The Effect of the Solar Cycle on Secondary Cosmic Ray Intensity and Cloud Formation

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Abstract

It has been proposed that there exists a link between the ~22 year-long solar cycle and the intensity of galactic cosmic rays (GCRs) that reach the Earth. In addition, GCRs have been thought to seed cloud formation, with possible ties to global warming among other phenomena. Using data from three detectors in the Netherlands, various analytical techniques were used to find a possible relation between the amount of solar activity and the number of cosmic rays detected. To show the greatest difference, data was chosen from two specific points in the solar cycle: the solar minimum (where solar activity is at its lowest), and the solar maximum (where solar activity is at its highest). For the cycle chosen – solar cycle 24 – the periods of interest were November 2009 – January 2010 and December 2013 – February 2014 respectively. Sun spot data from NASA compared against HiSPARC muon detection data has shown a significant anti-correlation, suggesting that the Sun's solar cycle has a strong influence on GCR intensity on Earth. Furthermore, weather data from Amsterdam during the solar minimum/maximum shows visually similar variation with cosmic ray intensity – giving rise to further evidence for the link between the terrestrial climate and the solar cycle.

Acknowledgments

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Introduction

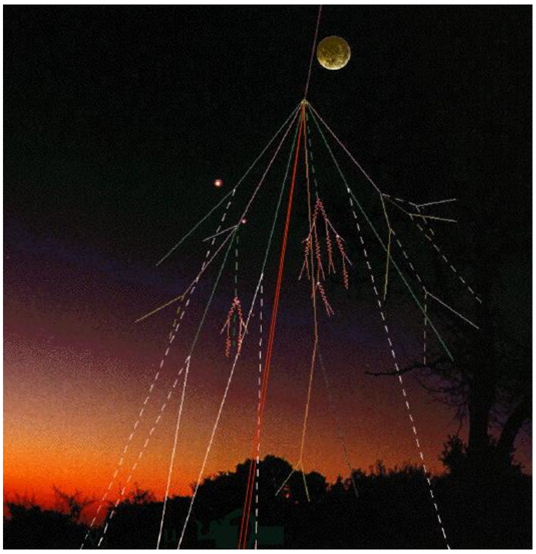
NASA (2012) stated that “Particles that bombard the Earth from *anywhere* beyond its atmosphere are known as **cosmic rays**”. These cosmic rays are the subject of much research, being thought to be linked with the solar cycle and the Earth’s climate.

A hypothesis was made that the Sun’s magnetic field deflected weaker cosmic rays, and so a change in solar activity would cause a direct change in the intensity of cosmic rays detected on Earth. The majority of this paper is divided into three sections, each covering the hypothesis or an extension of it. Section One relates to the initial proposal, investigating and establishing a link between the amount of solar activity (through the point in the solar cycle) and the Galactic Cosmic Ray intensity experienced on Earth. Section Two discusses a possible relation between the energy of incident GCRs with respect to the point in the solar cycle. The final section of the three analyses how much influence the intensity of GCRs has on the Earth’s climate in terms of cloud formation. This is then followed by a discussion of the findings describing interpretations of the results and a conclusion to the research.

Section One – Finding the link between the Solar Cycle and GCR Intensity

Cosmic rays are high energy particles with various origins and of differing energies. The difference in energy corresponds to the particles origins, that is, higher energy particles (Galactic Cosmic Rays) originate from outside our solar system, while those of lower energy come from the Sun (Solar Energetic Particles). Primary cosmic rays, produced through events such as supernova and solar flares, mostly consist of protons, as well as alpha particles and electrons (with percentages 85%, 12% and 2% respectively)(Kortland, 2014, p.1). Due to their electric charge, all cosmic ray particles are subject to Lorentz forces as they travel through various magnetised interplanetary media; as a consequence, the path travelled by such a particle can be significantly altered (Kortland, 2014, p.3).

One magnetic field of interest is the Sun's magnetosphere. Whilst many of the lower energy (10^9 eV) particles are deflected here, higher energy (10^{15} eV) particles are able to pass through with minimal effect (Kortland, 2015, p.1). The hypothesis was made that the magnetic field of the Sun deflected cosmic rays, thus a variation in the strength of the Sun's magnetic field would show a variation in cosmic ray detection.



A diagram representing the cascade of particles forming in an air shower as primary cosmic rays collide with the nuclei of atoms in the air to form secondary cosmic rays such as muons. (University of Oregon, 2015)

To study cosmic rays, HiSPARC (High School Project on Astrophysics and Research with Cosmics) detectors have been placed over the Netherlands and more recently, in parts of the UK, Germany and Denmark. The basic principal involves connecting two scintillator plates to light guides and photomultiplier tubes. The scintillator plates detect muons, secondary cosmic rays which are the result of primary cosmic ray decay in air showers. These muons decay into photons which are guided to the photomultiplier tubes to amplify the signal for detection. The HiSPARC ‘box’ which gathers this data is connected to a computer which then uploads the information to the HiSPARC public database with information on GPS location, altitude, air pressure and some include weather information as well.

To measure the amount of solar magnetic activity, sun spot data from NASA was used (NASA, 2015). A sun spot is a concentration of the Sun’s magnetic field in one particular area of the photosphere. This results in reduced convection subsequently leading to a lower temperature in the affected area. The characteristic darker spot is named a sun spot and is a direct indication of increased magnetic activity on the Sun (NASA, 1998). Tending to occur in clusters, sun spots can be difficult to count accurately. To combat this, the Wolf number (or Zurich number as it is sometimes called) was devised to compensate for factors beyond the observers controls such as dimness and poor weather conditions. The relative sun spot number, R , is calculated by the following formula:

$$R = k(10g + s)$$

Where g is the number of sun spot groups (clusters), s is the number of individual sun spots and k is a factor relating to location and instrumentation – a way to correct for global use of the equation.

