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Effect of Latitude of Sunspots on Earth-Intersecting Trajectory of Plasma

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Abstract. Solar flares and Coronal Mass Ejections form around the edges of sunspots. If the plasma from such events is incident on the Earth's magnetosphere, significant disruptions to electrical systems can occur. However, sunspots occur around the surface of the Sun and don't always produce plasma that reaches the Earth. The latitude and longitude of the source of the plasma on the Sun will be evaluated to determine the likelihood that random events will intersect with the Earth. The size of the typical plasma balloon will be found to find its path. Comparing data from locations of sunspots to data of Earth's orbit will provide a likelihood of incidence based on latitude or origin. The latitudes of sunspot centroids vary significantly through the solar cycle as they tend to migrate from mid-latitudes towards the equator. Sunspots from all latitudes are capable of producing plasma that reaches the Earth. However, as a solar event rotates in longitude away from the Earth, events at higher latitudes are less likely to have a trajectory that intersects the Earth. From analysis, 27% of dangerous events on the Sun should have trajectories towards Earth. The latitude has a small effect on this. It was determined that that the plasma balloon released from the Sun had a large spread of impact. Plasma from all latitudes could reach the Earth. However, if the Sun is rotated away, the combined effects of latitude and longitude can make the plasma trajectory pointed away from Earth.

Keywords: solar flare, coronal mass ejection, risk

1 Introduction

Space weather is the influence of solar wind on the Earth [1]. Charged particles come from the corona of the Sun towards the Earth as solar wind. These charged particles interact with the magnetosphere of the Earth to cause various problems. Solar flares have damaged satellites and electrical power distribution grids. Through that, it can disrupt systems of navigation for autonomous vehicles [2].

A coronal mass ejection (CME) is a sudden release of solar particles from the upper atmosphere of the Sun. Mass ejections are produced around sunspots, also called solar prominences. Sunspots are the expansion of magnetic lines of the Sun, but there is little understanding of why it happens [3]. Solar flares and CME originate from sunspots. Therefore, the terms can be interchanged when investigating the origin and trajectory.

The size of solar flares is related to their travel speed [4]. The most powerful solar storms have a travel time of about 24 hours to one astronomical unit which is the distance from the sun to the Earth. Therefore, there can be very little warning when the solar flares with the greatest impact will be striking the Earth.

The effects of solar events on the Earth are forecasted using observed data. Several parts of the prediction are necessary such as predicting and event, the strength of the wind stream and the interaction with the Earth's magnetosphere. The magnetosphere dynamics involved in prediction are nonlinear [5, 6]. A Wang-Sheeley-Arge (WSA) model can be used to predict the solar wind stream [7]. The predictions take into account mass, momentum, and energy [8]. Among the factors influencing the result on the Earth is the southward component of the magnetic topology [9]. A neural network can predict the effects of smaller flares with 40% accuracy or more [10]. The SMART model also uses machine learning [11]. Generally, all models are roughly equivalent but they are based on limited data from stronger events [12]. Recently, it has been shown that Zernike moments in the Sun's active regions can predict flares [13]. A machine learning classifier has been developed to predict flares with 0.76 accuracy as far as 10 days in advance [14]. This has the potential of providing more warning time.

The Sun and planets in our solar system share roughly the same orbiting plane. They all have very low inclinations from the sun's equator. The Earth's inclination to the Sun's equator is 7.155 degrees which is the highest of any planet in the solar system [15].

The Sun is a gaseous body, so its rotation varies by latitude [15]. Its rotation varies between 24 days at the equator to 38 days at the poles. Therefore, the Earth is being constantly exposed to different sides of the Sun as both are rotating at different rates, but the Earth directly faces only a band of plus or minus 7.155 degrees from the equator depending upon where the Earth is in its orbit around the Sun. Sunspots produced in that range of latitude could a trajectory directly towards the Earth. Sunspots originating closer to the poles would possibly have a glancing blow. This research evaluates likelihood of an Earth trajectory given various starting latitudes on the Sun.

