The Sun as a Rosetta stone for the evaluation of stellar winds in Sun-like stars

R. Reda (1), L. Giovannelli (1), M.P. Di Mauro (2), F. Berrilli (1), T. Alberti (3), L. Bertello (4), E. Corsaro (5), D. Del Moro (1), P. Giobbi (1), V. Penza (1)

(1) Department of Physics, University of Rome Tor Vergata
(2) INAF-Istituto di Astrofisica e Planetologia Spaziali
(3) INGV-Istituto Nazionale di Geofisica e Vulcanologia
(4) National Solar Observatory
(5) INAF-Osservatorio Astrofisico di Catania

ABSTRACT

The Sun is the only star that we can resolve with the spatial and temporal details needed to characterize its magnetic activity. As these details cannot be achieved for any other stars, our star has to be treated as a guiding light for the understanding of stellar dynamos, as well as for the evaluation of stellar activity and how the latter impacts on the planetary and circum-planetary environments. However, since it is not possible to obtain stellar data with the resolution of the solar ones, in order to compare the Sun with other stars, we have to adopt the Sun-as-a-star point of view for our star. In this framework, we start from disk-integrated data of the solar emission in the Ca II K line and we study the relationship with measurements of solar wind parameters performed by different satellites near the Earth. The results of our analysis, based on different techniques, show that a delayed relation between solar activity and solar wind parameter exists. Because measurements in Ca II H & K lines have been performed for thousand Sun-like stars during the last 50 years, this opens the possibility to extend the relations calibrated on the Sun to several stars. As a first step in this respect, as a case-study, we apply the relations found to a sample of Sun-like stars and, to test their validity, we compare the results with estimates from other models. By using this method, it is possible to determine the intensity of stellar wind speed and dynamic pressure around Sun-like stars. When combined in a synergic way with precise stellar parameters inferred from asteroseismology, this approach allows to obtain a more complete evaluation of the exoplanetary habitability conditions around Sun-like stars.

SOLAR ACTIVITY-SOLAR WIND RELATION

The dataset used to study the decennial time-scales relation between the solar activity and the solar wind properties consists of:

- Ca II K index (Jul. 1965 - Oct. 2017), *Bertello et al. (2017)* composite;
- Mg II index (Nov. 1978 - Apr. 2021), Bremen composite, *Viereck et al. (2004)*;
- Solar wind speed (v) and dynamic pressure ($P_{d,SW}$) (Jul. 1965 - Apr. 2021), OMNI database.

By extending the Ca II K index up to 2021 through the Mg II index, we are able to study such relation over 5 solar cycles. Since we are interested in the long-term behaviour, we filter out the high frequency components by means of a 37-month moving average.