Section One – Method and Results

The prediction based on the hypothesis was that the increase in solar activity would increase the number of cosmic rays deflected by the Sun and therefore decrease the number of cosmic rays detected on Earth by the HiSPARC stations. To test this, the data gathered from NASA regarding sun spot numbers was plotted on a graph against time, as shown in *Figure 1* (NASA, 2015). The result yields a curve showing the end of the 23rd solar cycle (since 1755 when records began) around 60 months after January 2004, placing the solar minimum around November 2009 – January 2010. Looking further shows the peak of the 24th cycle which is around 120 months after January 2004, placing the solar maximum around December 2013 – February 2014.

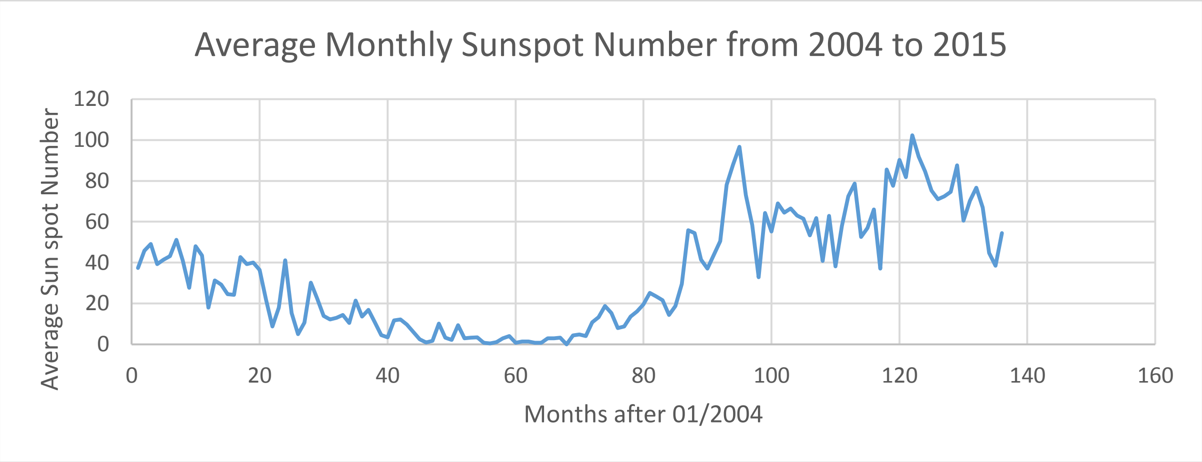


Figure 1. Graph of Sun Spot Data, 01/2004 – 07/2015. The average number of sun spots over a one month period was calculated and plotted for each month after January 2004 up to July 2015. Change in sun spots number directly relates to the change in solar activity with a high number of sun spots showing a high amount of solar magnetic activity.

To compare the change in sun spot number with the change in muons detected, HiSPARC data from the stations 501, 502 (Amsterdam Science Park) and 4001 (Groningen) was taken for each hour from 00:00:00 01/11/09 to 23:00:00 31/01/10 and averaged to find the mean number of muons detected every hour in this time period. The same was repeated for 01/12/13 – 28/02/14 and both graphs were plotted with a linear trend line (HiSPARC, 2015a). The graphs show a decrease and increase in coincidences (detections) respectively (see Appendix A). As expected, the decrease occurs as the solar activity is beginning to increase again. Conversely, as the solar activity begins to decrease, the number of muons detected begins to increase - thus supporting the claim that the solar cycle may influence the intensity of cosmic rays. To quantify the correlation between the two, several calculations were performed on the data collected from NASA and the HiSPARC detectors. As the NASA data was an average of the number of sun spots per month, the HiSPARC data was first converted from hourly data, to daily then averaged for each month. The standard deviation was calculated (and was given from NASA in the case of the sun spot data) to use the covariance formula and finally the correlation formula, shown below:

$$\sigma(A,B) = \frac{\sum_{i=0}^{N}(A_i - \bar{A})(B_i - \bar{B})}{N}$$

Covariance formula

$$\frac{\sigma(A,B)}{\sigma_A \sigma_B}$$

Correlation formula

The boundaries of the correlation formula produce a result between 1 and -1, with 1 being correlated and -1 being anti-correlated. The closer the value to zero, the less related the two variables are. Applying the formulae gave -0.91346482 (8 d.p) for the solar minimum period and -0.422326442 (8 d.p) for the maximum period. While both negative, the latter results proved closer to zero than -1, indicating the correlation may not be as strong during the maximum period. To test this, more data was collected from the November 2011 – January 2012 period (where a decrease in cosmic rays would have been expected to have been seen). Once again, applying the formula gave a result of -0.967663994 (8 d.p): a very strong anti-correlation. This calls the accuracy of the previous result into question as two of the three points in the cycle show a very strong anti-correlation.

Section Two – Investigating the Possible link between the Solar Cycle and GCR Energy

As the above evidence seemed to suggest an anti-correlation, it would be fair to assume the energy of incident particles would follow a similar, but opposing pattern. As the solar activity increases, so too must the energy of a particle for it to travel at a sufficient velocity to undergo minimal deflection by the magnetosphere. Naturally, the hypothesis would extend itself to suggest that the particles detected during a solar maximum would have a larger average energy than those detected during a solar minimum.

$$\chi^2 = \sum \frac{(O - E)^2}{E}$$

O = the frequencies observed

E = the frequencies expected

$\sum$ = the 'sum of'

Figure 2. Chi Squared Test Formula. This formula was later translated for use in Microsoft Excel to perform a series of calculations on each data point to determine the range of values for which each result would lie in.

