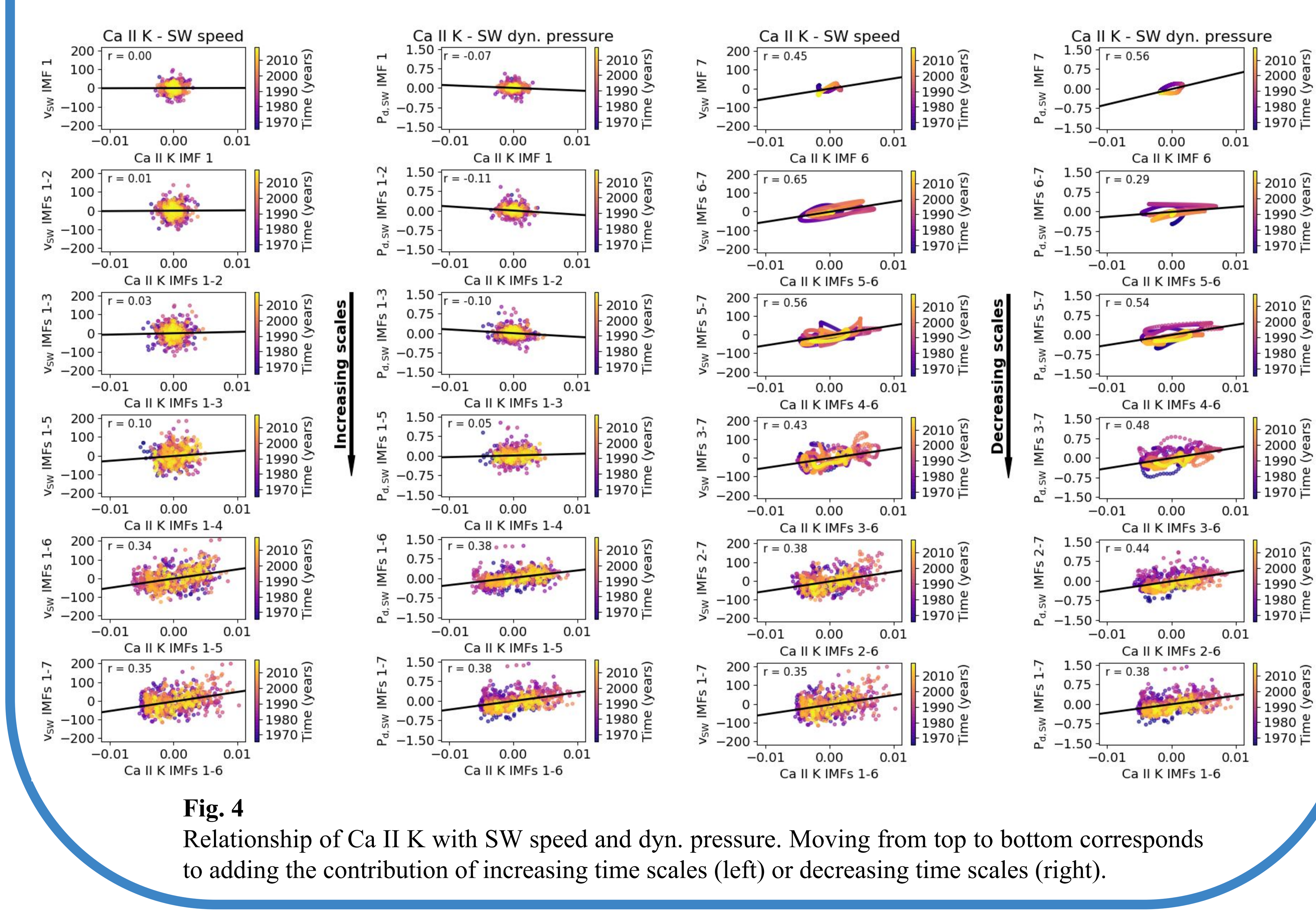

Fig. 4
Relationship of Ca II K with SW speed and dyn. pressure. Moving from top to bottom corresponds to adding the contribution of increasing time scales (left) or decreasing time scales (right).

5. CONCLUSIONS

- Phase coherence between Ca II K and SW speed (dyn. pressure) at same time scales up to τ ~ 2 yrs;
- Phase coherence over broader time scales for τ > 2 yrs;
- Delayed response of SW parameters to Ca II K with two observed mean states:
  - almost in anti-phase up to 1985-1990;
  - quadrature phase difference later on.
- Bifurcation in the phase-space Ca II K vs SW speed (dyn. pressure), with the time scale acting as bifurcation parameter.

REFERENCES

- *Donner & Thiel 2007, Astron. Astrophys, 475, 3, L33*
- *Bertello+2016, Solar Phys., 219, 9-10, 2967*
- *Samsonov+2019, J. Geophys. Res., 124, 6, 4049*
- *Reda+2023a, MNRAS, 519, 4, 6088*
- *Reda+2023b, Adv. Space Res., 71, 4, 2038*

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