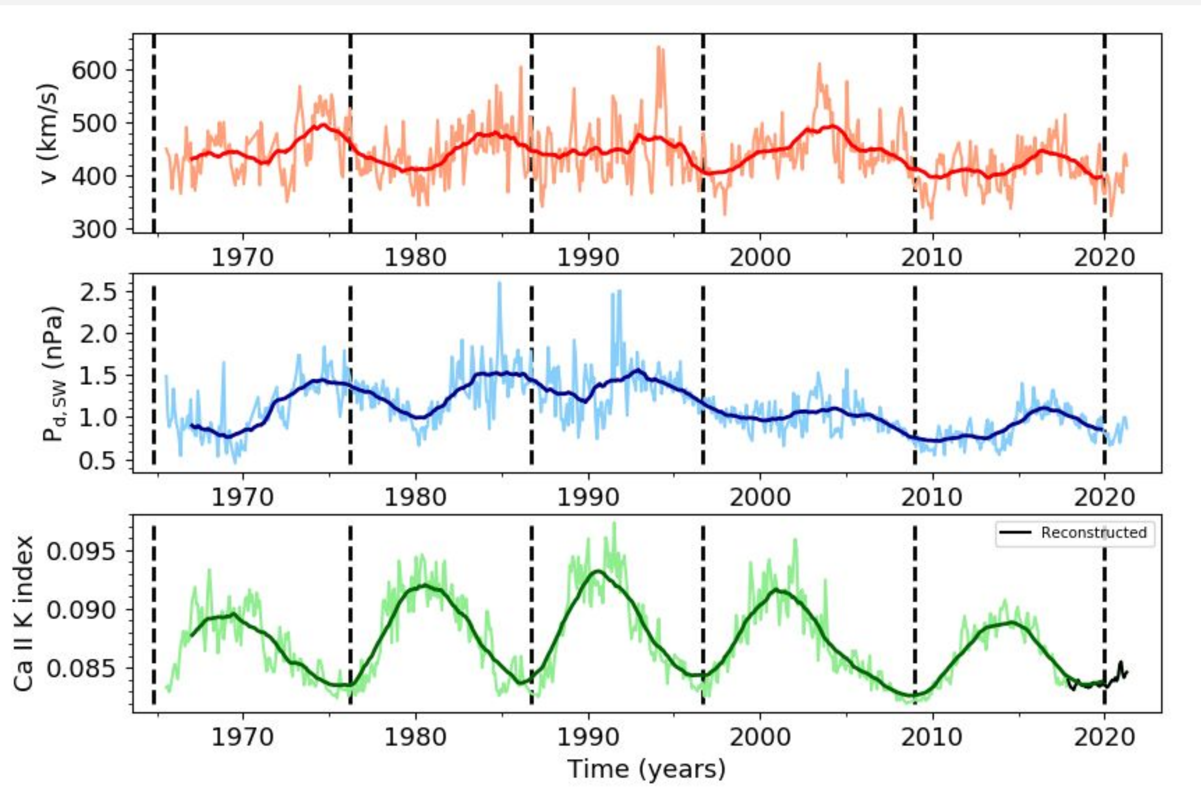
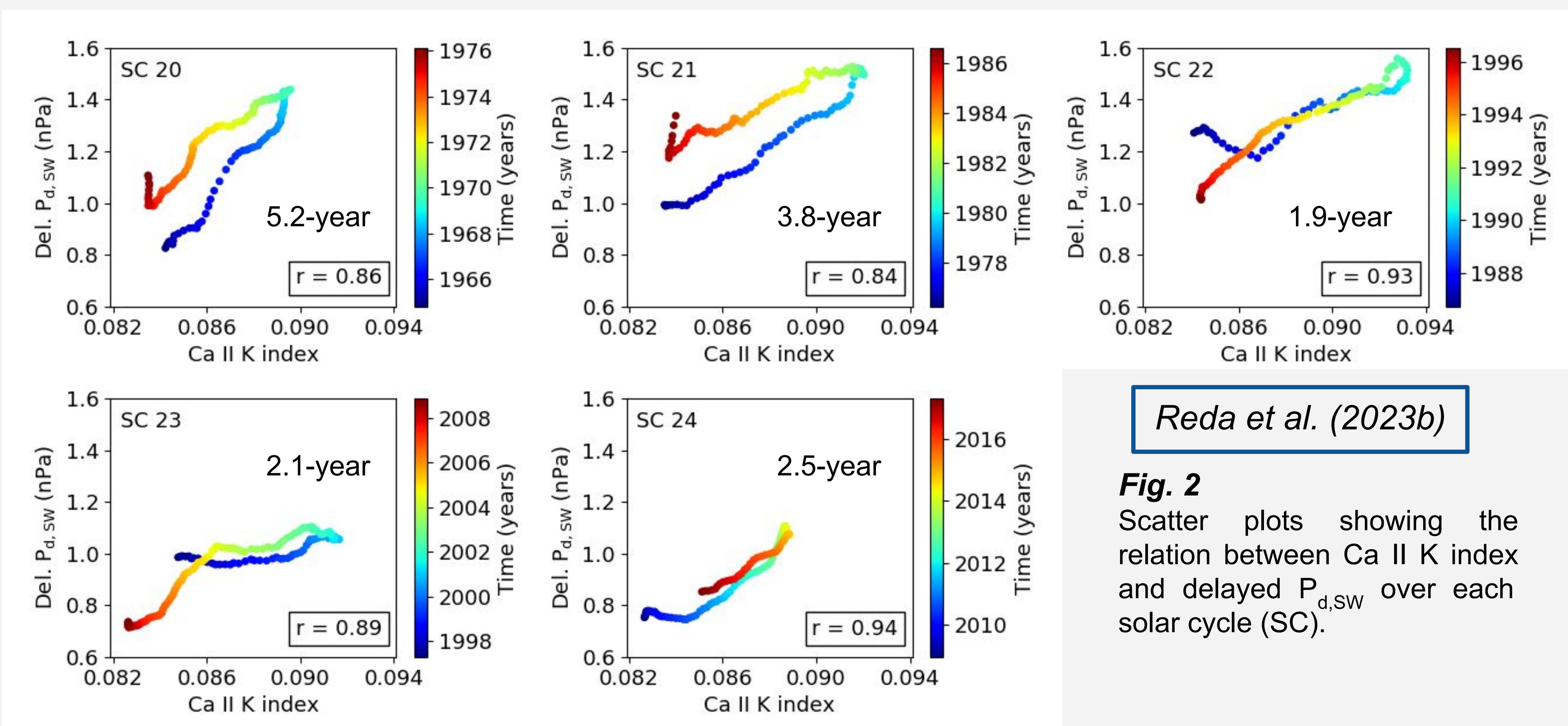


Fig. 1
Monthly averages and superimposed 37-month averages of the signals used for this work: v (top), $P_{d,SW}$ (middle) and Ca II K index (bottom).