One consideration made before this test was carried out was that HiSPARC detectors only collect information about cosmic rays over a certain threshold, that is, an energy limit is imposed on all data detections (Pavlidou, 2014, p.32). This translates to a decrease in readings for lower energy particles. Because of this, it may be the case that many more particles of lower energy could be found in one time period than in another, and this portion of the data would be cut off from the results causing a possible skew to the data. With no other way to obtain data from the time periods required, the test was carried out with the data available and analysed with this fact in mind. To collate the data for analysis, requests were sent to the jSPARC program which operates in the Netherlands at the centre of the HiSPARC program (HiSPARC, 2015b). jSPARC is a website that hosts HiSPARC data, and is a free tool mostly used by students for analysis of cosmic rays. Requests were sent for data

E4 =SUM(B4+((B4*C4)/100))

	A	B	C	D	E	F
1						
2		Energy	Error	Possible Values		
3				Min	Max	
4		1.28E+16	0.0207	1.27974E+16	1.28026E+16	
5		1.73E+16	0.8571	1.71517E+16	1.74483E+16	
6		1.28E+16	0.0207	1.27974E+16	1.28026E+16	
7		2.08E+15	0.0004	2.07999E+15	2.08001E+15	
8		1.23E+17	0.4328	1.22468E+17	1.23532E+17	
9		8.08E+16	0.4548	8.04325E+16	8.11675E+16	
10		2.16E+18	0.5257	2.14864E+18	2.17136E+18	
11		2.85E+15	0.002	2.84994E+15	2.85006E+15	
12		4.12E+16	0.9444	4.08109E+16	4.15891E+16	
13		4.57E+15	0.0567	4.56741E+15	4.57259E+15	
14		5.9E+15	0.1946	5.88852E+15	5.91148E+15	
15		7.15E+15	0.0722	7.14484E+15	7.15516E+15	
16		3.45E+15	0.4928	3.433E+15	3.467E+15	
17		3.4E+15	0.059	3.39799E+15	3.40201E+15	
18		1.58E+16	0.0056	1.57991E+16	1.58009E+16	

Figure 3. Chi Squared Test Calculator. By inputting the energy of a particle and its corresponding 'jSPARC error' the calculator will give a range of values for which the true value of a particle's energy

in the periods of solar maximum and solar minimum to compare the average energies across both time frames. The program allows the user to search for the shower core as well as the energy of the particles at this point, and calculates the error of the measurement by means of the Chi Squared test. This error is a direct result of the uncertainty of the shower core's location and so by considering the possible range of values for each energy value, it can be determined whether the energy value used in calculation was significantly affected. This became important during the graphing process as the log energy was considered, that is, the order of magnitude rather than the raw number itself. This would allow bar graphs to show a general curve in the energies as well as making the boundary between lower and higher energy particles more prevalent. In addition, errors in measurement would be minimised. This being the case, it was important to ensure that no piece of data had an error that would change the order of magnitude and hence the frequency of each bar when plotted. Using the formula for the Chi Squared test (*Figure 2*), a Chi Squared test calculator was created, (*Figure 3*), which allowed the possible range of values to be displayed. Each range was examined to test if the order of magnitude differed between minimum and maximum, and would therefore change the frequency of any bar on the bar chart. It was found that no such result existed and all values possessed a small enough error to be graphed.

Section Two – Method and Results

A total of 99 pieces of data were recorded for each portion of the solar cycle for a number of days in each range until sufficient data was collected (HiSPARC, 2015b). After the totals for each order of magnitude were counted and plotted, the graphs produced for the both the solar maximum and solar minimum were compared. Figures 4 and 5 show the energy of incident rays for the periods of solar minimum and solar maximum respectively for the first 99 data points recorded in the time period.

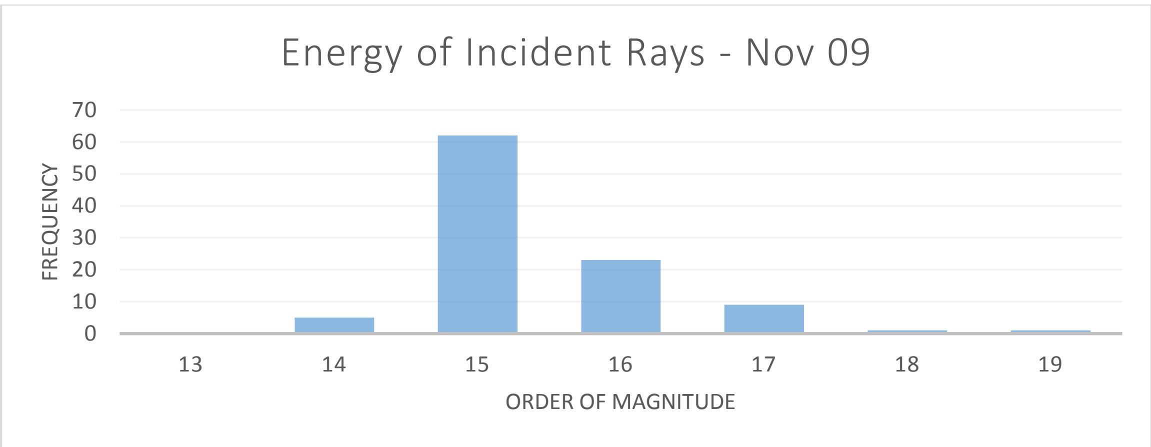


Figure 4. A Graph of the Energy of Incident Rays during the Solar Minimum. The first 99 data points of particle's energy for the solar minimum (taken as starting at November 2009) have been taken and the frequency of each order of magnitude is plotted.

