Second Semester Report

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Ph.D. Thesis title: Developing state-of-the-art Space Weather forecast tools

Description of research in the current semester

We further developed the analysis of evolution of the normalized emergence (EM), shearing (SH) and total (T) magnetic helicity flux components for 14 flaring and 14 non-flaring active regions (ARs) using Spaceweather Helioseismic Magnetic Imager Active Region Patches (SHARP) vector magnetic field data, in this semester.

In the previous semester, we constructed the wavelet power spectrum (WPS) for all 28 ARs then identified the local significant peaks in the WPS, with the 0th dimensional persistent homology method. Subsequently, we studied the distribution of the identified local WPS peaks of the original and smoothed EM/SH/T helicity fluxes with Kernel Density Estimation. One of the main findings from the distributions is that the localised periods of the WPS are in bands: between (i) 2–9 hours, (ii) 11–14 hours, and (iii) 19–21 hours. These bands may indicate global harmonic oscillatory properties of the EM, SH, and T fluxes. Therefore, to test this hypothesis, a Kolmogorov-Smirnov (KS) test was performed to compare the peak distributions of flaring and non-flaring ARs.

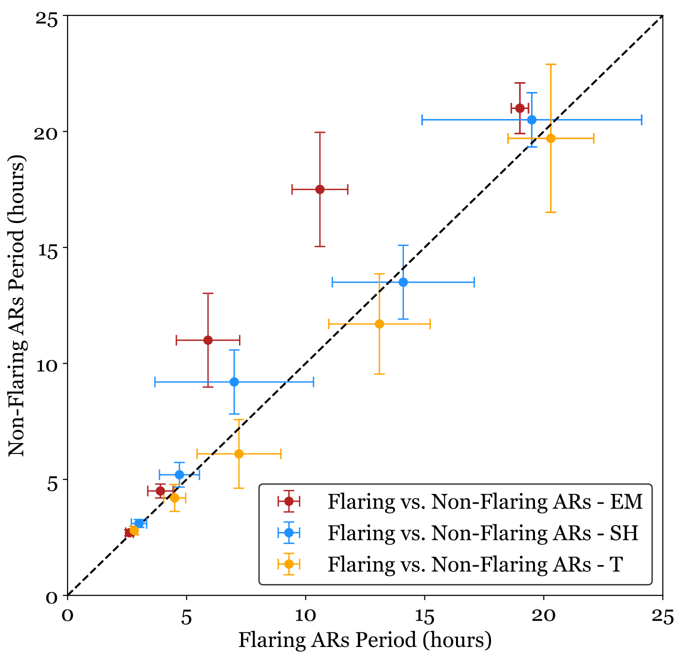

Figure 1: Correlation between periods of flaring and non-flaring ARs. The error bars are estimated with bootstrap. The EM helicity flux shows a clearly distinct behaviour from that of the T and SH fluxes. Therefore it is proposed that the EM helicity flux can be identified as an indicator or a pre-cursor of X-class flares or possibly even of CMEs. If one detects a δ-spot forming but does not see that the periods in the EM is not taking a different path, thereby no harmonic properties appear, then there are great chances that flare/CME may not occur.

While performing the KS analysis, our null hypothesis was that the similar periods are generated by the same driving mechanism for both the flaring and non-flaring ARs. From the results, we see that all of the p-values are below 1σ, which means that the null hypothesis is true. Of course, we do not know what exactly is the background driving mechanism for these oscillatory behaviors in the peak distributions of the three helicity fluxes. Therefore, since the null hypothesis is correct, we can assume that flaring and non-flaring ARs have the same global harmonic properties.

Also Gaussian curves were fitted to the original and smoothed probability density functions (PDF) of the EM/SH/T data, in the flaring and non-flaring cases. The Gaussian fits were performed by employing the Gaussian Mixture Model (GMM), which also supported our earlier findings that the periods are aggregated in bands. At first, the number of fitted Gaussian distributions was determined by the best Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values. The best choice for the number of the GMM components is 5, because in this case the bands are clearly identical in all of the cases.

Next, we investigated the relationship between Gaussian mean periods obtained by GMM of the flaring and non-flaring ARs. This relationship is visualised in Fig. 1, where the x-axis shows the periods of flaring ARs while the y-axis is the periods of non-flaring ARs. The errors of the mean periods are estimated for the obtained periods using the bootstrap method, re-sampled 10,000 times were for each case. The black dashed line represents a 100% correlation between the flaring and non-flaring cases.