Carrington observed that the location of sunspots on the corona changed in latitude through the solar cycle [16]. The solar cycle is the increase and decrease in sunspot activity over a cycle that averages twelve years. As the cycle progresses, the sunspots move from a mean location nearer the poles to closer to the equator. Sporer (also spelled Spoerer) was the first to quantify the movement [17]. During the whole cycle, according to Sporer's Law sunspots occur anywhere between the equator and about 40 degrees North and South. Early in the cycle, the median sunspot location is 25 to 30 degrees North or South latitude. Near the end of the cycle, the median sunspot location is 0 to 5 degrees north or south. Maunder found that at the time of the maximum number of sunspots, called the solar maximum, the median sunspot location is about 10 to 17 degrees North or South [18]. Therefore, most sunspots occur in the middle of the possible range of latitudes. According to Maunder, the top flares happen with 32 degrees of the Sun's equator, as shown in Figure 1 [18]. Recent data confirms these patterns are continuing [19].

The largest sunspots are of most concern for their possible impact upon systems on the Earth. Maunder found that Sporer's Law generally applied to the largest sunspots too [18]. Their location varied with time and came closer to the equator during the cycle. Recent analysis has shown that sunspot patterns follow Rician distribution [20]

This raises the question of whether the largest sunspots are less of a concern when they are away from the Sun's equator. If that makes them angled away from the Earth, then their impact may be lower.

The sunspot activity in the Sun's northern and southern hemispheres doesn't exactly match. Pulkkinen found that the mean latitude varies differently in each hemisphere [21]. Overall, the mean latitude of each twelve-year cycle approaches closer to the equator over a 90-year cycle. The range of variation is a few degrees. The variation is seen in Figure 1.

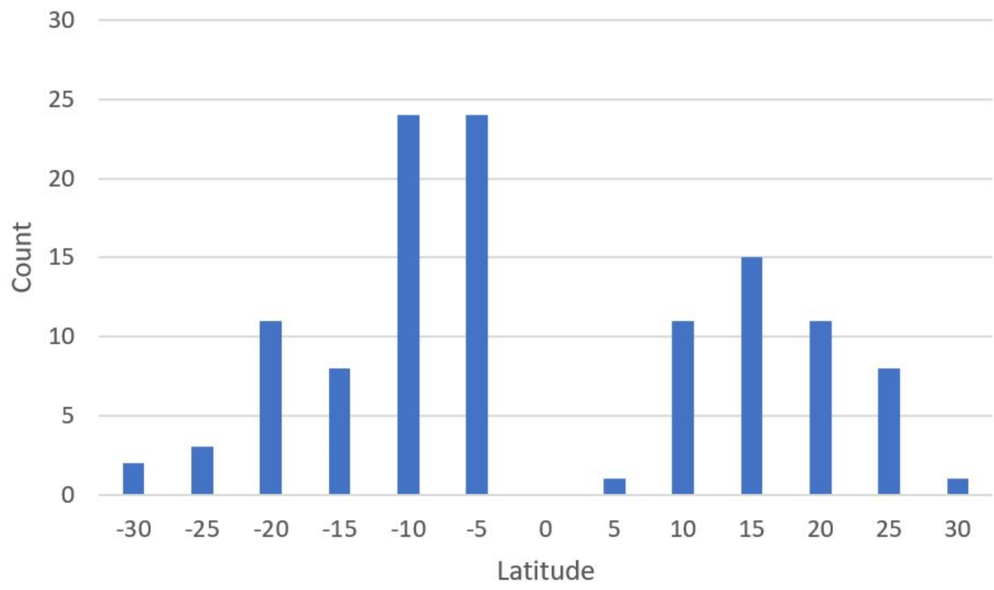

Figure 1: Distribution of Top Solar Flares by Latitude.

Another concern is whether the large solar flares could vary in characteristics, such as plasma ejection speed, by latitude. Hundhausen found that plasma ejection speed has very little difference by latitude [22]. Since Hoback related speed and to the size of the plasma release, it can be rationalized that there is no significant difference in plasma released with latitude [4].

