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STATISTICAL ANALYSIS OF THE ASYMMETRIC BEHAVIOR OF DIFFERENT SOLAR ACTIVITY FEATURES DURING SOLAR CYCLES 20-24

By

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Abstract

The study of North-South (N-S) asymmetry phenomenon is quite important because of its applicability in understanding the nature of solar dynamo action. The aim of our present work is to study and analyze various solar active phenomena occurring in both north and south hemispheres of the sun during solar cycles 20-24 (up to December 2011). The data of X-ray solar flares from 1975 to 2011 and of $H\alpha$ flares, Sunspot Area and Solar Active Prominences (SAP) from 1964 to 2011 are first normalized and then analyzed statistically. The N-S asymmetry indices and correlation for several solar phenomena have been calculated and plotted. Our study shows that most of the activity features in solar cycles 20-23 starts from northern hemisphere and afterward dominated in the southern hemisphere but in the rise phase of the solar cycle 24, activity features start in the southern hemisphere and afterward dominated in the northern hemisphere. The study indicates that some of the solar activity features like Sunspot Area and $H\alpha$ Flares are highly correlated with one another where as in the northern hemisphere Sunspot Area and north dominated Soft X-rays are poorly correlated.

2010 Mathematics Subject Classifications: 03H10, 85A99
Keywords and phrases: North-South asymmetry, X-ray solar flares, $H\alpha$ flares, Sunspot Area and Solar Active Prominences (SAP).

1 Introduction

There is stunning variety of magnetic field related phenomena across a wide range of spatial, temporal and energy scales displayed by the Sun. These time dependent processes are controlled by the magnetic fields generated by the combined action of convection and differential rotation of a nonlinear dynamo in the solar interior. Collectively, these processes are called solar activity. The activity exhibits a regular variation on a time scale called solar cycle. All solar activity phenomena viz. Sunspot number, Solar active prominences (SAP), $H\alpha$ flares, Soft X- ray flux (SXR) etc, are related to sunspots and thus magnetic activity. Sunspots often appear in bipolar pairs whose polarity orientation is opposite in two hemisphere. Years of sunspot observations have now firmly established that the sunspot cycle has an average period of 11 years. The related magnetic phenomena on the Sun like Solar flares, Solar Prominences, Coronal Mass Ejections etc. are caused by the Sun's twisting and turning magnetic field. Solar activity features have a great effect not only on climatological parameters but also its study is important for other scientific developments like telecommunications, power lines, geophysical explorations and long term planning of space missions.

It is well known that solar active phenomena are distributed non-uniformly over the solar disk. Non-uniform occurrence of the solar activity events in one (northern or eastern) or the other (southern or western) part is known as asymmetry (N-S or E-W). The study of asymmetries may find applications in predicting the behavior of activity in coming solar cycle which is important for the prediction of the space weather and climate. The study of N-S asymmetry of solar active features through the study of nonlinear solar dynamo models has attracted the researchers during the last couple of years. The (N-S) distribution, including asymmetries, of several solar activity indices such as flares , filament, magnetic flux , relative sunspot number, sunspot areas have been discovered by various authors ([21, 10, 22, 25, 8, 26, 24, 11]). Recently the asymmetry has been also reported in solar energetic particle events ($SEPs$) ([9, 6]). These studies indicate that there exists an asymmetry in the N-S distribution of the solar activity. Several studies have been done on the asymmetric behavior of solar activities using different features, such as Sunspot number, Sunspot group number and Sunspot area ([30, 27, 16, 4]), $H\alpha$ flares (SF), Soft X-ray flares ([22, 23, 12, 13]), Solar Active Prominences (SAP), SAP at low latitude ($\leq$40) and SAP at high latitude ($\geq$50) ([28, 17, 14]). [17] studied the N-S asymmetry of the SAP (low latitude $\leq$40), SAP (high latitude $\geq$50) from 1957 to 1998 (Solar cycles 19-22). [14] presented a comparison of N-S asymmetry and distribution of Solar Active Prominence (SAP) during solar cycles 20-23. They have also presented the same analysis for different disk features of SAP in two groups of cycles 23. [27] studied various solar phenomena occurring in both northern and southern hemispheres of the sun for solar cycle 18-22. They also calculated the N-S asymmetry indices for these solar active phenomena and plotted them against the number of solar cycles. Similarly, [3] have studied N-S asymmetry using different phenomena of solar activity. Summaries of the studies of hemispherical asymmetries of solar activity have been included in the works of ([29, 18, 19]). Statistical analysis show that the N-S asymmetry is statistically significant meaning thereby that it is a real physical phenomena and not a random mathematical fluctuation ([19, 5, 7]). The asymmetry tells that the magnetic field systems originating in the two hemispheres are weakly coupled, which was also inferred from the observations.

The aim of the present work is to make a detailed study of N-S asymmetry of daily solar activity features (Sunspot Area, $H\alpha$ Flares, Soft X- rays, Solar Active Prominences (SAP), SAP(Low latitude), SAP(High latitude)) from 1964 to 2011(Solar cycle 20-24).

2 Data Sets

For the present study we used the data from following sources:
The data have been collected from National Geophysical Data centers (NGDC) anonymous ftp server. The monthly north and south number of SAP (1964-2011) obtained from ftp//ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FILAMENT, with 149652 data points.
At low latitudes ($\leq$40) a total number of 135457 SAP events and at high latitude ($\geq$50) 5971 SAP events have been reported.

The monthly north and south soft X-rays flares (1975-2011), detected by the GOES satellites, and were downloaded from
ftp//ftp.ngdc.noaa.gov/STP/SOLAR_DATA/XRAY_FLARES/XRAYS_FLARES, with 33301 data points.
The monthly north and south H flares (1964-2011) obtained from
ftp//ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES.
The monthly north and south sunspot area (1964-2011) compiled by [26] from
http://solarscience.msfc.nasa.gov/greenwich.shtml.
This period covers solar cycle 20-24. The URL address of this website is
ftp//ftp.ngdc.noaa.gov/STP/SOLAR_DATA.

