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Statistical Analysis of Solar Geomagnetic Storm Occurrences

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SUMMARY

Space weather is a fairly new field in science today and has very interesting effects on the humans and technology in general. Geomagnetic storms are a part of space weather and the solar-terrestrial connection. These storms greatly affect the earth's atmosphere and ionosphere. This is important because it affects global communication and navigation systems as well as the satellites in ionospheric orbit. These satellites can have their signals disrupted or have entire systems shorted out. These storm events demand further study to understand when and why they occur. Prediction of these storms would be incredibly difficult, but finding a pattern is an essential step. Using 52 years of *Kp* (geomagnetic storm index) and F10.7 x-ray flux (solar activity index) data (1950-2002) from the MIT Millstone Hill Madrigal Database we performed an independent analysis. The primary goal of this study is to find a pattern in geomagnetic storm occurrences (if any), and confirm some long-standing ideas.

INTRODUCTION

Geomagnetic storms are caused when solar wind gusts or magnetic clouds impact the earth's magnetosphere The sun produces several different types of disturbances including solar wind (super heated coronal gases from the sun's corona), coronal mass ejecta (large magnetic explosions giving off magnetic clouds), and solar flares (large explosions producing magnetic clouds) When a group of charged particles (magnetic clouds or solar wind) collides with the magnetosphere it charges the magnetosphere and produces fluctuations in the earth’s magnetic field, known as a geomagnetic storm Geomagnetic storms have many effects on earth Geomagnetic storms produce beautiful auroras, but they also have the capability of disrupting cell phone use, Global Positioning Satellites, taking down power grids and threatening astronauts with harmful radiation Geomagnetic storms affect everything that uses radio waves, because radio waves pass through the ionosphere where the storm impacts. As society becomes increasingly dependent on modern technology, understanding physical processes during geomagnetic storms becomes not a matter of academic interest, but a matter of practical nature. However, collecting experimental data about the earth’s surroundings during geomagnetic storms is a challenging task by itself, because large storms occur rarely and currently cannot be predicted Unfortunately a continuous operation of a network of ground-based and space-based instruments is extremely costly and cannot be justified for economical reasons. Therefore, understanding patterns in geomagnetic storm occurrences becomes an important step in gaining knowledge about the Sun-Earth energy system.

Previous research about possible patterns and periodicity in geomagnetic activity includes number of studies of different geomagnetic indices with datasets of various lengths. The existing theoretical models and data analysis state that the maxima in geomagnetic activity are found near the equinoxes (March 22nd and September 22nd) Also it is believed that March and April are the most active periods of the year These ideas became the basis for our research; we wanted to confirm for ourselves that they were correct.

METHODS AND MATERIALS

The intensity of geomagnetic storms is measured in *Kp*.*Kp* ranges from 0 (no activity) to 9 (extremely high activity) and it is quasi logarithmic, very similar to the Richter scale for earthquakes *Kp* is derived 8 times a day (3-hour intervals) from mid-to-high latitude magnetometer measurements positioned all over the globe The level of solar activity is measured in F10.7 cm x-ray flux The F10.7 index is a measure of the noise level generated by the sun at a wavelength of 10.7 cm This measurement is taken from the ground at local noon at the Pentictin Radio Observatory in Canada It is derived only once daily, and is used as a main indicator of general solar activity.

Our research is done using both of these indices, (*Kp* and F10.7) and one goal was to find a pattern in geomagnetic storm occurrences Another goal of the project was to find the best time to plan radar operations to collect data on geomagnetic storms Our research was concentrated on very large storms ($Kp > 8$), however we also did a lot of research with all levels of geomagnetic storms ($Kp \geq 6$).

RESULTS

Broad View

The 11-year solar activity cycle has been studied for a very long time Sunspot data is known to possibly date back to the ancient Chinese astronomers However the sun- earth connection is relatively new The fact that the solar activity is directly related to space weather and geomagnetic activity is very well known Geomagnetic activity does rise and fall along with the solar activity, however it has its own dynamics The double peak in geomagnetic activity is another well-documented phenomenon, however the exact time span and intensity are up for dispute Our data in Figure 1 shows that the second descending phase geomagnetic peak occurs only 18-24 months after solar maximum This data also shows that the descending phase peak seems to be larger, which means more activity occurs during that period, than the ascending phase peak.