2 Methods

Two types of data need to be collected an analyzed. First, plasma spreads as it travels, so the widening should be quantified. Second, the sources of plasma events on the Sun can be found. The latitude and longitude of the source relate to its trajectory.

In a sunspot, the Sun's magnetic field is extended out from the corona. When the field lines reconnect between the front of the field and the corona, then a balloon is released. This releases a self-contained magnetic bubble with a plasma of electrons and protons contained in it. The resulting balloon has momentum and is driven outward by solar radiant energy and energetic particles.

The dynamics of the ejection process greatly influences the speed of travel of the balloon. It is necessary to discuss the transmission of the plasma from the Sun to the Earth to know whether an ejection of mass is likely to severely impact the Earth.

Generally, the speed of the plasma balloon decreases over time due to the gravity of the Sun. However, the solar wind provides an impulse to the balloons. Plasma balloons with more surface area have a greater impulse. McKenzie showed that the trend was the plasma increased speed for up to two solar radii from the solar wind and thermal heating effects [23]. Another factor is a quick gain of kinetic energy when the magnetic field lines snap closed on the back side [24]. This is called an Alfvén wave effect. If this happens, it often occurs when the plasma reaches roughly 0.3 Astronomical Unit.

The plasma balloon widens as it travels. The energetic particles are not all aligned but have their own directions. The magnetic fields holding the balloon together weaken as they spread out. The reduction of strength is beneficial because it lowers the impact, but the widening means the impact has a greater chance of hitting the Earth.

The analysis of plasma balloons is complicated. Several factors influence their speed and width. Therefore, it is not possible to predict the precise behavior of plasma. However, looking at previous large solar events can give a trend.

3 Data for Plasma Balloons

Observations are made looking at plasma ballooning. See Figure 2 which is for the solar flare of July 23, 2012 [25]. It was the fastest solar flare on record. It was very large but was emitted from the opposite side of the Sun, so it posed no risk to the Earth.

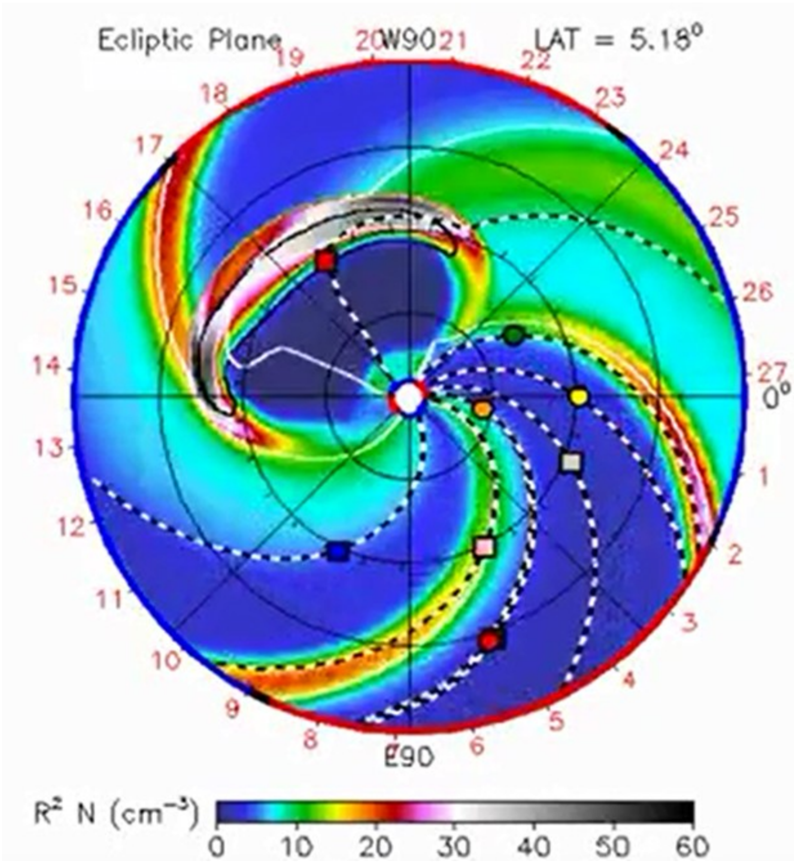

Figure 2: Solar flare of July 23, 2012, Ecliptic Plane View [14] (public domain).