3 Analysis Techniques

For the present analysis, first we have taken events both in the northern and southern hemisphere for different solar activity features like Sunspot Area (SA), Solar Active Prominences(SAP), Solar Active Prominences (low), Solar Active Prominences (high), Soft X-rays (SXR) and $H\alpha$ Flares. The north and south data have been normalized using the technique given below. After normalization the asymmetry (A_{NS}) of north and south events has been calculated. Finally, we have calculated the dispersion of the N-S asymmetry and for analyzing the significance level of the asymmetry we have used the following criteria:
If $A_{NS} > \triangle A_{NS}$, then asymmetry is insignificant.
If $A_{NS} \geq \triangle A_{NS}, > 2\triangle A_{NS}$ then asymmetry is significant.
If $A_{NS} \leq 2\triangle A_{NS}$, then asymmetry is highly significant.

3.1 Normalization

The process of taking raw data and reducing it to a set of relations or a particular range $[a, b]$, while ensuring the integrity of the raw data with data redundancy eliminated, is said to be normalization of the data. Particularly, in mathematical analysis, the data set is normalized by taking the range as the interval $[0, 1]$ for accurate analysis and minimization of errors. We use following formula for normalization of the data:

$$Normalized(x) = \frac{a + (x - p)(b - a)}{(p - q)}, \tag{3.1}$$

where: a = minimum range,
b = maximum range,
p = Minimum North events, South events,
q = Maximum North events, South events.
In order to characterize the N-S asymmetry of solar activity, usually the N-S asymmetry index is defined by

$$A_{NS} = \frac{N\text{-}S}{N + S}. \tag{3.2}$$

N represents number of solar activity phenomena in northern hemisphere,
S represents number of solar activity phenomena in southern hemisphere.
Thus, if $A_{NS} > 0$, the dominant hemisphere of activity is northern one and if $A_{NS} < 0$, the dominant hemisphere of activity is southern one.
To investigate that up to what extent the asymmetry is real, we have followed the method

of [20] in which we can define the asymmetry of random distribution on the solar disk as

$$\triangle A_{NS} = \pm\sqrt{2(N+S)}, \tag{3.3}$$

where $\triangle A_{NS}$ is the dispersion of the N-S asymmetry and N and S are defined as above.

3.2 Correlation Analysis

There are several methods to calculate the correlation coefficient, but Pearsons correlation is commonly used in linear regression. It indicates the strength of a linear relationship between two variables. In the present analysis we follow general criteria to describe strong and weak correlations, i.e., a correlation higher than 0.8 is as strong, whereas, and a correlation less than 0.5 as weak. For calculating the correlation coefficient we use the following mathematical formula

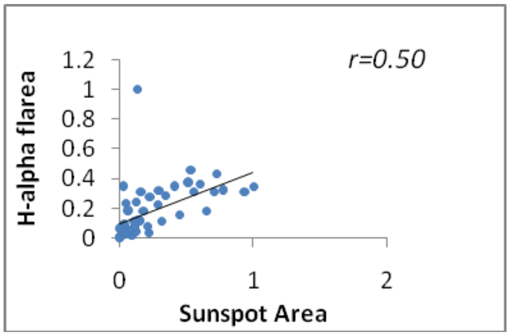
$$r = \frac{n\sum NS - (\sum N)(\sum S)}{\sqrt{\{n\sum N^2 - (\sum N)^2\}}\sqrt{\{n\sum S^2 - (\sum S)^2\}}}, \tag{3.4}$$

where r is correlation coefficient and

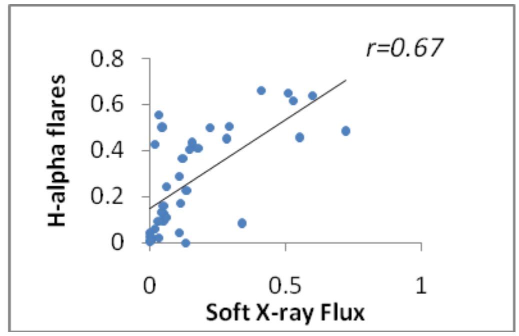
n : Total number of events.

N : Normalized North events.
S : Normalized South events.
$\sum N$: Sum of the Normalized North events.
$\sum S$: Sum of the Normalized South events.
$\sum NS$: Sum of the product of Normalized North South events.
$\sum N^2$: Sum of square of Normalized North events.
$\sum S^2$: Sum of square of the Normalized South events.

Further, the coefficient of determination (r^2) is calculated to discuss the proportion of the variance amongst the activity features.



(a)



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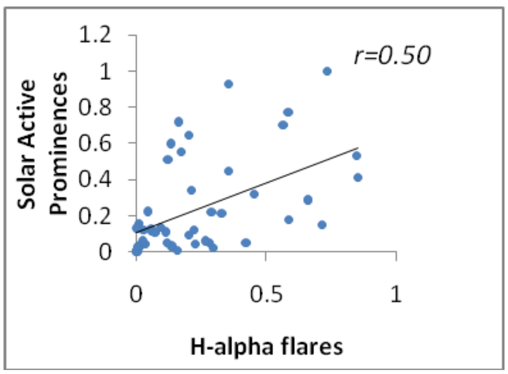

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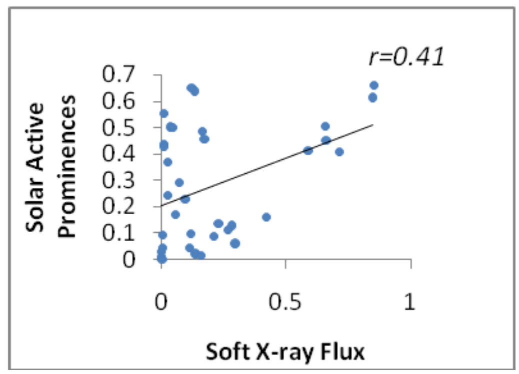
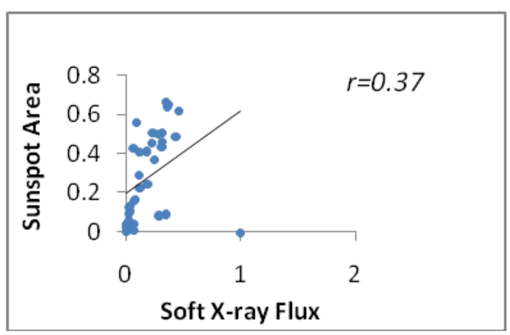
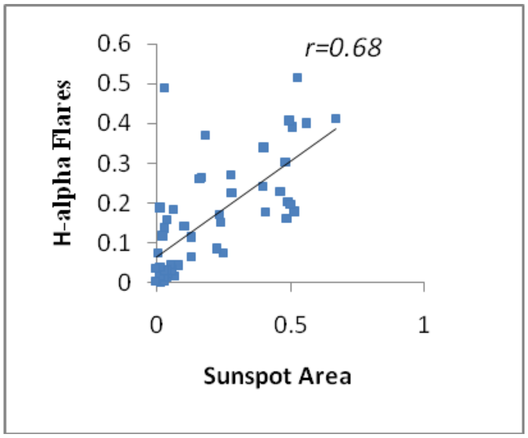