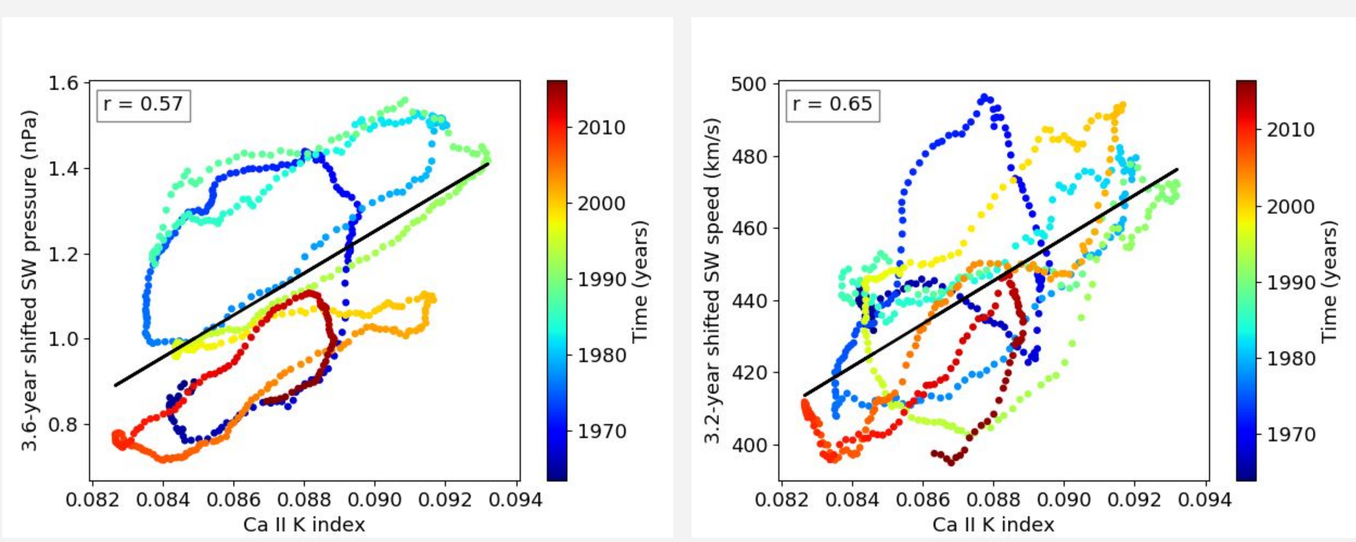
We find a strong correlation delayed correlation (r≥0.84) over each solar cycle for the Ca II K index with both v and $P_{d,SW}$, with the time lag showing cycle-to-cycle variations (*Reda et al. 2023b*).



Reda et al. (2023b)

Fig. 2
Scatter plots showing the relation between Ca II K index and delayed $P_{d,SW}$ over each solar cycle (SC).

However, since we are not interested in a particular solar cycle, we consider here the linear relations obtained by assuming the mean time lags over the last 5 solar cycles. Their values are 3.2-year for solar wind speed v and 3.6-year for dynamic pressure $P_{d,SW}$ (*Reda et al. 2023a*).



Reda et al. (2023a)

Fig. 3
Scatter plots showing 5 SCs relation of: Ca II K index with delayed $P_{d,SW}$ (left); Ca II K index with delayed v (right). The black lines show the best linear fit.

$$P_{d,SW}(nPa) = (49.1 \pm 2.8)\, Ca\ II\ K - (3.17 \pm 0.24) \qquad v(km/s) = (5930 \pm 280)\, Ca\ II\ K - (76 \pm 24)$$