In figure 2, the Sun is the white dot in the middle and the Earth is the yellow circle shown at zero degrees. Other bodies are planets and satellites. The color coding of the plasma strength is shown in the legend. The black areas represent the highest concentrations of plasma. The figure has many colors because the Sun is always emitting solar particles. The image was from July 24, 2012 which is the day after the solar event was detected. The plasma balloon is in the upper left quadrant of the figure. It has already passed the line black circle representing one astronomical unit. It doesn't appear that this balloon reconnected on the back side, but is still in contact with the Sun.

The area with the highest concentration of plasma is mostly contained in the region from West 90 degrees to 180 degrees. A graphical analysis shows that the region with the highest risk over an angle spanning 105 degrees. At an angle below West 80 degrees, and below East 175 degrees, the plasma levels are lower. The entire front edge of the plasma balloon contains the highest levels of plasma, so a wide swath of the solar system is at risk. Another observation is that the speed doesn't seem to vary much across the front of the balloon. At the side edges of the balloon, the speed is only 22% less than at the front. Therefore, the risk is relatively the same over the whole front width of the balloon.

Figure 3 shows the same event but a few hours earlier as the main body of mass passes Earth orbit (1.0 AU). The purpose of this article is to see whether solar flares originating from different latitudes of the Sun have different risk, so figure 3 is used to judge the vertical spreading. The plot is the plasma levels, using the same scale, at Earth orbit for about 60 degrees north and south of the orbit.

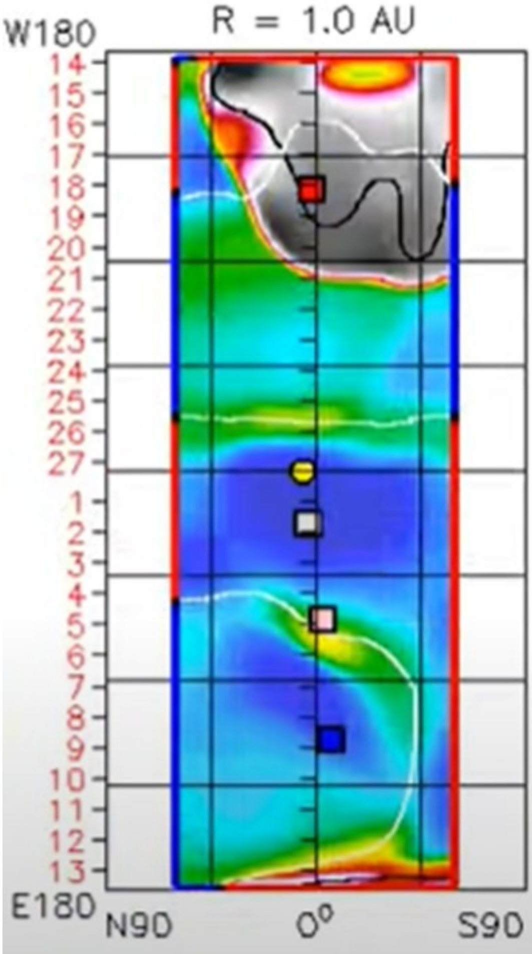

Figure 3: Solar flare of July 23, 2012, Orbital View [14] (public domain).

From Figure 3, we see that the plasma at the top of the figure. It is slightly offset towards the south or right. The shape of this balloon at this time is roughly circular about its center. Therefore, it appears that the balloon is spreading equally in each direction. It spreads about 50 degrees vertically towards each side which is the same as found horizontally about 50 degrees vertically towards each side which is the same as found horizontally.

