Analysis of Solar Activity and Atmospheric Pressure 
Competition Effects on Cosmic Radiation Events
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Abstract: In this paper, we analyze the influence of characteristic solar activity parameters as well as the competition effects in solar activity and atmospheric pressure on the records of cosmic radiation based on HiSPARC, a ground-based detector monitoring secondary cosmic ray intensity. We gather the data from No.501 HiSPARC station situated at Nikhef in Science Park, Amsterdam, Netherlands (52.3558963°N, 4.9509827°E, 56.18 m of altitude). From the anticorrelation between the number of solar flares, relative number of sunspots and that of events, we obtain the formula through an exponential fitting model. Furthermore, we quantitatively find the correlation between the daily average number of cosmic ray events and the characteristic solar activity parameters, including the number, the area and the latitude of sunspot groups within one month. Turning to the combined effects of solar activity and atmospheric pressure, we calculate the critical interval, beyond which the influence of solar activity on the number of events is weaker.

Key words: Solar activity; Atmospheric pressure; Cosmic radiation events; HiSPARC

1. Introduction

In the realm of cosmic ray physics and astrophysics, the significance of analysis on the physical nature of the cosmic radiation variations in different time scales is beyond dispute [1]. The Earth is continuously exposed to various and innumerable particles from the outer space. As soon as the particles bombard inside the atmosphere, the travelers will collide with atmospheric molecules and then scatter. Actually, the change of direction is negligible on the grounds that the velocity of particles is extremely high. Due to the high energy collision, new particles like pions, muons, photos and electrons are created [2].

During this process, some meteorological parameters, like atmospheric pressure and so on, can impose a noticeable influence on the collision and scattering, particularly in short time scales [3]. Consequently the number of cosmic radiation events is affected dramatically in the short term [4]. Turning to the longer time scales, nevertheless, solar activity plays a more significant role. Because the solar activity is periodic, the number of cosmic ray events detected on the Earth can simultaneously demonstrate a similar period. Ascribed to the correlation, the quantity of events can indicate the trend of solar activity and changes in some solar activity parameters.

One aspect of our work focuses on the effects of characteristic solar activity parameters on the number of cosmic ray events. McIntosh (1990) [5] proposed the McIntosh Classification of Sunspots which can reflect the morphological characteristics of solar active region. Li Rong et al (2009) [6] studied the correlation between the solar activity parameters, like the longitude of sunspots, area of sunspot groups and so on, and solar flare productivity. Currently solar flare is classified into 5 degrees – A, B, C, M and X, according to the magnitude of soft X-ray peak flux detected by the American GOES satellite [7]. In this paper, firstly we compare the monthly total number of solar flares, whose degree is C and above, with daily average number of events in a month observed by HiSPARC detector and find the correlation of their trend.

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Secondly, we study the correlation between the total yield of flares surrounding sunspot groups within 24 hours, the latitude and the area of sunspot groups. Meanwhile, flares which happen outside the sunspot groups are also taken into consideration. Lastly, the correlation between the number of events and some solar activity parameters, including the number, the area and the latitude of sunspot groups, is obtained.

Another aspect of our work is to analyze the combined effects of solar activity and atmospheric pressure. Loran de Vries et al (2012) [8] studied the correlation between the event rate and weather variables and formulated a linear model using the barometric coefficient. R. R. S. De Mendonça et al (2013) [9] analyzed the impact of atmospheric pressure and temperature on cosmic ray events. In this paper, we firstly study the correlation between the daily average number of events and that of sunspots within a month, and quantitatively demonstrate the relationship. Then we obtain the correlation between pressure and the number of events with the comparatively stable number of sunspots. Subsequently we build a linear model to calculate the gradient. Ultimately, we use the derivative function to show the competition of solar activity and atmospheric pressure and obtain a critical interval, beyond which the influence of solar activity on the number of events is weaker while that of pressure is more influential.

2. Material and methods

The study is based on a cosmic radiation detector called HiSPARC. The device focuses on the muons in cosmic ray whose energy is high and ultra high, in excess of $10^{18}$ eV to be precise. The configuration of the HiSPARC detector is shown in Fig. 1.

As is shown in Fig. 1, a single HiSPARC detector consists of two rectangular scintillator plates, which are wrapped in thin aluminum foil with a thickness of 25 μm. Each plate is attached with a triangular light guide, a terminal block and a Photo-Multiplier Tube (PMT). The whole system is connected to a HiSPARC box whereby two analogue signals received from the PMTs are transformed into digital signals, ready to be sent to the Internet via a computer. A GPS, which can record the location of detector and time accurately, is also connected to the computer.