EXTENSION TO SUN-LIKE STARS

The advantage of having used the Ca II K index is that the relations found for the Sun can be extended to Sun-like stars for which similar measurements are available. In particular, here we use data from the Mount Wilson Observatory (MWO), which has monitored the emission in Ca II H & K lines of thousand stars for about 30 years. We select a case-study sample of 10 Sun-like stars in the faculae-dominated activity regime, which corresponds to a Rossby number $R_0 > 1$ and age ≳ 2.55 Gyrs (*Reinhold et al. 2019*), and we compute the values of stellar wind v and $P_{d,SW}$ from Ca II data.

$$S\ (Ca\ II\ K) = (1.50 \pm 0.13)\ Ca\ II\ K + (0.031 \pm 0.013)$$ (*Egeland et al. 2017*)

Star	v (km/s)	P (nPa)	P^{P}_{See14} (nPa)	P^{CS}_{See14} (nPa)
Sun	440.8 ± 25.5	1.12 ± 0.24	-	-
HD 10780	896 ± 113	4.89 ± 0.98	4.19	4.79
HD 100180	452 ± 79	1.20 ± 0.68	1.30	1.76
HD 13043	387 ± 73	0.66 ± 0.63	1.93	1.35
HD 179958	398 ± 73	0.76 ± 0.63	1.12/1.42	0.36/0.83
HD 185144	665 ± 93	2.97 ± 0.81	2.32/2.72	1.24/1.66
HD 34411	375 ± 73	0.56 ± 0.63	1.26	3.04
HD 71148	410 ± 73	0.86 ± 0.63	1.44/1.84	1.03/1.96
HD 76151	736 ± 100	3.56 ± 0.86	1.91/3.08	7.65/17.62
HD 86728	375 ± 73	0.56 ± 0.63	1.24	0.52
HD 9562	345 ± 72	0.32 ± 0.62	1.30	3.51

Table 1
Col.1: Star ID;
Col.2-3: Stellar wind speed (v) and dynamic pressure ($P_{d,SW}$) estimated in this work;
Col.4-5: Comparison with the $P_{d,SW}$ values by *See et al. (2014)*.

Within the confidence intervals, our results (*Reda et al. 2023a*) are in agreement with previous estimates for the same stars (see e.eg. *See et al. 2014*).

SYNERGY WITH ASTEROSEISMOLOGY

The method described above can be used in a synergic way with asteroseismology in order to characterize Sun-like stars and their wind interaction with exoplanets (see e.g. *Reda et al. 2022*). This synergic strategy allows to determine not only highly accurate stellar parameters of the host-star, and thus of its planet, but also to define the conditions of the exoplanetary environment and to quantify the extension of the planetary magnetosphere (R_{MP}), which is directly related to the stellar wind dynamic pressure $P_{d,SW}$.

$$R_{MP}(R_E) \simeq \frac{\mu_0 f_0^2 M_E^2}{8\pi^2 10^{-9} P_{d,SW}} = \frac{\mu_0 f_0^2 M_E^2}{8\pi^2 10^{-9} (\alpha\ Ca\ II\ K + \beta)}$$

where α and β are the fit parameters, μ_0 is the vacuum permeability, M_E is the Earth's magnetic moment, while f_0 is a form factor.

HD 81809

Reda et al. (2022) approach

We report here the results of the application of the synergic strategy to the case of the solar-like star HD 81809, for which we obtained asteroseismic global parameters by analyzing TESS data.

	Present value
log L ($L_\odot$)	0.74 ± 0.03
M ($M_\odot$)	1.40 ± 0.05
R ($R_\odot$)	2.19 ± 0.08
Age (Gyr)	3.58 ± 0.55
P_{cyc} (yrs)	8.01
S-index	0.172 ± 0.010
Ca II K index	0.094 ± 0.012
v_{SW} (km/s)	481 ± 79
P_{SW} (nPa)	1.45 ± 0.69

Table 2
Stellar and stellar wind parameters obtained with the synergic strategy.