Additionally, there is not much variation in Figure 3 across the plasma from North to South. It appears that whenever the front of the plasma hits, the impact is about the same.

4 Discussion of Plasma Balloons

The spreading of the balloon increases risk because the plasma can affect a larger area. If sunspots originating from high or low latitudes on the Sun didn't spread much, then there would be less risk from them. The sunspots come from latitudes on the Sun between 40 North and 40 South according to Sporer's Law, but according to Maunder's observations, the most concerning events happen within 32 degrees of the Sun's equator. The Earth is inclined by 7.155 degrees so that can add or subtract from the total angle depending on season. However, the spreading of the plasma balloon is about 50 degrees in each direction. Therefore, any coronal mass ejections in the same quadrant of where the Earth is orbiting at that time will impact the Earth with roughly the same effect regardless of the latitude of the sunspot origin. A glancing or diminished blow is likely only if the Earth is orbited beyond the front of the plasma balloon. However, the plasma balloons have significant variation across them, so a less severe impact is always a possibility.

5 Methods for Latitude and Longitude of Source

Next, the latitude and longitude of the event origin will be considered in a three-dimensional statistical analysis of trajectories. From the previous section, it was found that latitude alone didn't prevent plasma from reaching the Earth. However, as the Sun rotates away, the interaction of latitude and longitude will create differences in likelihoods. Further from the Equator, longitudinal rotation moves sunspots out of range more quickly.

First, the geometric location on the Sun will be found where the solar events have possible trajectories towards Earth. This is limited by 32 degrees north and south latitude on the Sun by Sporer's Law and Maunder's observations of larger sunspots. Additionally, this is limited by a spread of 50 degrees according to the results plasma balloon analysis in the previous section

Second, a statistic will be found for the likelihood of Earth trajectories from differing latitudes. Since plasma spreads only through an angle of 50 degrees in each direction, along the equator of the Sun, a sunspot located within an arc of the equator of 100 degrees could have a trajectory towards Earth. However, at higher latitudes, such as 32 degrees, the sunspots are already turned away from Earth by that angle, so not as much longitudinal rotation is necessary in order to move the trajectory out of a path to Earth. A statistic will be found by looking at the likelihoods of large sunspots at each of the latitudes and comparing possible longitudinal rotations to plasma balloon expansion. Additionally, the effect of the incline of the Earth's orbit will be considered because Earth could be up to 7.155 degrees from the Sun's equator.

6 Results of Latitude and Longitude of Source

Figure 4 shows the region from 32 degrees north to south, and in a cone of not more than 50 degrees away. This shows that further from the equator, less of the Sun is within 50 degrees. At the equator, 100 of 360 degrees or 27.8% of the solar flares are within the arc aimed at the Earth. At 32 degrees, 22.6% of the arc around the Sun could have plasma reaching the Earth.

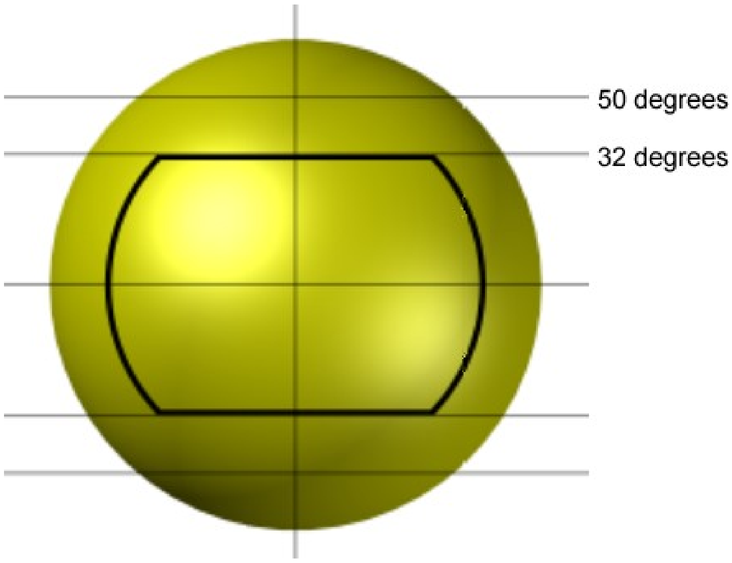

Figure 4: Region of Risk from Sun

Next, the geometry of Figure 4 is applied to the actual latitudes of solar events in Figure 1. The latitude of top solar events was found by Maunder. Solar events were distributed with random longitudes around the Sun. A likelihood is created for a solar event being at each latitude, and longitude, and comparing to Figure 4, it is determined that the overall likelihood is 26.7%.