Seasonal Dependence

Equinoctial

A main goal of the project was to verify the maxima at the equinoxes We found this variation to be very apparent in nearly every way we analyzed the data The maximum during September and during March are very apparent Interestingly the maximum in September boasts the most activity, however the March/April maximum seems to be a much broader base of activity Clearly in Figure 2 we see the large variation This histogram shows each month and the number of geomagnetic events that occur in them Also in Figure 3 we can clearly see how close those maxima are to actual equinox Our data showed several different days as being maxima Each different storm level that we chose produced different dates We felt that geomagnetic storms that are Kp >=6 should be the lowest level The middle level would be storm elements with Kp>=7 and the highest level Kp>=8 All this data can be found in Table 1 The dates are all relatively close to equinox, but they are not exact These dates are also very different from the models given on the semi-annual periodicity Table 2 shows the theoretical models and the dates that are given as the maxima None of these dates are exactly on equinox, just centered near it This periodicity is very hard to explain, no one has been able to successfully explain it fully or model it without some speculation.

Table 1. This table gives the derived maxima for 3 levels of *Kp* found using our data. The reason that the dates are within 3 days is due to the 3-day grouping used to eliminate scatter. Actual equinoxes are March 22nd and September 22nd, our data was fairly close on all levels of *Kp*. To answer the question; there is clearly maxima around the equinoxes.

	Maximums Found (within 3 days)	
Kp Level	**Vernal Equinox**	**Autumnal Equinox**
$Kp \geq 6$	April 4, May 2	September 21
$Kp \geq 7$	March 28, April 2	September 4, 22
$Kp \geq 8$	April 2	September 4

Table 2. This data was taken from Clua de Gonzalez et al., 1993. This table shows the names and dates of three theoretical models that concentrate on the semiannual variation. Below them are the dates they give to be maximum points during the semiannual variation.

Axial Mechanism 1912	Equinoctial Mechanism 1959	Russel-McPheron 1973
March 5	March 21	April 5
Sept. 6	Sept. 23	Oct. 5

July

The first time we noticed this July variation was during a study with geomagnetic storms at or above *Kp* 8 (Figure 4) These storms are very large and fairly rare, therefore statistics for them are relatively poor Several tests were done and we found that this is a significant maximum.

In order to check if maximum in July doesn't come from single extreme storm, we found all the events with large storms (Kp>=7) through the 52-year dataset Figure 5 showed us that large storms in July happen almost every solar cycle. We also compared this maximum to the equinoctial maxima (FIG.3). Figure 3 shows that for very large storms with $Kp \geq 8$ the July maximum is very close in number of elements to the equinoctial maxima With these we verified that this peak in July is a significant maximum for very large storms, and should be considered during radar operations. This was a very interesting and unexpected discovery because it is commonly believed that geomagnetic activity peaks at equinoxes and decreases at other seasons. After completing a literature search we realized that very few people even noticed the maximum in July and no one has explained it yet.

Winter and Summer Solstices

Even though significant amount of research was done to study maximums in geomagnetic activity, little attention was paid to minimums of activity; this is in spite of the fact that understanding the underlying physical reasons for minimum can help explain maximums as well. We found that there is a very broad minimum occurring during December and January (see Figure 2) A possibility of the minimum could be the winter solstice in December but we feel that can not be the only reason The winter solstice has been listed before as the cause for the minimum in December, however it was also linked to a minimum in the summer Contrary to popular expectations, our data shows that the summer solstice seems to have no minimizing effect on the geomagnetic activity In Figure 2 we clearly see winter minimum, however the summer months appear to be about average When considering radar operation we believe that the winter months (December and January) are the worst choices.