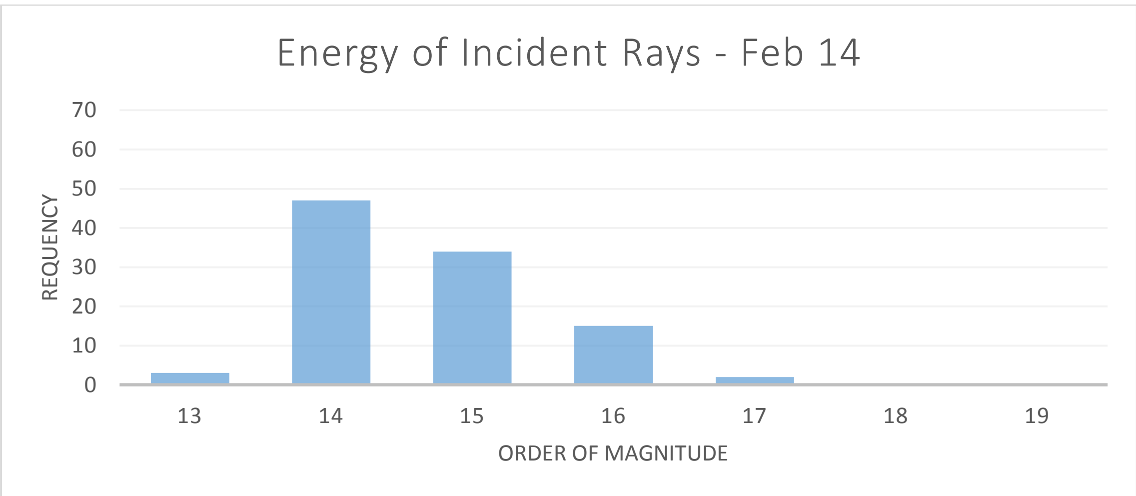


Figure 5. A Graph of the Energy of Incident Rays during the Solar Maximum. The first 99 data points of particle's energy for the solar maximum (taken as starting at February 2014) have been taken and the frequency of each order of magnitude is plotted.

Simple measures of location as well the variance and standard deviation for each graph were calculated and tabulated below:

Order of Magnitude Calculations:

	Solar Minimum (Nov 2009)	Solar Maximum (Feb 2014)
Mean	15.42574257	14.66336634
Median	15	15
Mode	15	14
Range	5	4
Variance	0.699931379	0.698558965
Standard Deviation	0.836619017	0.8357984

Energy Calculations:

	Solar Minimum (Nov 2009)	Solar Maximum (Feb 2014)
Mean	4.13985E+17	1.86527E+16
Median	4.56E+15	8.8E+14
Mode	1.28E+16	1.24E+15
Range	3.61E+19	7.96E+17
Variance	1.27926E+37	8.87685E+33
Standard Deviation	3.57668E+18	9.42171E+16

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	99	4.18061E+19	4.22284E+17	1.31807E+37
Column 2	99	1.86259E+18	1.8814E+16	9.14575E+33

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.05801E+36	1	8.05801E+36	1.221848564	0.270353	3.889340998
Within Groups	1.29261E+39	196	6.59494E+36			
Total	1.30067E+39	197				

Figure 6. Results of the Single Factor ANOVA test. Using Excel's built-in ANOVA operation to compare two sets of data through comparison of the mean and variance showed no significant difference between the data sets from the solar minimum and solar maximum.

Basic observations from the graphs as well as the table above indicate a difference between the two periods, namely an increased modal and range value as well as larger variance and therefore standard deviation values during the solar minimum. This is contradictory to the hypothesis which would predict that the energy of incident particles would be higher during periods of solar maxima. To test whether this difference is significant and not due to chance, a technique called the Analysis of Variance (ANOVA) test was used. There are various forms of this test based on the arrangement and type of data – as this was a simple two column table comparing just two sets of data, the single factor ANOVA test was used (as opposed to the double or multiple factor tests). The results of this test were generated in Microsoft Excel and presented in a table as shown in *figure 6*. ANOVA testing can be conducted on various significance levels; the level in this test was a 5% as is standard for most statistical hypothesis testing. One variable calculated in the test is the 'F' value, which is the ratio of the two mean square values from the two data sets. As the F value calculated is less than the critical value for significance, F *crit*, it has been shown that the two data sets are not significantly different, thus providing no evidence for an increase in average energy of incident particles in periods of solar maximum. With note of the conditions imposed on data via the energy threshold, these results yet to be interpreted in a real world context.

Section Three – Analysing the Influence of GCR Intensity on Terrestrial Climate

As the results from Section One seemed to show the link between the solar cycle and GCR intensity and supported the causal mechanism described, it was finally hypothesised that a link to cloud seeding may exist and thus could be linked to the solar cycle itself. Currently there are two proposed mechanisms that attempt to link cloud formation and cosmic rays: the ion-aerosol near-cloud hypothesis and the ion-aerosol clear-sky hypothesis (Real Climate, 2011). Although experimentally the former is somewhat misrepresented, there is evidence reinforcing both theorems.

The ion-aerosol near-cloud hypothesis describes how cloud formation is affected by the global atmospheric electrical circuit (Real Climate, 2011). As cosmic rays consist of charged particles, the surrounding air in the ionosphere becomes ionized. This leaves a trail of ions through which an electric current can conduct. Existing clouds in the ionosphere build up a large amount of charge, with the top positively charged and the underside negatively charged. This is believed to alter the properties of the cloud, such as increasing the rate of collisions between aerosols and cloud droplets (Real Climate, 2011). However, it has not yet been shown that this mechanism can predict an increase or decrease in cloud coverage based upon the cosmic ray intensity - just a change in the cloud's properties (Real Climate, 2011).