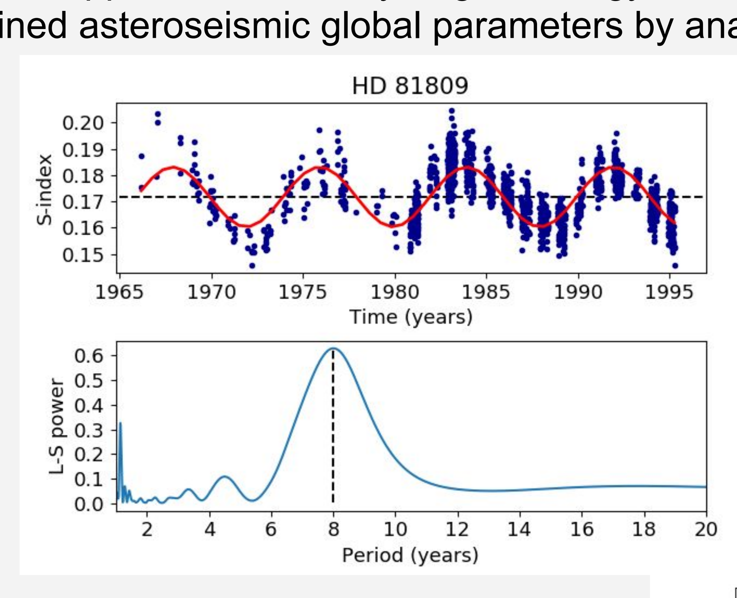


Fig. 4
S-index measures from MWO (top) and corresponding Lomb-Scargle periodogram (bottom). The red line shows the sinusoidal fit to the highest peak.

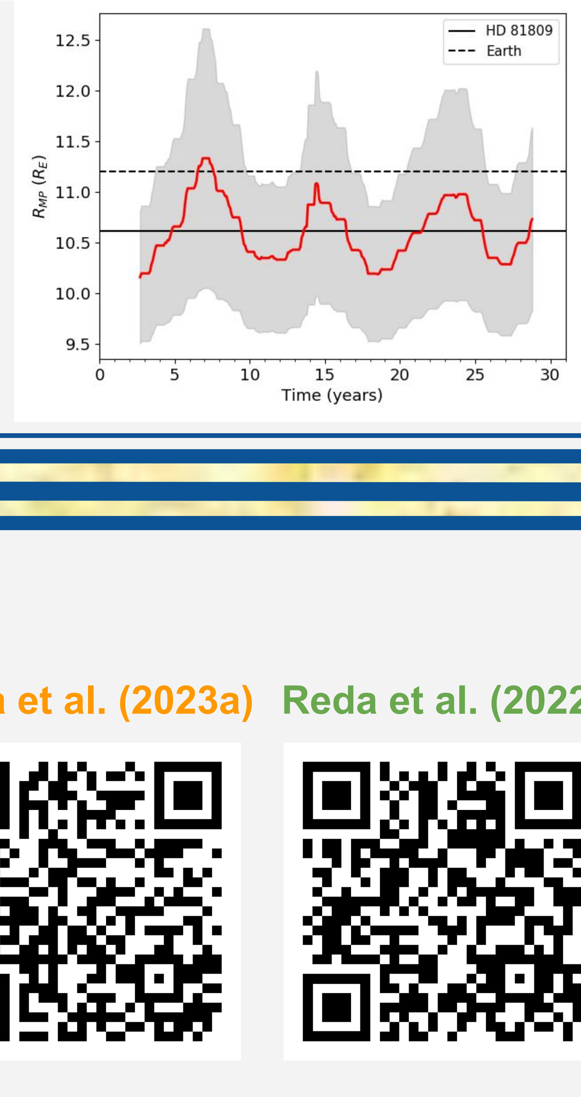


Fig. 5
Magnetosphere extension (red line) and its confidence interval (shaded area) of a fictitious Earth-twin planet at 1 AU.

It's possible to conclude that HD 81809 displays stellar wind conditions suitable for hosting a potentially habitable Earth-like planet in its habitable zone.

CONCLUSIONS

- → The Sun constitutes our guiding light for the study of Sun-like stars;
- → Here we use the Sun-Earth system as a Rosetta stone for the evaluation of stellar wind properties in Sun-like stars;
- → We found the presence of a delayed response of solar wind properties (both v and $P_{d,SW}$) to solar activity (e.g. Ca II K index);
- → The relations found can be easily extended to Sun-like stars;
- → When used in a synergic way with precise stellar parameters from asteroseismology, this approach allows to obtain a more complete evaluation of the space climate environment around Sun-like stars, giving insights about the habitability conditions.

REFERENCES

- → *Bertello et al. (2014)*, Sol. Phys., 291, 2967
- → *Egeland et al. (2017)*, ApJ, 835, 25
- → *Reda et al. (2022)*, Front. Astron. Space Sci., 9, 909268
- → *Reda et al. (2023a)*, MNRAS, 519, 4, 6088
- → *Reda et al. (2023b)*, Adv. Space Res., 71, 4, 2038
- → *Reinhold et al. (2019)*, A&A, 621, A21
- → *See et al. (2014)*, A&A, 570, A99
- → *Viereck et al. (2004)*, Space Weather, 2, S10005

Reda et al. (2023a) **Reda et al. (2022)**