From Fig. 1, we can see that the dependence of the EM clearly becomes deviated from that of the SH and T fluxes. Also, the mean periods of EM of the non-flaring ARs are longer than the flaring ones. Based on these findings above, the evolution of the EM flux component may have a more prominent role in the flare-CME triggering processes when compared to that of the other two helicity flux components.

We determined the harmonics for each case of the period peaks of the oscillatory behaviour of the various helicity flux components. From this, we can see that only the peaks appearing in the EM of flaring ARs are the ones that follow the properties of the harmonics well for an oscillatory waveguide system that still needs to be determined in the future. It is worth noting that the $1/n$ dependence (n=1,2,3,...) of the fitted Gaussians of EM of flaring ARs is consistent with the assumptions of such an oscillatory system. Furthermore, we may also state that such clear harmonic properties are not detected in the different flux components of non-flaring ARs.

In summary, if the following series of events/features occur, during the evolution of an AR, it may alert us to an impending flare/CME:

- once a δ-spot is forming,
- where shorter periods appear in the EM,
- where these periods show the properties of harmonics of a resonant waveguide system.

Furthermore we have also investigated the distributions of peaks before and after the flares. For each flaring AR, we subtracted the moment of time of the local peak of the EM/SH/T periods from the onset time of the largest flare. We plotted these local peaks as function of this relative time, see Fig. 2. In general, we found that shorter periods (2–8 hours), are continuously present. However, the peak of longer periods ($\geq$10 hrs) are more often observed before or just few hours after the flares. In summary, it can be seen that the distribution of periods in the EM/SH/T helicity components changes after a respective flare. For EM and SH, the shorter periods are significantly separated into two groups. Respectively, after the flare, only few large periods can be observed.

Next, the peak distributions of non-flaring ARs were examined, separately for the EM, SH and T helicity fluxes. Since there is no distinguished moment of flare onset time, we selected an arbitrary reference time in