Diurnal Variation

Figure 6 shows number of events with Kp>6 as a function of universal time (UT). We clearly see a diurnal variation in number of storms Similar variation happens for all three of the studied levels of *Kp (Kp>6, Kp>7, Kp>8)* and can be considered a general feature We always seem to find a minimum at 9:00 UT and we seem to find at maximum during 18:00-3:00 UT When this was broken down by season the 9:00 UT minimum was still very apparent This variation is very difficult to explain; however other diurnal variations have been seen in the past They have all been related to the Russell- McPherron effect of the interplanetary magnetic field We cannot speculate as to the cause of this variation.

Probability

Working with the data led us to do a probability study This study meant that we would use the F10.7 data and the *Kp* data to check if there is a correlation between solar activity and magnetic activity Increase in probability of geomagnetic activity was only really seen when the F10.7 was fairly high, as seen in Figure 7 This was interesting because it further shows how the geomagnetic activity is directly corresponding to the solar activity This study produced interesting information reinforcing the previously seen maxima and minima In general, probability of the storm increases with solar activity at equinoxes. This high probability seen during September and March could be attributed to the equinoctial maximums The increase in probability with increase in solar flux is also seen in Figure 8 during the summer months (June, July, August, September) This could be directly linked to the maximum found in July. Also we see a very low probability during the winter months, and it seems to be low for all levels of solar activity Also it could be linked to the extreme minimum found during December and January.

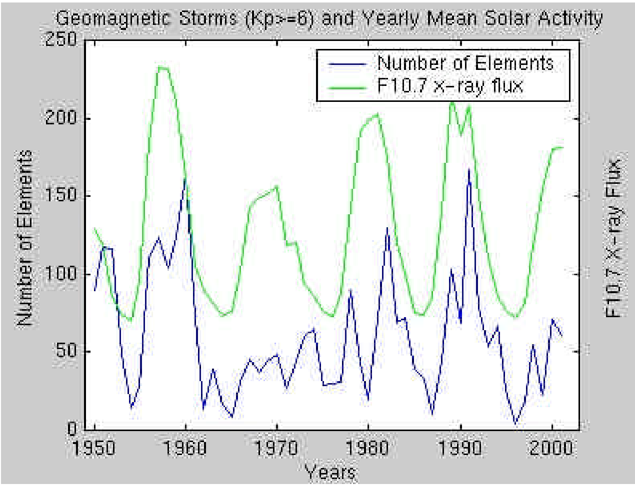

Figure 1. This graph shows the solar cycle (yearly average of F10.7 cm X-Ray Solar Flux in Green) and the number of geomagnetic storm elements that reach above *Kp* > 6 (histogram of *Kp* > 6 in Blue). Clearly there is a relationship here between the sun and the earth.

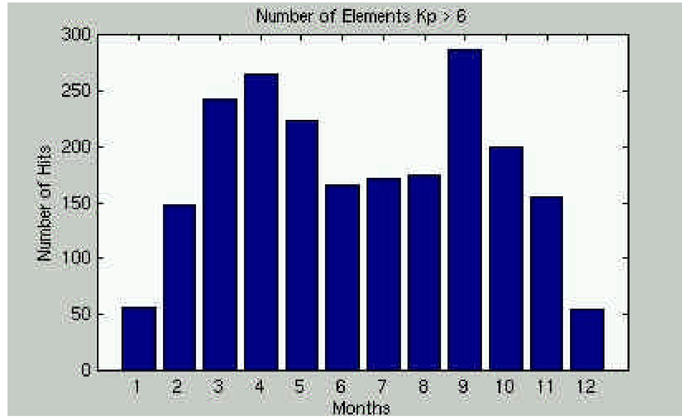

Figure 2. This histogram shows the number of storm elements above *Kp* 6. The months are numbered on the x-axis. September has the maximum, however March and April are a close second.