In this paper, we only use the data of events provided by HiSPARC Station No. 501, which was installed in March 2004. The station is situated at Nikhef in Science Park, Amsterdam, Netherlands (52.3558963°N, 4.9509827°E, 56.18 m of altitude). The history data of daily average atmospheric pressure is provided by a closest meteorological station operated by Royal Netherlands Meteorological Institute (KNMI) at Schiphol, Amsterdam. The linear distance of these two places is 11.3 km. The history data of sunspots, the area and location of sunspot groups is provided by Solar Activity Prediction Centre, National Astronomical Observatories, Chinese Academy of Sciences (CAS). The data of solar flares is provided by the American GOES satellite, National Oceanic and Atmospheric Administration (NOAA). All of the data is collected within the 24th solar circle. Because the HiSPARC detector was frequently under check-up before 2009, the data we gather is from January 2009 to March 2016.

3. Results and Discussions

3.1. Analysis on the effects of characteristic solar activity parameters

Solar flare is the most intense phenomenon that happens in chromosphere. Substantial flares emerge around sunspot groups [10]. The yield of flares is correlated with many solar activity parameters like the area and location of sunspot groups [11]. If a quantitative relationship between the number of events and that of flares is obtained, we can find the correlation between the number of events and characteristic solar activity parameters.
Numerous particles (mainly positively charged protons), electromagnetic radiation and high energy are emitted from flares on the visible hemisphere of the sun to the Earth [12]. Because most primary particles of cosmic ray are protons, these two particle flows can repel against each other. The number of muons with high and ultra high energy in cosmic ray will be negatively affected by the drastic ascent in the intensity of solar activity. We study the correlation between the total number of solar flares and the daily average number of events within one month from January 2009 to March 2016. We only concentrate on solar flares whose degree is C and above, including C, M and X. The time dependency is shown in Fig. 2.

To demonstrate the trend, we use a Savitzky-Golay filter (S-G filter) to smooth the curve and remove high frequency noise. We mention that this method neglects the marginal difference in the atmospheric pressure in different seasons. This may not be absolutely accurate and therefore indicates the limitation of our method, but it can in fact correctly show the negative correlation between these two trends. Fig. 3 quantitatively shows this negative correlation.

The function of the exponential fitting curve is:

\[ N_1 = N_{10} + k_1 e^{AF_t} \]  

where \( N \) is the daily average number of events, \( F_t \) is the monthly total number of flares, \( N_{10}, k_1 \) and \( A \) are constants whose values are 60802.98, 23545.33 and \( -0.03135 \) respectively. The coefficient of determination is 0.88037.

The emergence of flares is associated with the intensity of solar activity. The likelihood of occurrence of flares surrounding sunspot groups, where the solar activity is usually intense, is higher. The intensity of solar activity can be depicted by the number and area of sunspot groups. Because the angular velocity of sunspot groups with diverse latitude is different [13], the number and life span of sunspot groups can be affected. So, the latitude is another crucial factor that needs to be considered.

We look at the total yield of flares surrounding different sorts of sunspot groups with similar area and latitude within 24 hours. The formula to calculate average yield is given by the following relation:

\[ P(S, \theta) = \frac{\sum_i p(S_i, \theta_i)}{\sum_i G(S_i, \theta_i)} \]
where $P(S_i, \theta_i)$ is the average yield of flares emerging within 24h around a specific sort of sunspot groups sharing similar area ($S_i$) and latitude ($\theta_i$), $\sum_i p(S_i, \theta_i)$ is the total yield of flares emerging within 24h around the sunspot groups, and $\sum_i G(S_i, \theta_i)$ is the total number of the sunspot groups.

**Fig. 4** shows the average yield of flares emerging around sunspot groups with various area and latitude.

Fig. 4 (A) The average yield of flares emerging around sunspot groups within 24h versus the area and latitude of sunspot groups. As for the latitude, negative value represents the southern hemisphere of the sun. (B) Apply a piecewise surface fitting model to the scatter 3D diagram.

As is shown in the **Fig. 4** (A), when the latitude of sunspot groups is outside the interval of ($-30^\circ, 30^\circ$), the average yield of flares is almost 0. Meanwhile, in this interval, the average yield increases significantly accompanied with a growth in the area of sunspot groups. Additionally, for the most part, the yield of flares emerging around the sunspot groups in the southern hemisphere is slightly larger than that in the northern hemisphere. Hence, a piecewise surface fitting can be applied to the scatter 3D diagram, which is shown in the **Fig. 4** (B). The function is:

$$
\begin{cases}
P(S, \theta) = P_0 + aS^2 + bS + c\theta^2 + d\theta + fS\theta, & \theta \in (-30^\circ, 30^\circ) \\
P(S, \theta) = 0, & \text{else}
\end{cases}
$$

where $P_0, a, b, c, d$ and $f$ are constants whose values are $0.262, 7.42 \times 10^{-6}, -1.89 \times 10^{-3}, 2.97 \times 10^{-4}, -2.26 \times 10^{-4}, -2.28 \times 10^{-5}$ respectively. The coefficient of determination is 0.89334.