The ion-aerosol clear-sky hypothesis describes how the presence of ions (increased by the number of cosmic rays) enhances aerosol nucleation, a process in which particles around the size of one nanometer form. These particles grow in size (to around 50 nm) and become the cloud condensation nuclei (CCN) from which clouds are produced. This more clearly links the fluctuation of cosmic rays to formation. However, the increase in CCN production rates is so far only attributed to 5-20% of cloud formation, bringing the overall effect of cosmic rays into question (Real Climate, 2011).

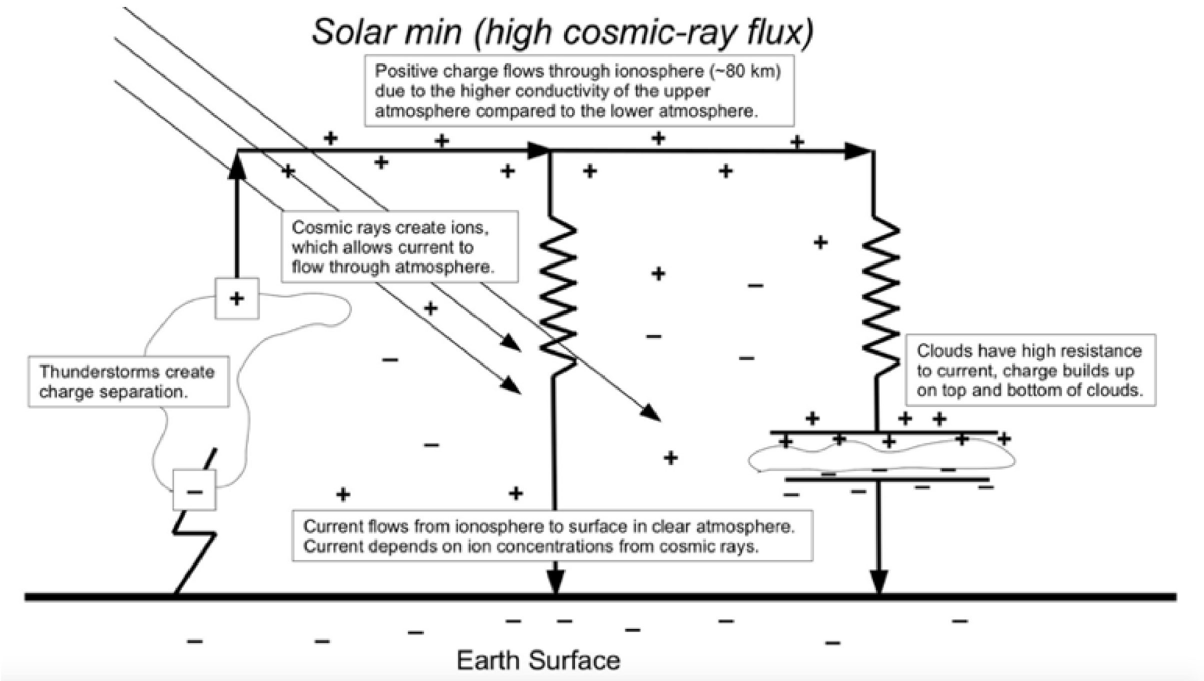


Figure 7. A Diagram showing the Ion-Aerosol Near-Cloud Mechanism. The cosmic rays incident on Earth pass through the ionosphere, ionising the surrounding atoms and molecules in the atmosphere. This creates a path for an electric current to flow through and interact with existing clouds in the atmosphere.

Section Three – Method and Results

To directly compare the intensity of cosmic rays and the 'intensity' of the terrestrial climate, a scale had to be devised for numerical comparison. The table shown in *Figure 8*, describes the weather condition and its corresponding Weather Condition (WC) value as used in calculation and graphing. Weather Underground (2015), provides weather data across multiple nations, including the Netherlands. Local data was obtained which was measured by the weather station for Amsterdam Airport Schiphol, a distance of 19.9km from Amsterdam Science Park Nikhef cluster in which the stations collecting muon data are located. Some HiSPARC stations carry on-board equipment to measure this data; however the stations used do not. Once collated, the data could be split by the hour giving the number of muon detections every 60 minutes and the weather conditions at every hour for 14 days. During the solar minimum the data was selected between 01//11/2009 and 14/11/2009, and during the solar maximum the time period was 03/02/14 and 16/02/14. The dates were chosen to be as close to the start of the month as possible, as this was the reference point for the start of the minimum /maximum. However, due to a lack of weather data from 01/02/14 and 02/02/14, the starting point for analysis was moved forward. From here, the Weather Condition values were added and plotted alongside muon detection against time as shown in *figure 9* and *figure 10*, full graphs shown in Appendix B. When plotted, the results gave a poor image showing very little relationship between the two variables. However, once adjusted a very similar rise and fall pattern could be seen to be replicated in the WC values, mirroring the muon detection numbers.

Weather Condition	WC Value
Clear	0
Scattered Clouds	1
Partly Cloudy	2
Mostly Cloudy	3
Overcast	4
Light Drizzle / Drizzle /Heavy Drizzle	5
Light Rain Showers / Rain Showers	6
Light Rain / Rain / Heavy Rain	7
Light Thunderstorm / Thunderstorm	8

Figure 8. Weather Condition Value Table. To compare the number of coincidences numerically to the weather condition, a table had to be devised assigning numbers based on severity of the weather type.