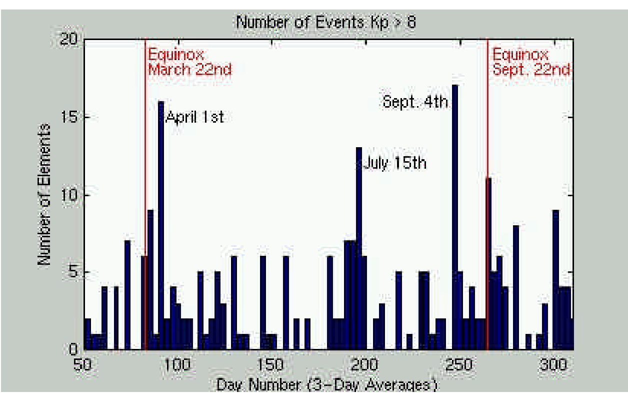

Figure 3. Histogram for storm elements greater than *Kp* 8. As in Figure 4 we see the equinoctial maxima during September and March/April. In addition this histogram shows the July maximum, as well as the winter (January and December) minimum.

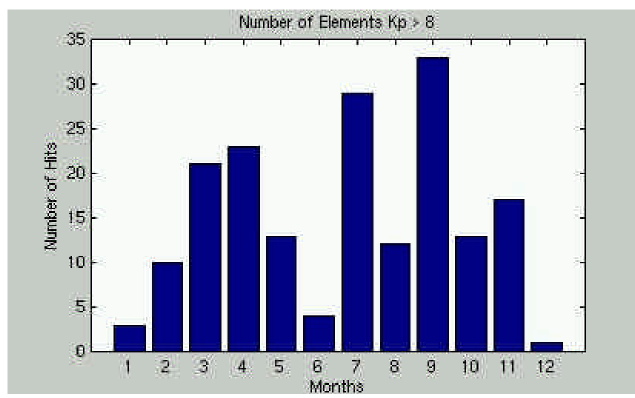

Figure 4. This graph to the left shows the entire year in three-day interval averages. It is a histogram of geomagnetic storms with *Kp* levels greater than 8. The red lines show the equinoxes, and it shows how close the maximums are to exact equinox. Also this graph shows the maximum in July.

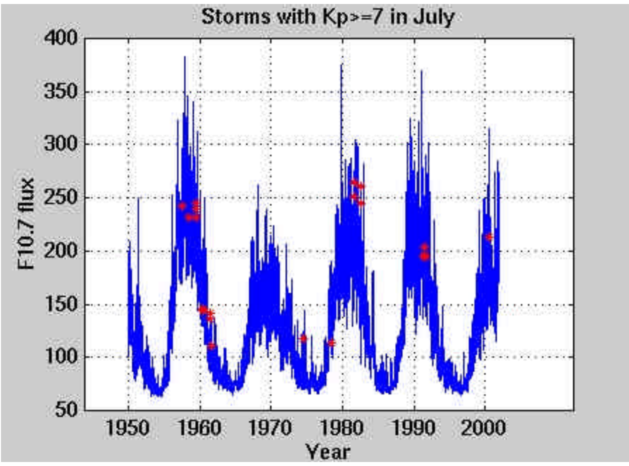

Figure 5. This plot shows the 11-year solar cycle of F10.7, and the points on the plot show the elements in July when *Kp* goes above 7. These points occur on nearly every solar cycle, and they mostly seem to occur following solar maximum.

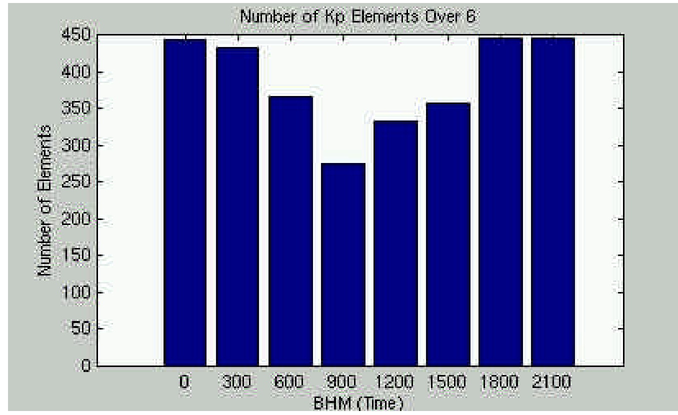

Figure 6. This graph was created over BHM or universal time. It is a histogram for geomagnetic storms with Kp greater than 6. This graph clearly shows a maximum between 18 UT (1800 BHM on the graph) and 3 UT (300 BHM on the graph). It also shows a minimum around 9 UT (900 BHM).