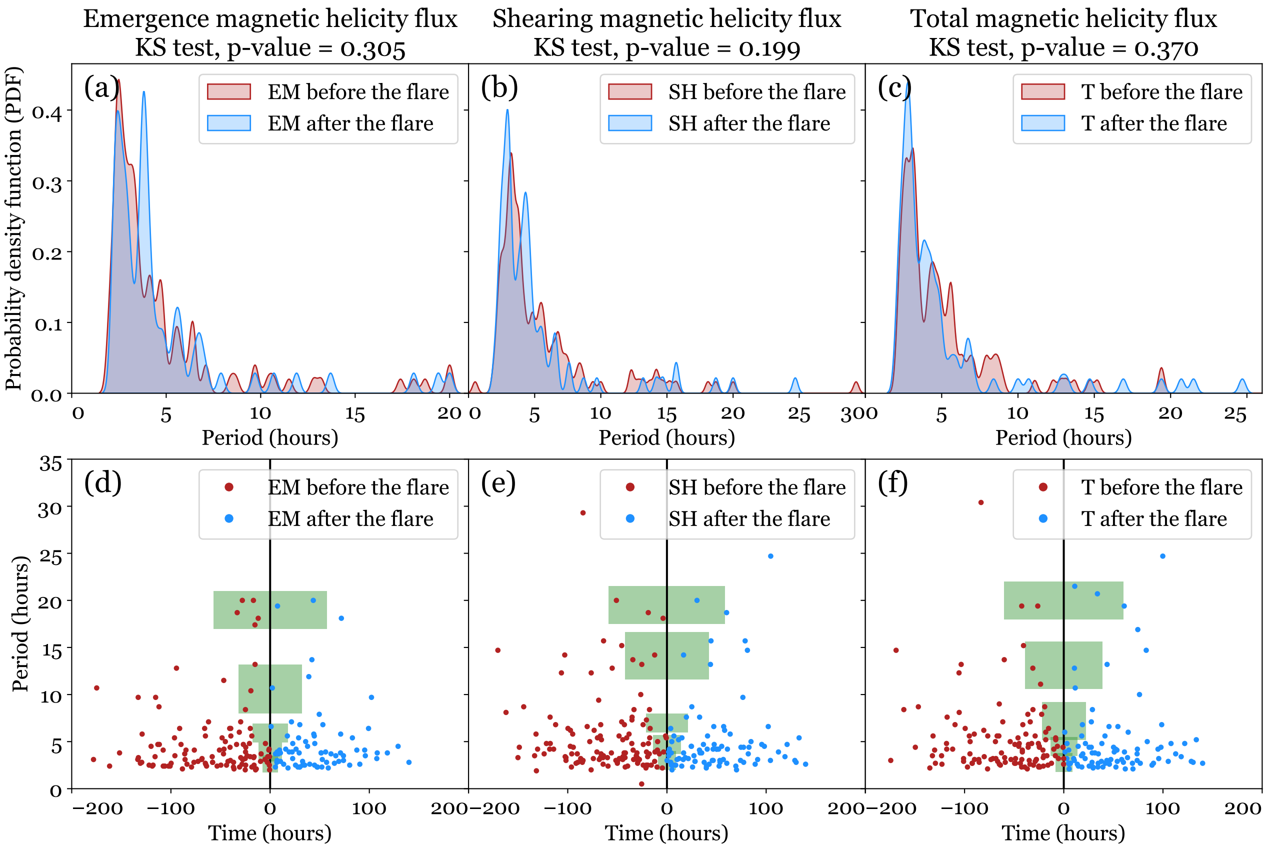

Figure 2: Panels a-c: Distribution of EM/SH/T peaks before (red) and after (blue) the flares. In the EM (a) case the most striking feature is that the short periods split into ∼2.5 and ∼4.5 hours after the flare occurred. Similar to the peaks of SH (b). Panels d-f: EM/SH/T periods of all flaring ARs. The black vertical line marks the reference time of the flares. The center of the green rectangles is given by the center of the Gaussian distributions fitted by the GMM method. The height of the rectangles corresponds to the FWHM value of the Gaussians fitted by the GMM method. The width of the rectangles corresponds to 3 periods.

every non-flaring ARs from what we subtracted the moments of the period peaks found in the WPS. However, since the average investigated time interval of an AR was about 7-9 days in duration, we made this arbitrary time to scroll from 0 to 200 hrs, in 5-hour increments. Next, for each arbitrarily chosen time, the distributions of EM/SH/T were analysed. The studied time intervals (between 50 and 140 hours) give an appropriate distribution before and after the arbitrary time, because outside of these time intervals, the peaks sometimes run very high due to the normalization of the distribution.

In summary, and most importantly, there is not much of a significant change in the peak distribution before and after a suitably chosen (say 40–50 to 130–145 hour) arbitrary time when compared to the corresponding counter-parts of analyses of flaring ARs.

In Figs. 2d–2f, the WPS periods of all flaring ARs are plotted, separately for the EM, SH, and T helicity flux components. The black vertical lines represent the flare event, as a relative reference time, given the fact the real onset time is different for each flares. The center of the green rectangles is determined by the center of the Gaussian distributions fitted by the GMM method. The height of the rectangles corresponds to the FWHM value of the Gaussians. Finally, the width of the rectangles corresponds to 3 periods.

Then, we counted the number of periods appearing for the different helicity flux cases of both the non-flaring and flaring ARs, in an interval three periods earlier of the arbitrarily chosen reference times. In Fig. 3, we plotted the periods summed up in the green rectangles as a function of the arbitrarily chosen reference times for the magnetic helicity flux components of flaring and non-flaring ARs.

The presence of long periods found in EM and T fluxes suggests that in the case of long periods, the EM component does play a crucial role in the formation of flares.