Actually, not all the flares will erupt surrounding sunspot groups. The number of flares emerging outside sunspot groups should also be considered. We assume that if the total number of flares ascends, the number of flares surrounding sunspot groups will simultaneously increase. **Fig. 5** quantitatively shows their correlation.

Fig. 5 The monthly total number of flares versus the monthly total number of flares around sunspot
groups. A linear fitting model can be applied to the scatter diagram.

The function of the linear fitting curve is:

\[ F_t = F_0 + k_2 F_s \]  

where \( F_t \) is the monthly total number of flares around sunspot groups, \( F_s \) is the monthly total number of flares around sunspot groups, \( F_0 \) and \( k_2 \) are constants whose values are 15.466 and 2.495 severally. The correlation coefficient is 0.9587 and the coefficient of determination is 0.9191.

Because \( F_s \) is the monthly data, it can be statistically calculated through the following relation:

\[ F_s = \sum_i P(S_i, \theta_i) \]  

where \( i \) is the ordinal of sunspot groups within one month.

The statistical correlation between the trend of daily average number of events and characteristic solar activity parameters (including the number, area and latitude of sunspot groups) within one month can therefore be attained through simultaneous equations (1) ~ (5). The relation is given as equation (6):

\[ N_i(i, S, \theta) = N_{10} + k e^{F_i + k_1 \sum_i P(S, \theta_i)} \]  

where \( P(S, \theta) \) is determined by equation (3).

As is shown in equation (6), the number, the area and the latitude of sunspot groups in one month can dramatically influence the daily average number of events we detect on the Earth. What is noticeable is that the impact of solar activity is distinct only in the long term rather than a short time interval, when meteorological parameters like atmospheric pressure on the Earth are more influential [14]. The statistical analysis on the competition of solar activity and atmospheric pressure and the critical point of their interaction will be explained in the next section.

Turning to characteristic solar activity parameters, we focus mainly on the number, the area and the latitude of sunspot groups, while there may also exist correlation between the yield of flares and the sunspot magnetic classification, the McIntosh classification and solar radiation current, thus affecting the number of events. These parts can be scrupulously studied in further research.

3.2. Analysis on the joint effects of solar activity and atmospheric pressure

Sunspots, which happen in photosphere, is the basic signal of solar activity. Relative number of sunspots is the most common and fundamental parameter which depicts the intensity of solar activity [15]. According to the definition given by R. Wolf in 1848, relative number of sunspots, which is also known as the Zurich number, is determined by the equation given below:

\[ R = k (10g + f) \]  

where \( R \) is the relative number of sunspots, \( g \) is the number of sunspot groups on the visible hemisphere of the sun, \( f \) is the number of single sunspots, \( k \) is a conversion factor correlated with observation instrument, method, weather condition and so on.

We study the correlation between the daily average relative number of sunspots and that of events within one month from January 2009 to March 2016. The S-G filter is used to smooth the curve and remove high frequency noise. As is referred before, this method neglects the slight difference in the atmospheric pressure in different seasons, which is a limitation. Fig. 6 shows the time dependency.
sunspots (dashed line), trend of daily average number of events within one month (solid line), and the actual number of sunspots and events within one month (dotted line).

It is apparent that the two trends demonstrate a negative correlation. Quantitatively, we extract the data of two trends (smoothed curve) and employ an exponential fitting model to express the correlation. Fig. 7 shows the quantitative correlation.

\begin{equation}
N_2 = N_{20} + k e^{Bn}
\end{equation}

where $N_2$ is the daily average number of events, $n$ is that of sunspots, $N_{20}$, $k$ and $B$ are constants whose values are 60299.51, 27522.08 and $-0.03723$ respectively. The coefficient of determination is 0.83401. The parameters are similar to equation (1). Because the period of solar activity is similar to that of sunspots and flares, in turn the accuracy of these two equations can be verified.

According to the scatter diagram given by Fig. 7, there exists a critical point whose value is in the vicinity of 80. When the relative number of sunspots is smaller than it, the regularity of fluctuation is stronger. As soon as the number transcends this point, nonetheless, the fluctuation will be in chaos and the amplitude will be immensely larger. Fig. 8 shows this phenomenon.