(d)

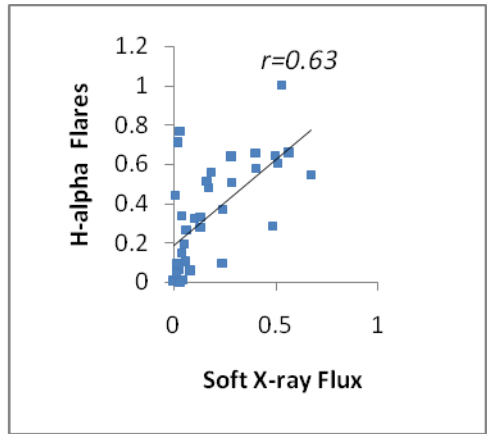


(e)

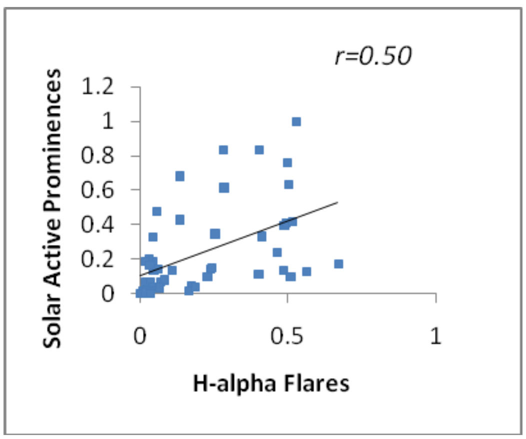
Figure 3.1: (a), (b), (c), (d), (e). Correlation Plots of Normalized North Events for different Solar Activity Features during Solar Cycle (SC) 20-24 (1964 to 2011).



(a)



(b)



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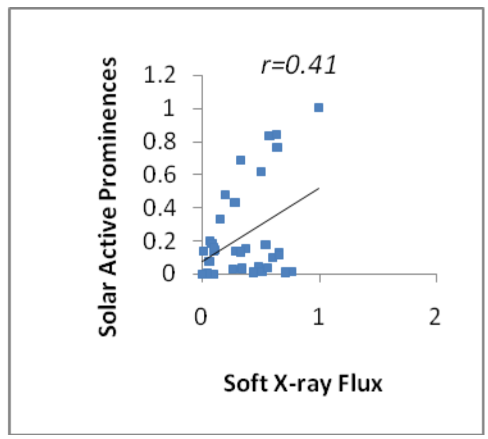

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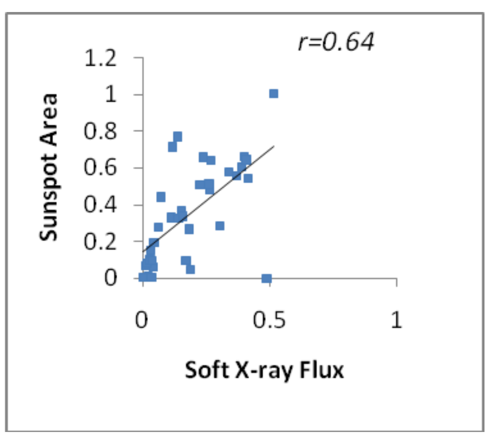


(e)

Figure 3.2: (a), (b), (c), (d), (e). Correlation Plots of Normalized South Events for different Solar Activity Features during Solar Cycle (SC) 20-24 (1964 to 2011).