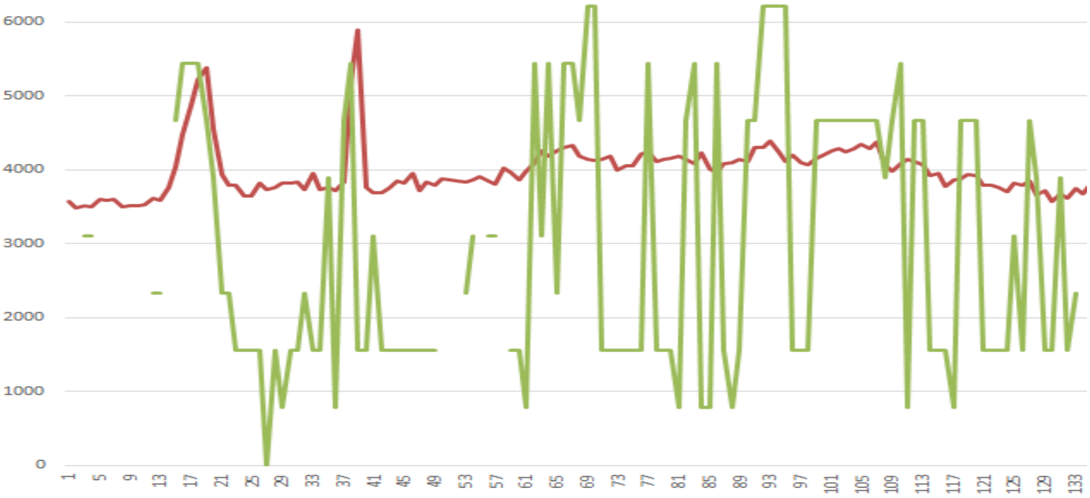


Figure 9. A graph a WC values and Muons Detected against time (Unadjusted). Using the WC scale to quantify weather conditions, the number of muons was plotted alongside WC values against time to find a possible correlation between GCR intensity and cloud formation.

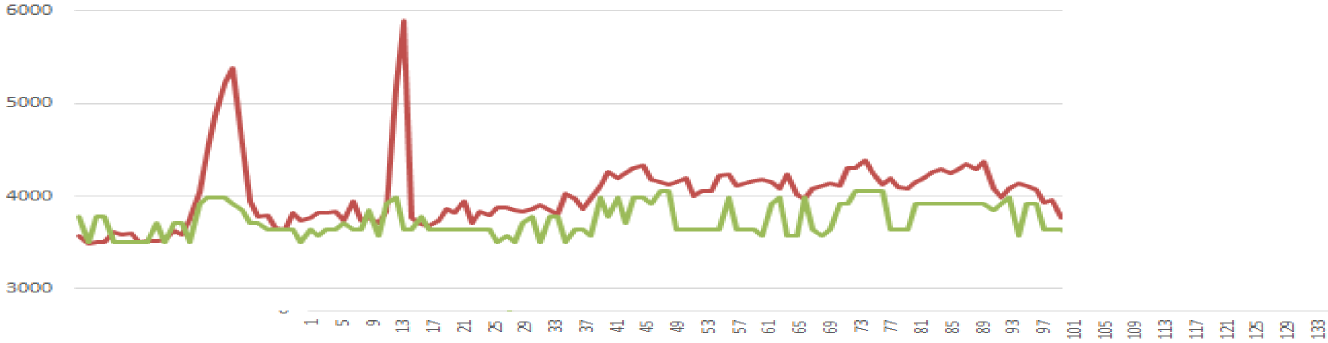


Figure 10. A graph a WC values and Muons Detected against time (Adjusted). Using an adjusting factor of 50 to bring the WC values to a similar sense of scale, the rise in muons detected can be seen to strongly correlate to a rise in WC value. Similarly, a fall in muon detection can also be seen to lead to a fall the severity of the weather conditions as indicated by the WC value.

Discussion

As similar research indicates, the link between the intensity of cosmic rays and the solar cycle is very strong. Giving an anti-correlation of -0.91346482 (8 d.p) for the solar minimum and -0.967663994 (8 d.p) for the November 2011 – January 2012 period, the data gathered from the HiSPARC stations shows an unambiguous connection between the two variables considered in the hypothesis. However, an unexpected result was produced from the solar maximum period. With a value of -0.422326442 (8 d.p), the connection shown in this period is questionable at best. Several factors may have been responsible for this result, such as the limited data during the solar maximum period from station 502. This left an average to be calculated from stations 501 and 4001. Due to the difference in location, the number of coincidences registered differed, ultimately contributing to the result seen here.

Section Two provided an unexpected result also. As the connection established in the first section showed the muon count decreased during the solar maximum, it was assumed that the decrease in particles was the result of lower energy rays being deflected. Subsequently, only particles of higher energy would be found during this time. As no significant difference was found, this would either imply the statement to be false, or there be error within the analysis. Considering the latter, the ANOVA technique relies upon comparison of the mean and variance. With both of these statistics being designed to be representative of an entire population, it must be recognised that a small sample may not be representative. Elements of bias may be present, such as data taken over a few days from a three month longs period may focus on a period in which unusual solar activity has taken place. To combat this, data should be taken from various points throughout the three-month period. In addition, as data was gathered manually, sample size was restricted 100 entries per period. In comparison to the thousands of particles incident over the three-months, this number is small and should be increased for future analysis. One final note would be that the number of particle with lower energies (expected to be $< 10^{13}$) may be misrepresented. This is due to the fact that HiSPARC stations do not register, and therefore do not collect data for, energies of this magnitude. Significant distinction between data sets, that is solar minimum and maximum, could be seen with the inclusion of this data so for further testing this should be a consideration.