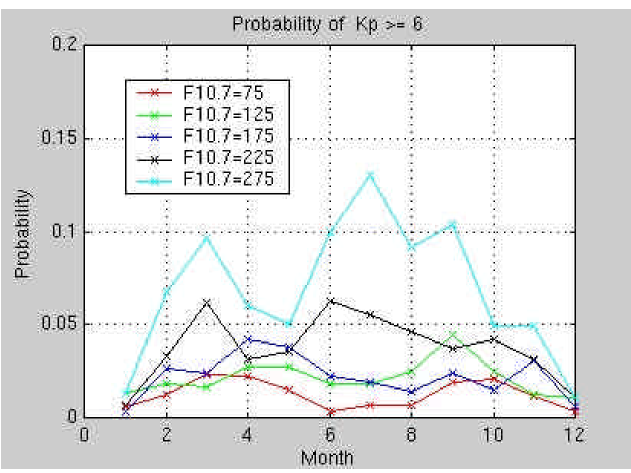

Figure 7. This time series plot shows the probability of a geomagnetic storm greater than or equal to *Kp* 6. The different lines are bins of F10.7 data, and the legend states the middle of each bin. So the first bin on the legend is 75, which means the bin is from 50 to 100.

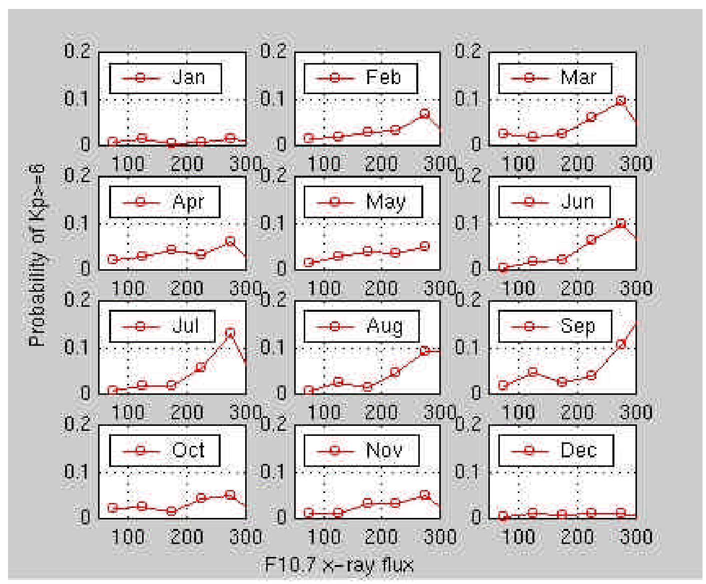

Figure 8. This is the monthly profiles for probability of geomagnetic storms greater than or equal to *Kp* 6. The probability for geomagnetic activity increases with solar activity increasing.

DISCUSSION

Several questions were directed to me before the start of this project Some of the questions were:

- Are there maxima found near the Equinoxes?
- Do geomagnetic storms occur the most during March and April?
- Do very large storms happen at random or do they follow a pattern?
- When is the best time to plan radar operations to collect data on these storms?

The answers to these questions summarize our results very well The first question is very important to the study It is widely known that geomagnetic activity seems to peak at the equinoxes (however that was not confirmed at the start of the research) Our research confirmed that there are maxima within a few days of equinox.

The second question on the list was answered with a simple histogram When the histogram was done on geomagnetic storms with Kp > 6, we found that March and April made a very large peak However, September had the most elements Therefore geomagnetic storms occur most during September, followed closely by March and April.