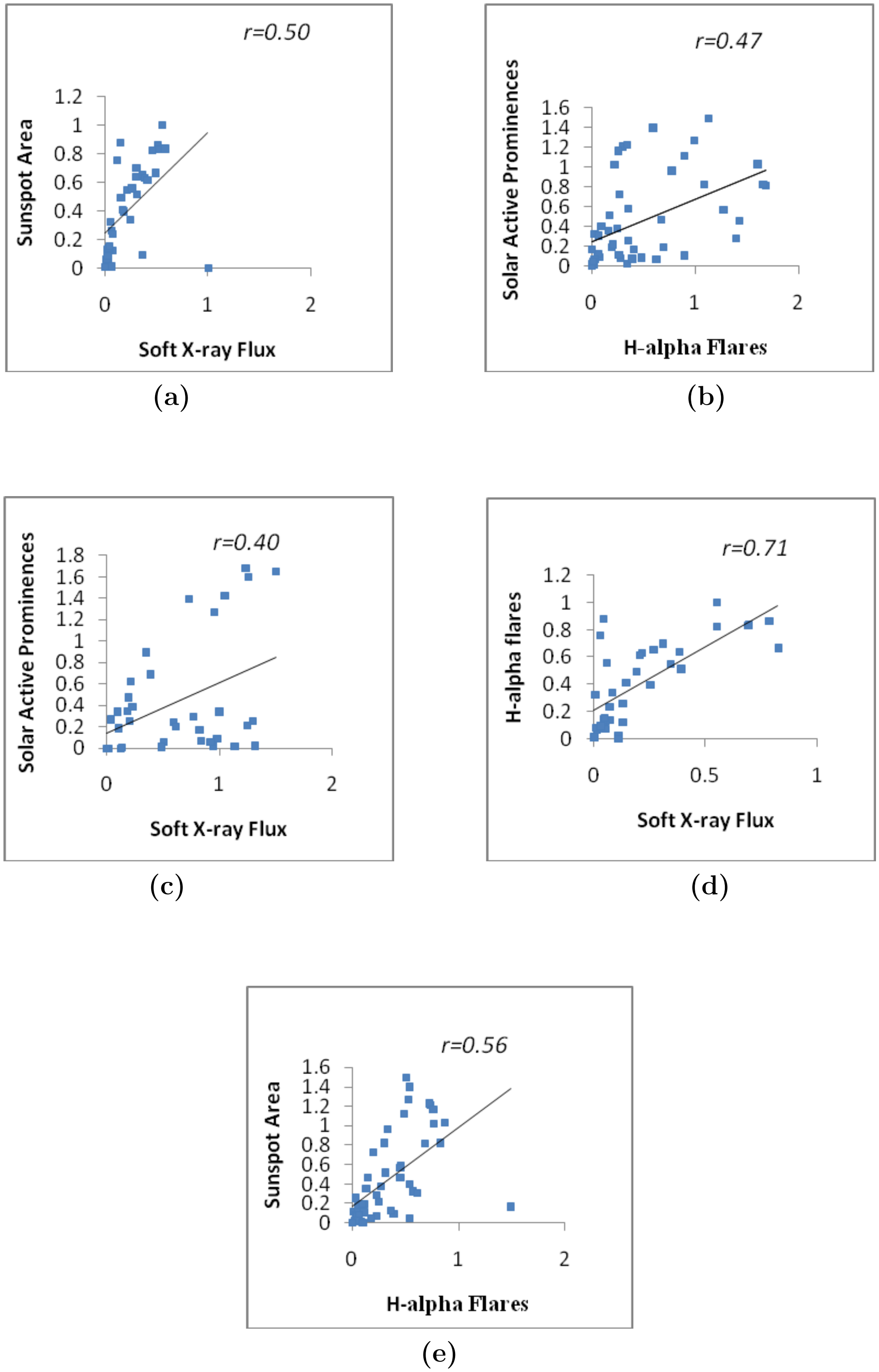


Figure 3.3: (a), (b), (c), (d), (e). Correlation Plots of Normalized Total (N+S) Events for different Solar Activity Features during Solar Cycle (SC) 20-24 (1964 to 2011).

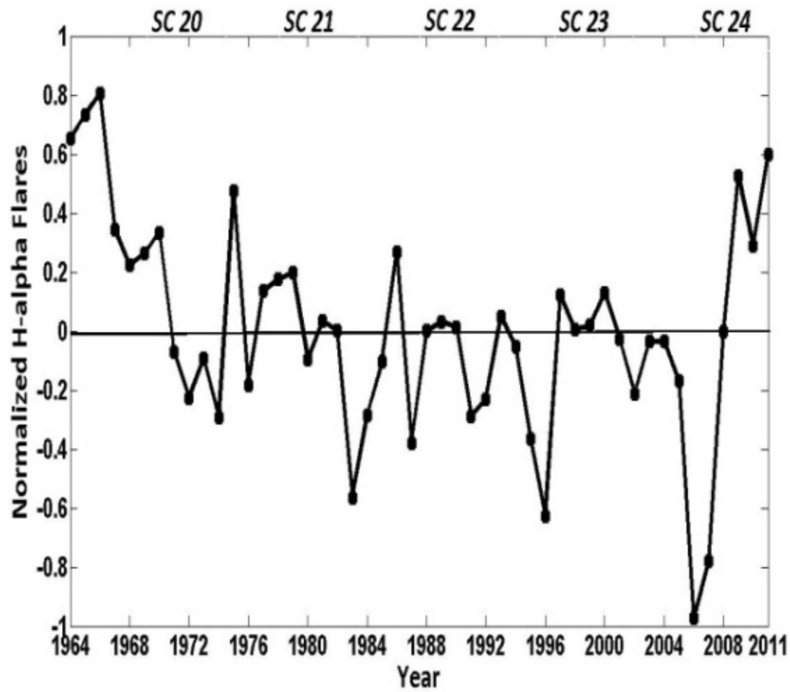


Figure 4(a). Asymmetry plot for normalized $H\alpha$ Flares for Solar Cycles (SC) 20-24 (1964 to 2011).

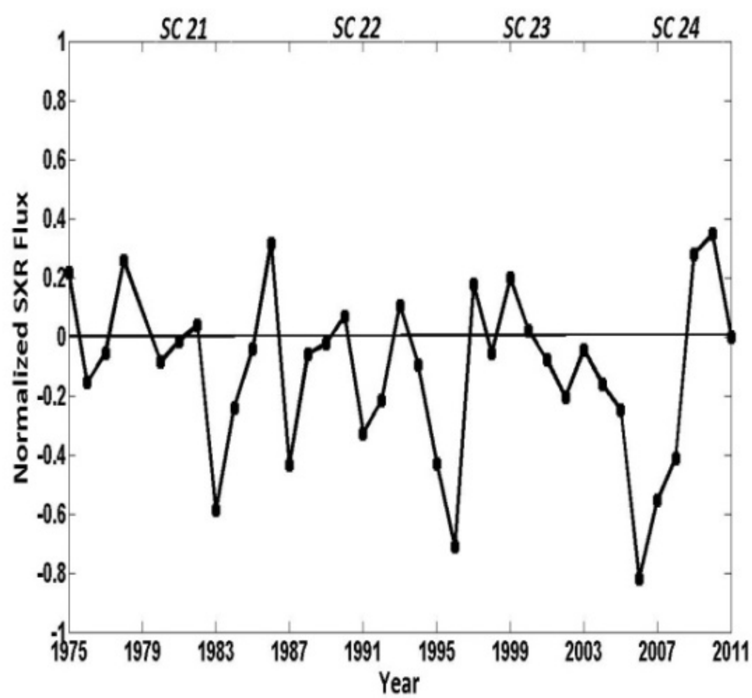


Figure 4(b). Asymmetry plot for normalized SXR Flux for Solar Cycles (SC) 21-24 (1975 to 2011).

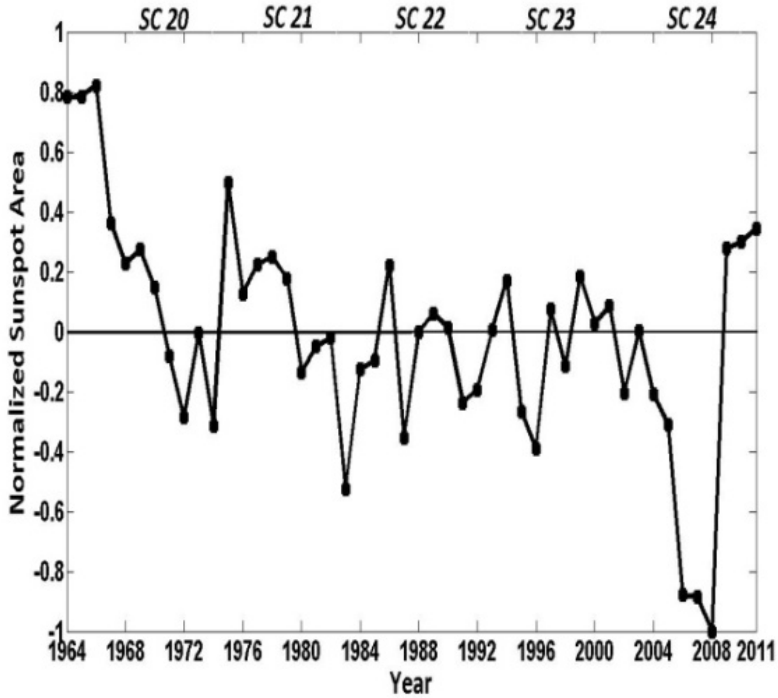


Figure 4(c). Asymmetry plot for normalized Sunspot Area for Solar Cycles (SC) 20-24 (1964 to 2011).

