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Substorms and Solar Eclipses: A Mutual Information Based Study

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Key Points:

- In a given 2 hr window between 2001 and 2021, a substorm occurs roughly 40% of the time, increasing to 67% during windows including an eclipse
- Conditional Point-wise Mutual Information analysis suggests the probability of eclipse-substorm co-occurrence is higher than random chance
- The mutual dependence between eclipses and substorms is likely the result of ionospheric conductivity feedback into the magnetosphere

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Abstract Solar eclipses present a rare glimpse into the impact of ionospheric electrodynamics on the magnetosphere independent of other well studied seasonal influences. Despite decades of study, we still do not have a complete description of the conditions for geomagnetic substorm onset. We present herein a mutual information based study of previously published substorm onsets and the past two decades of eclipses which indicates the likelihood of co-occurrence is greater than random chance. A plausible interpretation for this relation suggests that the abrupt fluctuations in ionospheric conductivity during an eclipse may influence the magnetospheric preconditions of substorm initiation. While the mechanism remains unclear, this study presents strong evidence of a link between substorm onset and solar eclipses.

Plain Language Summary Geomagnetic substorms are a long-studied phenomenon with significant potential for impact on human infrastructure and activities. Despite decades of research, a comprehensive description of what causes these violent eruptions of space plasma near earth has yet to be agreed upon. Although their evolution is well documented, the precise conditions required for substorms to manifest appear to be more complex than previously understood. We present evidence in this manuscript of a mutual dependence between solar eclipses and substorms, which suggests that changes to the upper atmosphere like those occurring during an eclipse may influence substorm development.

1. Introduction

Geomagnetic substorms are one of the most studied geophysical phenomenon in space physics (6,872 online search results in Journal of Geophysical Research: Space Physics as of June 2023), second perhaps only to the study of geomagnetic storms (7,335 results). Because substorms happen relatively often (Borovsky & Yakymenko, 2017), they make for an appealing target to investigate how energy can couple between the solar wind and Earth's near space environment. However, the exact details of energy coupling relating to substorm development is still a matter of debate.

Several investigations have looked into substorm morphological timing (Ferdousi & Raeder, 2016; Henderson, 2009; Weimer, 1994), their periodicity (Borovsky et al., 1993; Borovsky & Yakymenko, 2017; Hsu & McPherron, 2003; McPherron & Chu, 2018), and seasonal dependence (Chua et al., 2004; Liou et al., 2001; Wang & Lühr, 2007). Despite this robust history of research, there remain open questions about how exactly a substorm comes to occur (Baker et al., 1999; M. P. Freeman & Morley, 2009; Newell & Liou, 2011), as well as how we might try to predict them (Blanchard et al., 2000; M. Freeman & Morley, 2004; Momani et al., 2011). One area of continued research has probed the dependence of substorm activity on ionospheric conductance (El-Alaoui et al., 2023; Newell et al., 1996; Wang et al., 2005). This subject can present analytical difficulties due to the inherent seasonal dependence of ionospheric conductance, which shares a seasonal dependence with other important factors like dipole tilt.

One avenue for untangling this dependence is by surveying periods of solar eclipse. It is well known that an eclipse can modify the ionospheric conductivity in the region of shadow (Chen et al., 2021), but a recent study (Coyle et al., 2023) have suggested that eclipse related ionospheric disturbances may also couple into the global magnetosphere. Eclipse related ionospheric modulation is a unique phenomenon with magnetospheric implications that cannot be replicated outside of a realistically coupled ionosphere-magnetosphere model. As such, it provides a naturally occurring experiment to observe the impacts of ionospheric conductivity on the coupled current system. Perhaps coincidentally, during both Antarctic total solar eclipses in 2003 and 2021, a substorm

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occurred near the time of peak obscuration. It is therefore valuable to look at the substorms through the lens of solar eclipses in the hopes that some insight might be gleaned about substorm development. In this letter we show a mutual co-dependence between substorm occurrence and eclipses, which implies that ionospheric feedback is an important element of substorm development that should be accounted for in comprehensive substorm models.