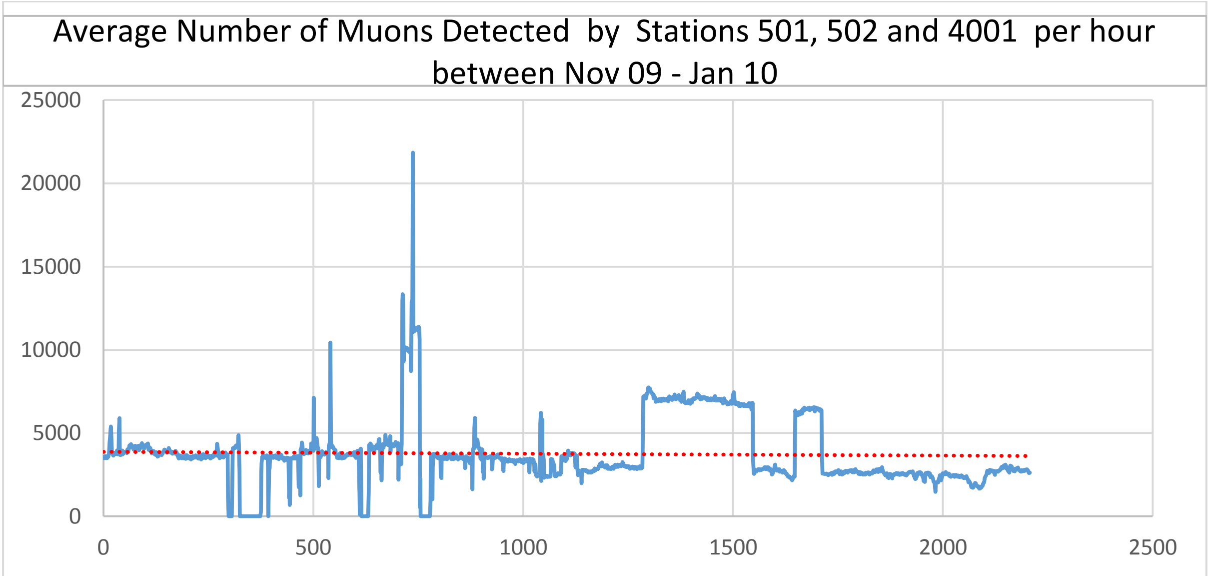
The final section produced the results anticipated from the hypothesis extension. Though insufficient analysis was carried out and the results are yet to be replicated, the striking resemblance between WC value and GCR intensity may prove to be the ground work for evidence of a reasonably unexplored phenomenon. However, correlation does not necessarily mean causation, and without a confirmed mechanism linking the two, an increase in GCR intensity is not certain to cause an increase in cloud formation. Furthermore, as only 336 data points were graphed, it is important for replication to confirm the results, with data from different points along the solar cycle.

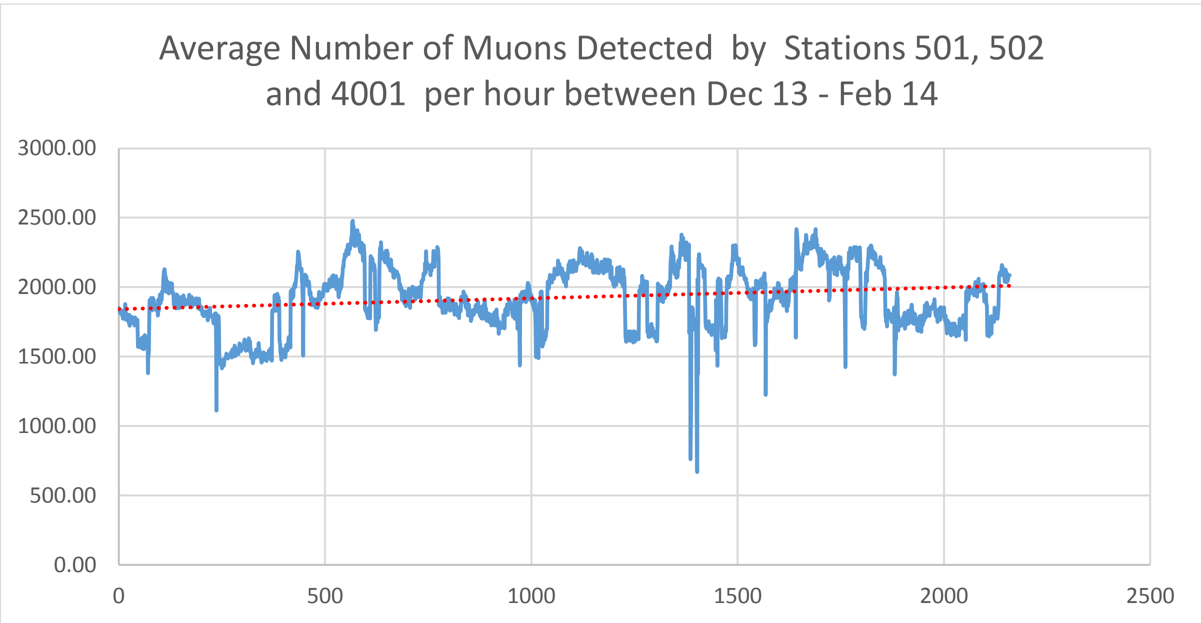
Conclusion

From these results it can be concluded that there is strong evidence to support the claim for a link between GCR intensity and the solar cycle. With a mechanism described that had held true across multiple tests (with the exception of the likely flawed energy hypothesis in Section Two). As for the results found in the second section, it is quite possible that the results have been skewed by the limits imposed by the available equipment. To either confirm/disprove this, the calculations should be repeated using data collected from detectors with a larger range, recording data with energies below 10^{13}. Finally, a very strong visual correlation can be seen between GCR intensity and cloud formation, promoting the idea that there indeed exists a link. Should the link be found, it may then be possible to link weather patterns to the ~22 year solar cycle of the Sun.