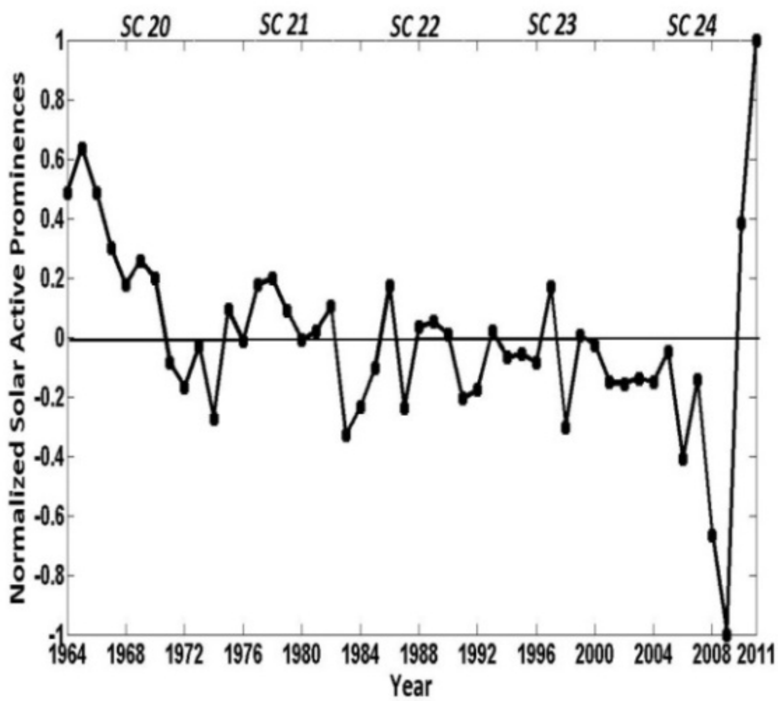


Figure 4(d). Asymmetry plot for normalized Solar Active Prominences for Solar Cycles (SC) 20-24 (1964 to 2011).

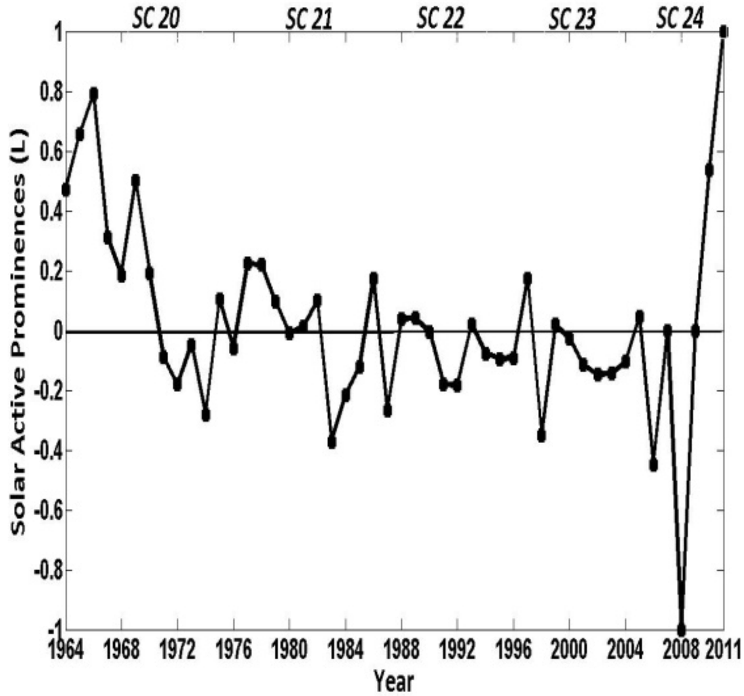


Figure 4(e). Asymmetry plot for normalized Solar Active Prominences (Low) for Solar Cycles (SC) 20-24 (1964 to 2011).

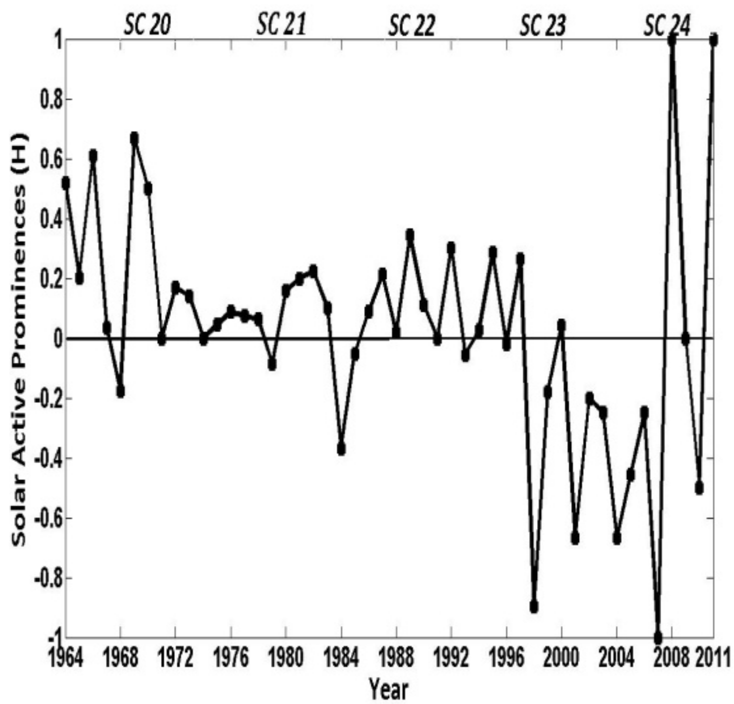


Figure 4(f). Asymmetry plot for normalized Solar Active Prominences (High) for Solar Cycles (SC) 20-24 (1964 to 2011).