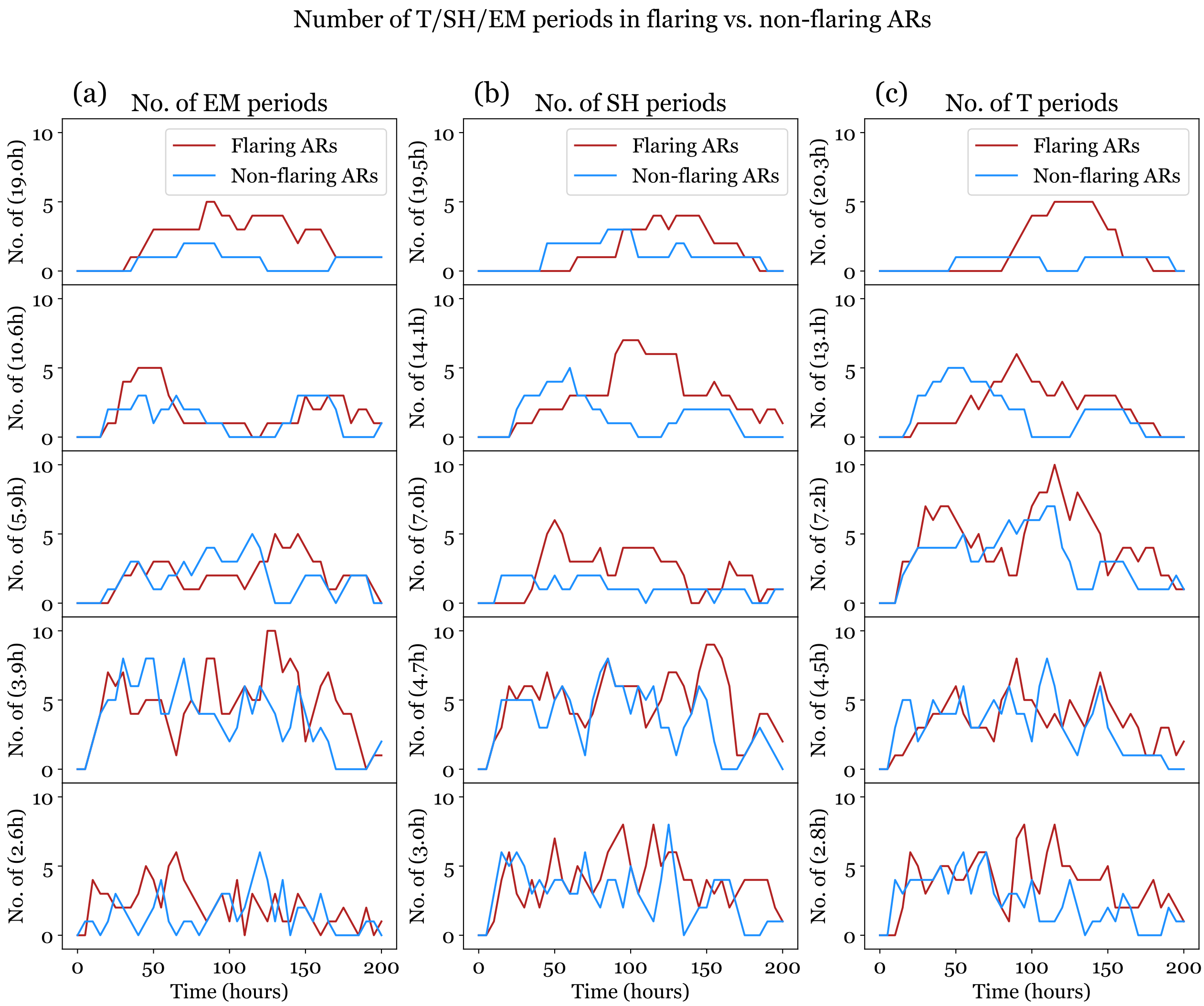

Figure 3: Number of (a) EM, (b) SH and (c) T oscillatory peak periods in flaring and non-flaring ARs. The blue/red lines correspond to non-flaring/flaring ARs. Long periods (∼20 hour) appear in the oscillatory peaks of the WPS of the T and EM fluxes of flaring ARs, from what it can be concluded that if these periods appear, one can expect flare/CME eruptions. The presence of long periods found in T and EM suggests that in the case of long periods, the EM component may play a crucial role in the formation of flares.

Publications

Completed, and imminently (i.e. one-two weeks as of writing, as under supervisory final reading) to be submitted to The Astrophysical Journal: Different periodic behaviours of magnetic helicity flux in Active Regions; Sz. Soós, M. B. Korsós, H. Morgan, R. Erdélyi

Studies in current semester

- Solitons and instantons 1 (FIZ/2/008E)
- Fejezetek a többes csillag- és bolygórendszerek elméleti és megfigyelési kérdéseiből II. (FIZ/2/100E)

Conferences in current semester

- ESPOS (European Solar Physics Online Seminars), from 10 September 2020, Thursday on each second week.
- UK-SOSS (UK Solar Online Seminar Series), from 17 September 2020, once a month on Thursdays.
- Cool Stars 20.5 (March 2-4, 2021)
- SDO 2021 Science Workshop (March 11 & 25, April 8 & 15, 2021)
- 27th Open Young Scientists' Conference on Astronomy and Space Physics (April 26-30, 2021)
- RAS SDM, MHD oscillations and waves (May 14, 2021) with poster: On the oscillatory behaviour of magnetic helicity in flaring and non-flaring solar active regions (Link to poster!)
- SolFER Spring 2021 (May 24-26, 2021)
- (NAM2021 (July 22, 2021) with oral talk: Different periodic behaviours of magnetic helicity flux in flaring and non-flaring AR cases)

Teaching in current semester

- Csillagászati észlelési gyakorlatok 1 (cg1n4eg1), 2 hours a week during semester time.