The effect of the incline of the orbit of Earth is considered next. Since the Earth is inclined at an angle of 7.155 degrees, when the Earth is at the peak of the incline as shown in Figure 5, the area of risk is higher. Additionally, Figure 5 shows a sample plasma trajectory that is outside of the region of risk. The result of considering the effect of the incline is that the likelihood is 26.6%.

7 Discussion of Latitude and Longitude of Source

The calculated risk is 26.6%. This means that there is about a one-quarter chance that any extreme solar event will have a trajectory towards Earth within the main area of impact of the plasma balloon. This is in the range between 27.8% and 22.6% found at zero-degrees and 32-degrees latitude. The result of 26.6% is closer to the risk of 27.8% at the equator because more of the solar events are closer to the Sun's equator.

The effect of the incline of the Earth's orbit was considered. It had very little effect on the result. As the Earth is inclined upwards, as in Figure 5, it has very little effect on the

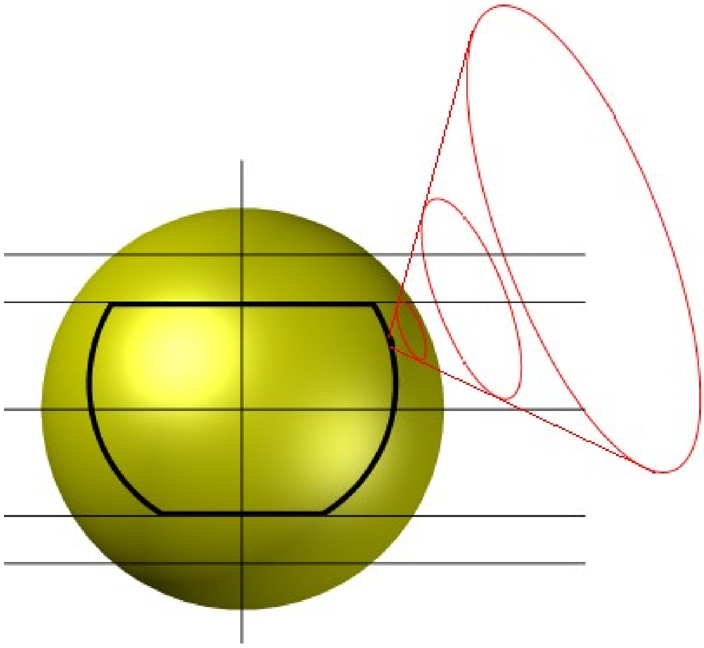

Figure 5: Inclined Location with Plasma Illustration.

risk from solar events near the equator. There is a larger effect on the solar events further from the equator, but those are less likely to occur.

8 Conclusion

Solar flares regularly impact the Earth. They affect radio signals, satellites, and electrical power systems. The Earth has been lucky that there have been no direct hits by the largest solar flares since the Information Age. However, there have been several large solar flares that were directed away from the Earth.

The latitude of a solar flare's origin and the behavior of plasma were studied to see if it would influence the potential effect on the Earth. Solar flares mostly occur within a band around the Sun's equator, and that is the same plane that the Earth is located in. Plasma balloons spread as they travel. They spread vertically and horizontally. The strongest levels of plasma are located along the whole front of the balloon, so getting hit by any part of it has about the same impact. Since the plasma spreads significantly, the effect of the latitude of origin of the sunspot likely has very little effect on diminishing the impact on the Earth.

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