The fluctuating interval, which is reflected in Fig. 8 (B), becomes noticeably larger when the relative number of sunspots exceeds 80. So, we assume that there could be a specific meteorological parameter which will impose combined effects together with solar activity on the number of events. Furthermore, a critical point in the relative number of sunspots should exist somewhere around 80. Beyond this point the impact of solar activity is much less distinct than the meteorological parameter, thus resulting in the seemingly unpredictable fluctuation.

Turning to the specific meteorological parameter,
previous research found that the correlation between outside relative humidity, air temperature and the event rate detected by HiSPARC devices was weaker, while as for the atmospheric pressure, the reverse was true [8]. The atmospheric pressure should be the research object.

To avoid interference of solar activity, the influence of pressure should be studied with the comparatively stable number of sunspots. We divide the relative number of sunspots into 9 groups whose intervals are [15, 24), [25, 34), [35, 44), [45, 54), [55, 64), [65, 74), [75, 84), [85, 94) and [95, 104) severally. In each group we extract the data of events and atmospheric pressure and plot the graph. Fig. 9 shows an example when the relative number of sunspots is [55, 64).

![Fig. 9](image)

The number of events versus atmospheric pressure when the relative number of sunspots is around 60. The gradient of the line is \(-46.02\). The correlation of coefficient is \(-0.86235\).

The gradient of the line can portray the velocity of change, thus characterizing the influence the atmospheric pressure on the number of events. We apply the linear fitting model to each group and calculate the gradient. The data is given as Table 1.

| group          | [15, 24) | [25, 34) | [35, 44) | [45, 54) | [55, 64) | [65, 74) | [75, 84) | [85, 94) | [95, 104) |
|----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| gradient       | -48.78  | -52.73  | -52.11  | -53.99  | -46.02  | -32.56  | -35.54  | -43.70  | -40.25  |
| Pearson’s r    | -0.633  | -0.787  | -0.769  | -0.758  | -0.862  | -0.742  | -0.840  | -0.799  | -0.732  |

The gradient of different groups is comparatively stable with a slight fluctuation. In the meantime, similarly, the derivative function of equation (8) can be calculated to depict the influence of solar activity on the number of events. The diagram which shows the gradient and derivation function is given as Fig. 10.

![Fig. 10](image)

Differential coefficient versus the relative number of sunspots. The thin dashed line is the upper limit of the fluctuating interval of the gradient while the dotted line is the lower limit. The thick solid line is the average value of the gradient. The thick dashed curve is the derivation function of equation (8).

The intersection of the fluctuating interval and the derivation function should be the critical point. Because the gradient has a fluctuating interval instead of a single value, the critical point should be within an interval as well. The critical interval is (79.06, 92.64) according to calculation, and the mean value (the corresponding critical point of the average value of the gradient) is 83.90. The result is similar to the estimated value (around 80), so the assumption can be verified. In the light of Fig. 8, when solar activity is comparatively weak (the relative number of sunspots is smaller than
any value within the critical interval, the influence of it on the number of events we detect on the Earth is much stronger than atmospheric pressure. Nevertheless, the converse will be true if the relative number of sunspots surpasses the upper limit of the critical interval. In this case, the impact of atmospheric pressure should be considered when researching the influence of solar activity.

4. Conclusion

In this paper, we analyzed the data of cosmic ray events and solar activity, including the number, the area and the location of sunspot groups and solar flares, based on HiSPARC detector.

Turning to the first aspect of our work, we concentrated on the correlation between the number of cosmic ray events and characteristic solar activity parameters. Firstly, we found that there existed an anticorrelation between the daily average number of events and the total number of flares, whose degree was C and above, within one month and attained the function expression through an exponential fitting model. Secondly, we observed the correlation between the total yield of flares surrounding different sorts of sunspot groups within 24h, the area and latitude of sunspot groups. In the meantime, solar flares emerging outside sunspot groups were considered as well. Entering the eventual phase, the formula between the daily average number of events and the number, the area and the latitude of sunspot groups within one month was calculated.

In terms of the second aspect of our work, at the outset, we quantitatively found the correlation between the daily average relative number of sunspots and that of events within one month. Moreover, we calculated the residual and fluctuating interval, and assumed that atmospheric pressure could be more influential than solar activity when the relative number of sunspots transcended 80 approximately. Then we divided the relative number of sunspots into 9 groups, and in each group, we calculated the gradient by applying a linear fitting model in the number of events-atmospheric pressure diagram. Ultimately, the critical interval (79.06,92.64) was attained by calculating the intersection of the fluctuating interval of gradient and the derivative function. The assumption was verified.

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