4 Results and Discussions

4.1 N-S Asymmetry

The *N-S* asymmetry of different activity features i.e. $H\alpha$-flares, *SXR* flux, Sunspot area, Solar Active Prominences and Solar Active Prominences (both low and high latitude) have been investigated and shown in Figures 4(a), 4(b), 4(c), 4(d), 4(e) and 4(f) respectively. Figure 4(a) shows that occurrence of $H\alpha$-flares activity is dominated in the northern hemisphere in solar cycle 20, and during the decay phase of solar cycle 20 it moved towards the southern hemisphere. Again in solar cycle 21 it moved to northern hemisphere. In solar cycle 22, the activity was started from northern hemisphere and again it moved to southern hemisphere. Throughout the solar cycle 23, it was dominated in southern hemisphere. In the rise phase of solar cycle 24 the flares activity started in southern hemisphere and afterward got dominated in the northern hemisphere. Our results confirm the earlier results of ([1, 15]). In addition to previous studies, our study extends the results up to rising phase of solar cycle 24 (up to December 2011).

Further, the same trend of asymmetry as noted in case of $H\alpha$-flares activity have been found for *SXR* flares (Figure 4(b)), Sunspot Area (Figure 4(c)), Solar Active Prominences (Figure 4(d)) and Solar Active Prominences (low latitude) (Figure 4(e)). However, in the case of Solar Active Prominences (high latitude) (Figure 4(f)), the eruption of the activity was dominated to northern hemisphere up to solar cycle 22. In solar cycle 23, it was shifted to southern hemisphere. Again, in the rise phase of cycle 24, it was shifted into northern hemisphere as commonly noted in other activity features also.

4.2 Correlation among different features

Apart from the *N-S* asymmetry, we have also presented the correlation study between different solar activity features. The correlation between different solar activity features have been ploted in Figure 3.1 (for northen hemishere), Figure 3.2 (for southern hemishere) and Figure 3.3 (for total number of events). In northern hemisphere the Sunspot Area and number of soft X-ray flares are poorly correlated (r=0.37) (Figure 3.1(e)). The poor correlation shows that for soft X- rays flares production, Sunspot Area is solely not responsible. There may be other reasons for the production of X-rays Flares. As reported in the literature the flares can be produced by the complexivity of the Sunspot group. Therefore, in the northern hemisphere, the sunspot may be less magnetically complex. Good correlation (r=0.68) is observed in the southern hemisphere between Sunspot Area and $H\alpha$ Flares (Figure 3.2(a)). However, it is not significantly high. One possibility for the good correlation may be that the active region in the southern hemisphere are more magnetically complex. It is interesting to look in the magnetic configuration of Sunspot group in details to understand the above correlation better. However this is not the scope of this paper.

The correlations between the *SAP* and X-ray flares, and *SAP* and $H\alpha$ flares in north as well as south hemishere are 0.41 and 0.50 respectively (Figures 3.1(d), 3.2(d), and 3.1(c), 3.2(c)). One possible explanation may be that the prominances/filament eruption produces weak reconnection and hence the weak X-rays and $H\alpha$ flares are produced.

The good correlation (r=0.71) between total soft X-rays and $H\alpha$ flares(Figure 3.3(d)) shows that almost all the soft X-rays produce $H\alpha$ emission. Almost similar correlations have been obtained in case of northern as well as southern hemisphere (r=0.67 and r=0.63 resp.) for these events (Figure 3.1(b) and 3.2(b)). This study also confirms the earlier findings ([2, 15]). This shows that soft X-rays emissions are usually orignated in the higher solar atmosphere.The particle orignated during X-ray flares emission later produced the $H\alpha$ emission in the lower solar atmosphere. There is no firm conclusive statement for correlation between certain activity features like total SAP and $H\alpha$ flares, total Sunspot Area and X-rays, total sunspot area and $H\alpha$ flares, Sunspot Area and X-rays in southern hemisphere etc. as the correlation lies between 0.47 and 0.64.

It is quite interesting to note that the correlation coefficient increases drastically between certain activity features if few of the outlying data points are removed. The respective revised correlation plots are given in Figures 5,6 and 7 below. It is found that the correlation between total soft X-rays and $H\alpha$ flares as well as in northern and southern hemisphere is strong as the correlation coefficient are 0.83, 0.80 and 0.86 respectively (Figures 7(e), 5(b) and 6(b)). This shows that regression line is quite close to the data points as the coefficient of determination is greater than 0.64 in all cases. Similarly, the Sunspot Area and Soft X-rays are highly correlated as the correlation coefficients are 0.86, .82 and 0.92 in total, northern and southern hemisphere respectively (Figures 7(a), 5(e), and 6(e)) and the coefficient of determination is greater than 0.67. Further, Sunspot area and $H\alpha$ flares are also highly correlated as shown in Figures 5(a), 6(a) and 7(d). It is also to be noted that rest of the activity features like SAP and $H\alpha$ flares, SAP and Soft X-rays show good correlation (Figures 5(c), 5(d), 6(c), 6(d), 7(b), and 7(c)).