2. Methodology

Information about solar eclipse timing is maintained by NASA and available via the internet (Kirk, 2023). This catalog of eclipses is based on estimated solar and lunar ephemeris data, and provides an estimated time of greatest eclipse with uncertainties of approximately 1 min during the period of interest. Eclipses are typically categorized as partial, annular, total, and hybrid, but for the purposes of this study we ignore this distinction entirely. This study investigates the 46 eclipses having occurred between January 2001 and December 2021.

In order to estimate the likelihood of substorm occurrence, it is necessary to first acquire a list of identified substorms. Historically, this has been achieved by manual inspection of the Auroral Electrojet (AE) index via WDC Kyoto or similarly by inspection of the SuperMAG Electrojet (SME) index (Gjerlov, 2023). While visual identification is an acceptable technique, several quantitative methods exist as well. This study utilizes the substorm lists available through SuperMAG derived via the method published in Forsyth et al. (2015) for the period of interest.

Mutual Information (MI) is a concept in information theory that measures the mutual dependence of two random variables that can capture non-linear correlations unlike the commonly used Pearson correlation. There are several examples of mutual information being used in space physics to investigate substorms, as well as magnetospheric physics in general. Cameron et al. (2019) provides a thorough explanation of the technique in their investigation of solar wind phase front geo-effectiveness. Herein, we investigate the point-wise mutual information (PMI) between two variables: the occurrence of substorm onset, and the peak of eclipse totality. We divide the period between 2001 and 2021 into 2 hr windows overlapping every 1 min, and determine the number of windows where each variable combination occurs (reported in Table 1). This gives us information about each variable's independent probability as well as the probabilities of their joint occurrence. The PMI is given by the binary logarithm:

$$pmi(x;y) = \log_2\left(\frac{p(x,y)}{p(x)p(y)}\right) \tag{1}$$

where x and y represent the occurrence time of substorms or eclipse peaks respectively, $p(x, y)$ is the joint probability of co-occurrence (taken as the number of windows where both events occur simultaneously divided by the total number of windows), $p(x)$ is the number of windows containing a substorm onset divided by the total number of windows, and $p(y)$ is the same but for eclipse totality peaks. The mutual information contained within these two variables is the sum of all PMI scores for each possible combination of x and y multiplied by their probability of co-occurrence:

$$I(X;Y) = \sum_{x\in X}\sum_{y\in Y} p(x,y)\log_2\left(\frac{p(x,y)}{p(x)p(y)}\right) \tag{2}$$

In an effort to reduce the amount of influence any secondary variables may have on our results, we subsequently conduct a conditional point-wise mutual information (CPMI) study relating substorm occurrence, eclipse totality, interplanetary magnetic field (IMF) "northward turnings." We define a "northward turning" of the IMF as at least 20 min of negative $B_{Z_{GSM}}$ followed by a positive transition as recorded in the 1-min OMNI solar wind database (Papitashvili, 2023). The solar wind data provided by OMNI is nominally propagated to the magnetosphere bowshock, and therefore any mismatch in timing between the solar wind and substorms would be well within the 2-hr window we've chosen for this analysis. In this case, the purpose of using northward turnings is to apply a proxy for solar wind driving of substorm onsets as has been suggested in prior works (Russell, 2000). Additionally, we conduct a separate PMI analysis on this northward turning variable with substorms to provide a baseline comparison of this method for analysis.

By comparing the amount of additional information with the unconditioned case, we are able to determine how much influence each conditioning variable has on the result.

Table 1
Number of Occurrences for Each Event Type

Eclipse	Substorm	$B_{S\to N}$	Event description	Number of occurences
N	N	N	Nothing Observed	3,976,310
N	N	Y	Only northward turning	2,698,131
N	Y	N	Only substorms	1,786,749
Y	N	N	Only eclipses	1,430
N	Y	Y	Substorms and northward turnings	2,578,089
Y	N	Y	Eclipse and northward turnings	1,400
Y	Y	N	Eclipse and substorms	1,462
Y	Y	Y	All variables detected	1,228
Total				11,044,799

$$I(X;Y|Z) = I(X;Y) - (I(X;Z) - I(X;Z|Y)) \tag{3}$$

$$I(X;Y|Z) = \sum_{x\in X}\sum_{y\in Y}\sum_{z\in Z} p(x,y,z)\,\log_2\left(\frac{p(z)p(x,y,z)}{p(x,z)p(y,z)}\right) \tag{4}$$