Large storms (Kp > 8) happen fairly rarely, but when they do happen, they create havoc in the interplanetary solar wind and within the Earth's magnetosphere and ionosphere In order to find out if they follow a pattern we ran a series of tests which looked at only geomagnetic storm elements with Kp > 8 We found that they occur in the same pattern that smaller storms occur, they have maximums at the equinoxes and minimums in December and January However in doing this study we came across something very interesting, we found a large maximum in July This maximum is only apparent for large storms but in running tests we confirmed that it is significant The answer to the third questions is; large geomagnetic storms essentially follow the same pattern that small storms do, except for the maximum in July.

The final question on the list is probably the most important Operating the radar is very expensive, so knowing the best time to do it is vital knowledge In running many different tests on many aspects of the data we found the best time to start radar operations We feel that the best time is 18-24 months following solar maximum during the month of March, April, July and September These times have the greatest probability of producing storms Unfortunately it is impossible to completely predict storm activity, but statistical studies like the one I performed help guide scientists.

Scientists have seen many different levels of variation in geomagnetic activity The most researched is the semiannual variation centered on the equinoxes The equinoctial maxima were discovered nearly a century ago [Cortie, 1912] The exact dates of these maxima and the exact reason for this variation are a large debate Several theoretical models [Cortie, 1912; Russell and McPherron, 1973; McIntosh, 1959; Berthelier, 1976; Green, 1984; Orlando, 1995; Clua de Gonzalez et al., 1993; Cliver et al., 2000] have attempted to explain the variation, however all of the models differ in their predictions of which days should be the maxima Another commonly studied variation is the diurnal variation The diurnal variation has been linked together with the equinoctial maxima by the Russell- McPherron Effect [Russell, 1989; Berthelier, 1990; Russell and Scurry, 1990; Orlando, 1995; Siscoe and Crooker, 1996;] The position of the IMF (Interplanetary Magnetic Field) plays a role in the variation of geomagnetic activity Most of these studies were done using the *am* index; our study is done using the *Kp* index This becomes an entirely different basis of research.

Another well-researched variation is seen in correlation with the solar cycle Every 11 years the solar cycle reaches a maximum, however geomagnetic storms seem to have two maxima One geomagnetic peak is found during the years prior to the absolute solar maximum, and the other peak is found during the years after the absolute solar maximum Several studies have mentioned this interesting phenomenon and there are two basic results One states that the second geomagnetic peak will occur three to four years after solar maximum [Gonzalez et al., 1990; Gonzalez et al., 1994], the other states that the second geomagnetic peak will occur only 18-24 months after solar maximum [K. Schlegel, 2001].

Less well-known variations are seen in our data as well One of these is a maximum seen in July Clua de Gonzalez et al., 1993, saw this maximum however they never attempt to explain its origins Also a minimum in December and January is found, which was seen by Cliver et al., 2000 However they only talk of the winter solstice and its affect on the semiannual periodicity.

Overall the results from the data were very concise One of the reasons that some of the results were so new is because of the very large data set The data set we used (52 years, 1950-2002) was among the largest that was used for this type of research We found a maximum in September, which covered the Autumnal Equinox, and we found a maximum in March that verified the Vernal Equinox The maximum during March however must also include April We believe they create just one very broad maximum The interesting research into the July maximum has produced several new questions into geomagnetic periodicity The interesting minimum in December and January has also produce several new questions within the semi-annual periodicity, and the affect of the winter solstice The well known double peak geomagnetic data during the 11-year solar cycle has been confirmed Also we have reinforced the idea of the second peak in geomagnetic activity being within 18-24 months of the solar maximum The diurnal variation, which was seen as a minimum during 900 UT, is very hard to explain The

results of the diurnal experiments simply showed us that there is a diurnal variation.
The results seen through the probability back up the rest of the data The high probability during July, March and September all collaborate with the July maximum and the Equinoctial maxima Also the very low probability reinforces the winter minimum seen during December and January However the very high probability during the summer months (June and August) are very surprising and quite interesting.

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