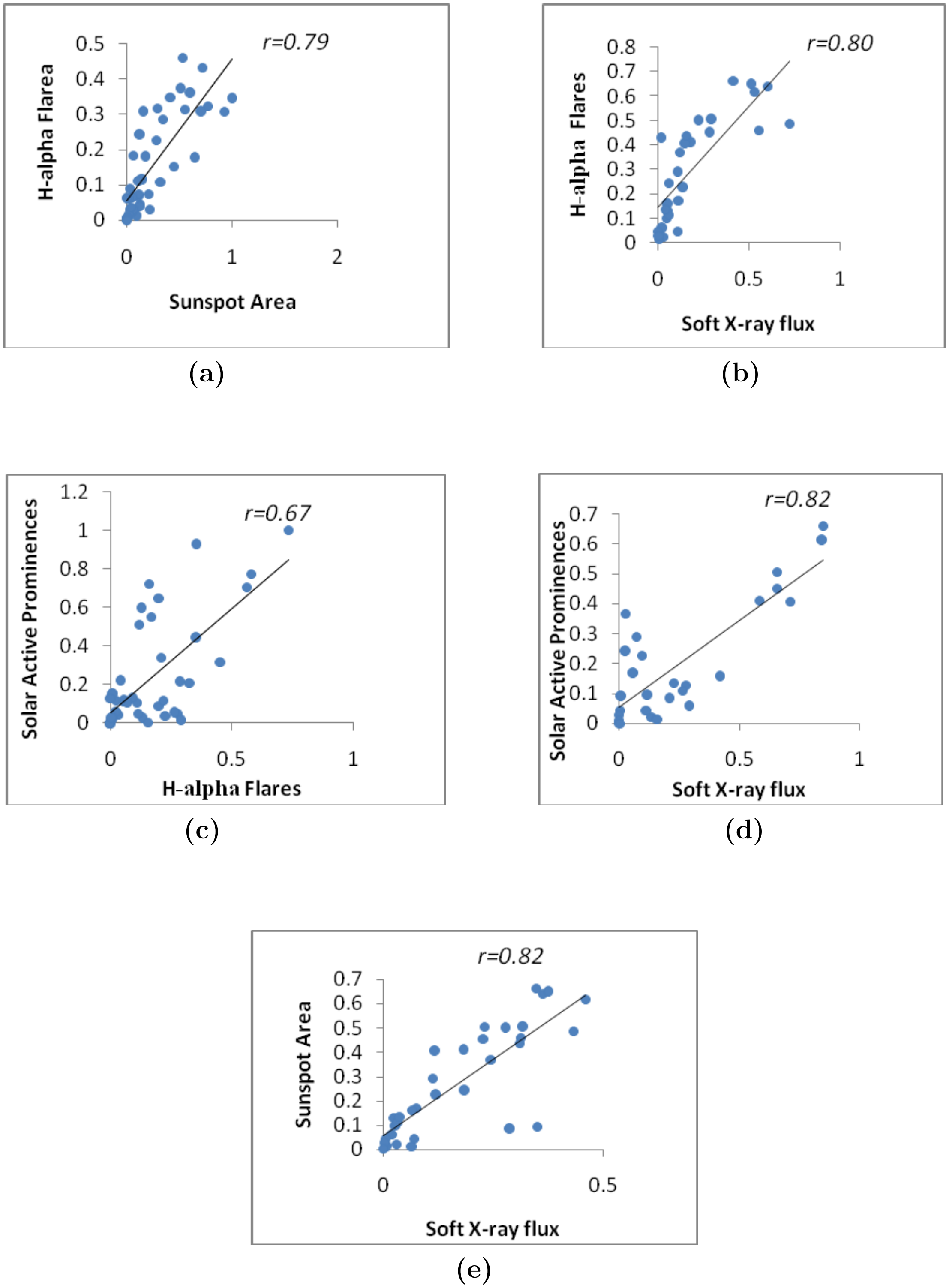


Figure 5 (a), (b), (c), (d), (e). Correlation Plots of Normalized North Events for different Solar Activity Features during Solar Cycle 20-24 after removing outliers.

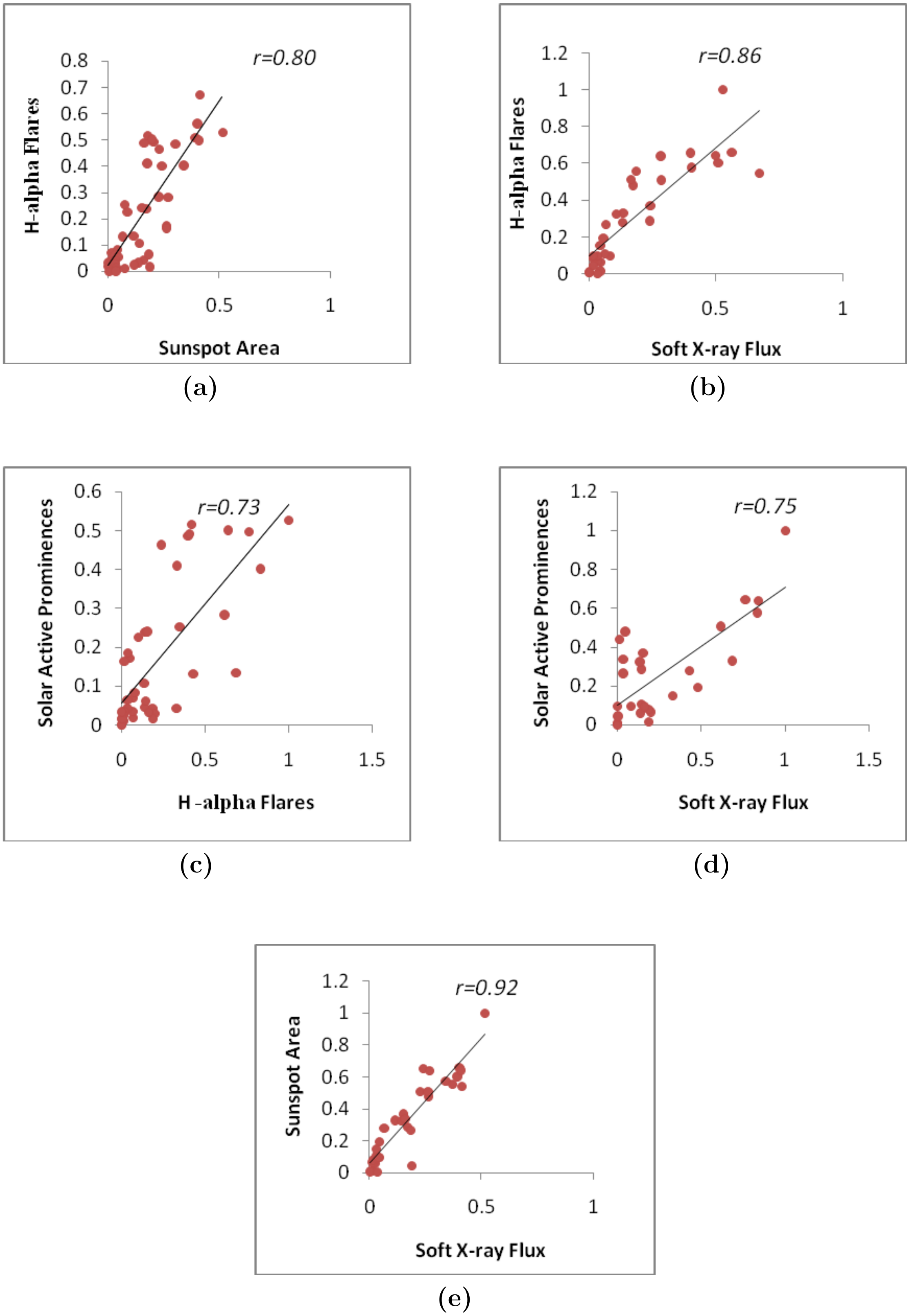
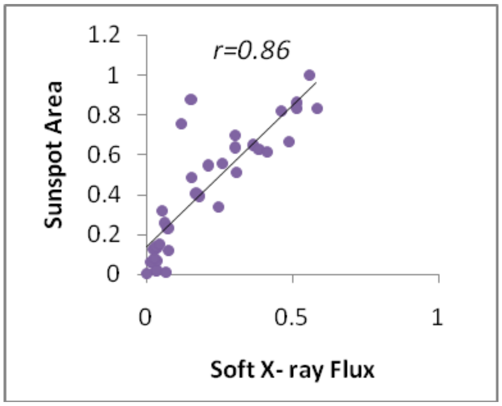
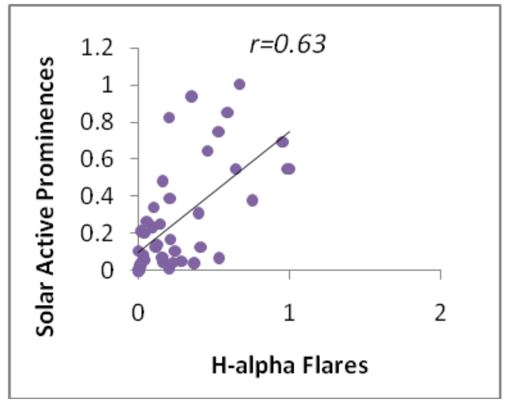