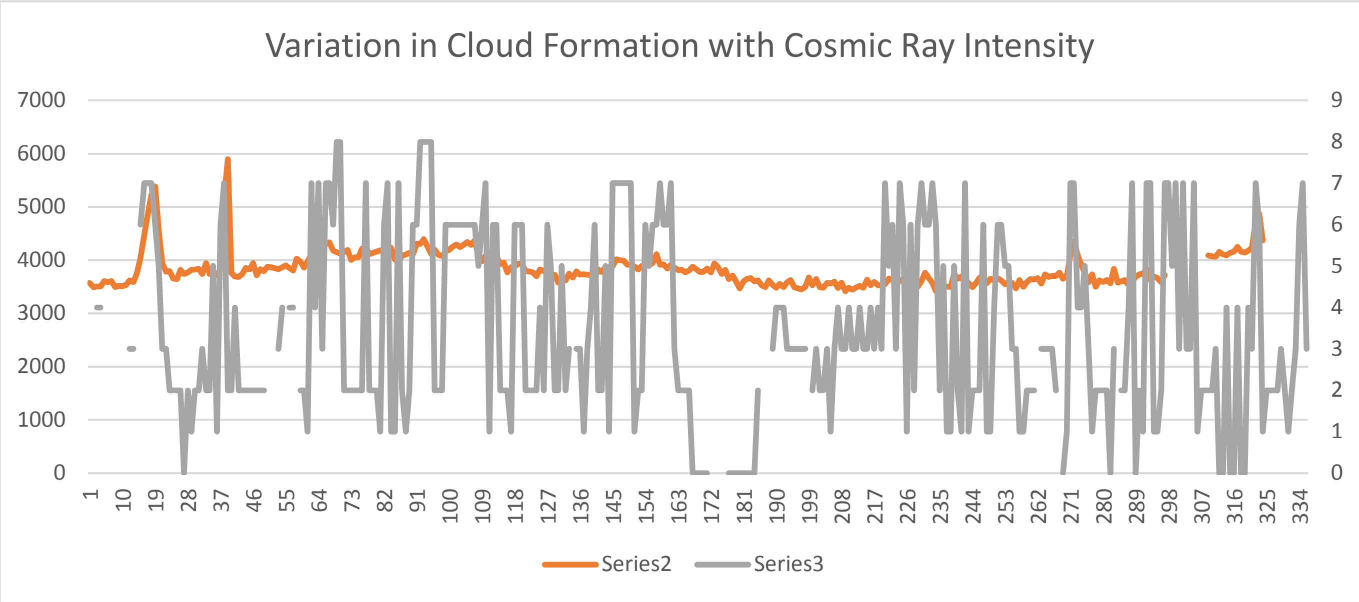
Appendices

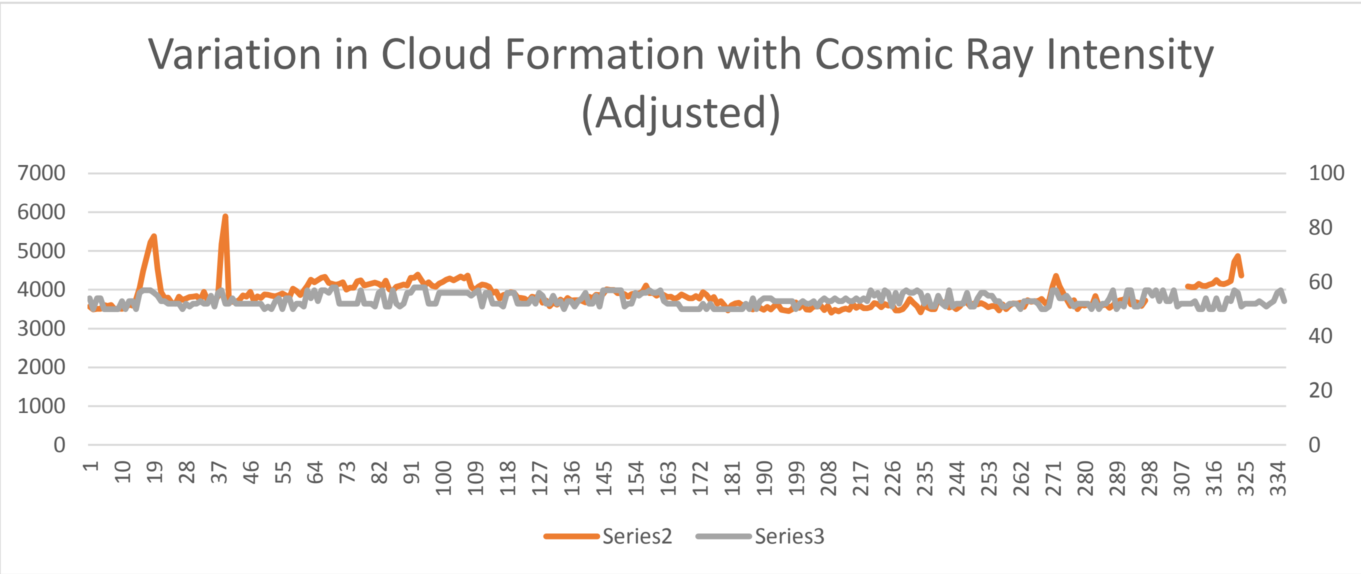
Appendix A





Appendix B


Variation in Cloud Formation with Cosmic Ray Intensity
7000
6000
5000
4000
3000
2000
1000
0
9
8
7
6
5
4
3
2
1
0
1 10 19 28 37 46 55 64 73 82 91 100 109 118 127 136 145 154 163 172 181 190 199 208 217 226 235 244 253 262 271 280 289 298 307 316 325 334
Series2
Series3


Variation in Cloud Formation with Cosmic Ray Intensity (Adjusted)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
1 10 19 28 37 46 55 64 73 82 91 100 109 118 127 136 145 154 163 172 181 190 199 208 217 226 235 244 253 262 271 280 289 298 307 316 325 334
Series2
Series3

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