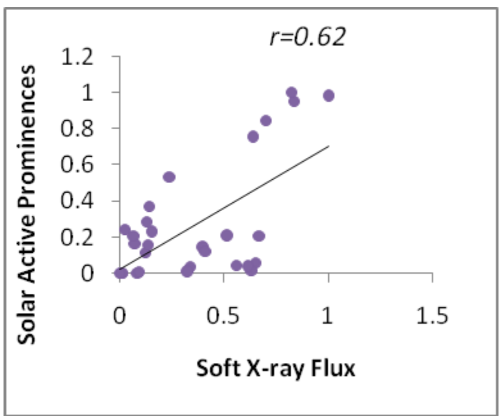
Figure 6. (a), (b), (c), (d), (e) Correlation Plots of Normalized South Events for different Solar Activity Features during Solar Cycle 20-24 after removing outliers.



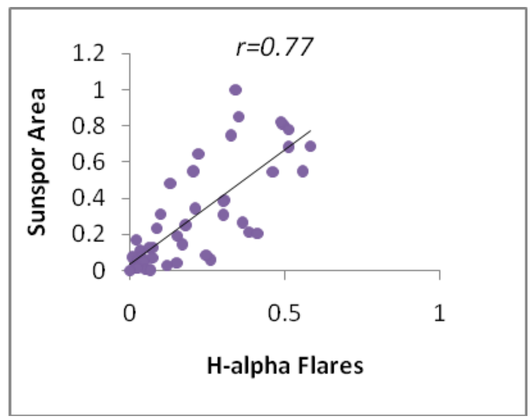
(a)



(b)



(c)



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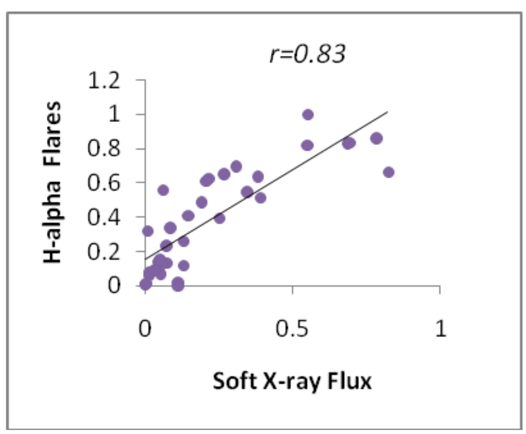

(e)

Figure 7 (a), (b), (c), (d), (e). Correlation Plots of Normalized Events for different Solar Activity Features during Solar Cycle 20-24 after removing outliers.

5 Conclusions:

To understand the nature of the solar dynamo system, it is important to analyze the N-S asymmetry phenomena of solar activity features. In this paper, the normalized data of Sunspot Area, SAP, SAP(low latitude), SAP (high latitude) and $H\alpha$ flares for solar cycles 20-24 (1964-2011) and soft X-rays (SXR) for solar cycles 21-24 (1975-2011) have been analyzed statistically to observe the asymmetric behavior of the solar active phenomena and correlation among them. It is concluded that the normalized N-S asymmetry of all solar activity features shows a drift from northern hemisphere to southern hemisphere during solar cycle 20. For the remaining cycles 21-23, all activities except $SAP(H)$ are dominant in southern hemisphere. However, the asymmetry of $SAP(H)$ varies dominantly in northern hemisphere for solar cycles 20-22 and shifts to southern hemisphere during solar cycle 23. In the beginning of the solar cycle 24, all the activities were started in southern hemisphere and afterward dominated in northern hemisphere. The different solar activity features are physically associated with each other. It becomes important to discuss the correlation among them. In this study it is found that there is a weak correlation between sunspot area and number of X-ray flares in northern hemisphere, where as the correlation is stronger in southern hemisphere. This result indicates that only the Sunspot Area is not responsible for the production of X-ray flares. Also, there is weak correlation between the prominence/filament eruption and X-ray and $H\alpha$ solar flares, which confirms the idea that all the filament eruptions are not associated with the flares. Further, there is a strong correlation between $H\alpha$ and X-ray flares, which supports the earlier studies. Here it is important to mention that the correlation amongst the activities increases tremendously as few of the outliers are removed from the data tables. In some cases, like sunspot area and X-ray flares, $H\alpha$ and X-ray flares, SAP and X-ray flares etc. strong correlation has been obtained. This may be because of some observational errors in data or any other hidden reasons, but the strong correlation supports the dependency of solar activity features on one another.

Acknowledgments

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