Equation 3 states that the mutual information in X and Y but not Z is equivalent to the mutual information between X and Y minus the information common to X and Z minus the information shared also with Y. When this number is 0, the information contained in X and Y is also contained in Z. We rearrange Equation 3 by moving the original MI to the left-hand side to make it easier to understand.

$$I(X;Y) - I(X;Y|Z) = I(X;Z) - I(X;Z|Y) \tag{5}$$

This form, called the "interaction information," approaches 0 if no new information is added by controlling for variable Z. Additionally, comparing the resultant scores between cases where the conditioning variable is present or otherwise ($z = \{0, 1\}$) can give insight into the influence of the dependence on the conditioning variable. In the case that the interaction information is negative, we can conclude that the conditioning variable has some redundant information; that is the conditioning variable does not add new information about the mutual dependence of the original variables.

Both PMI and CPMI scores can be difficult to interpret as their limits are not well constrained. There are several techniques to normalize PMI scores, and in this study we use a particularly straightforward approach of dividing by the joint self information:

$$npmi(X;Y) = \frac{pmi(x;y)}{h(x,y)} = \frac{pmi(x;y)}{\log_2 p(x,y)} \tag{6}$$

This technique yields a score between $[-1, 1]$, where -1 means the events never co-occur, and 1 means total co-occurrence. Given the mismatch in the number of events in each set of substorms and eclipses, it is not expected that the resultant scores will actually approach ± 1. Nevertheless, this normalized point-wise mutual information (nPMI) score is useful for interpreting the scores relative to each other when conditioned on different variables. In the case of the substorm and northward turning PMI analysis, it may well be expected by skeptics of solar wind driven substorms to predict an nPMI score of near 0.

3. Results and Analysis

Of the approximately 11 million 2-hr long windows analyzed in this study, 39.5% of them contain at least one substorm onset. 10.4% contain more than one onset in the same window. Roughly 47.8% of windows contain a northward turning event as described previously. Less than 0.05% of windows contain the peak of a solar eclipse. If one selects only the windows centered on eclipse peaks, the occurrence rate for substorms increases to nearly 67%.

Table 2
Normalized Point-Wise Mutual Information Scores - Eclipses

Eclipse	Substorm	nPMI score
N	N	1.509×10^{-4}
N	Y	-1.252×10^{-4}
Y	N	-2.034×10^{-2}
Y	Y	2.450×10^{-2}

Table 2 shows the normalized PMI scores for eclipses and substorms from 2001 to 2021. Scores when there is no eclipse are on the order of 10^{-4} and are interpreted to be the "noise floor" of the mutual information score. The value in this column is expected to be nearly zero, because substorms do not require an eclipse to occur and so little information can be gathered about their mutual dependence when an eclipse is not present. However, the scores when an eclipse is occurring are approximately 200 times larger than otherwise ($\pm 2 \times 10^{-2}$), signifying that more information is available in that case. Moreover, the sign of the values indicate that it is more likely than random chance that substorms and eclipses co-occur, while it is also less likely than random chance that an eclipse occurs without an accompanying substorm. The mutual information contained in the list of substorm onsets and eclipse peaks is $I(X;Y) = 1.2478 \times 10^{-5}$. We will compare this value to the other PMI and CPMI scores to understand its relative importance.

A similar PMI analysis of northward turnings and substorms yields the results shown in Table 3. Each of these results are on the order of 10^{-1}, signifying a comparatively stronger dependence between the two variables. The sign of these results indicate that substorms are more likely to co-occur with northward turning than random chance, and the same relation exists between an absence of northward turning and no substorm. It is also less likely than random chance to have one without the other, though the strongest negative dependence is reported for substorms without a northward turning. The total mutual information contained in this table is $I(Y;Z) = 2.409 \times 10^{-2}$. This value is larger than the eclipse based PMI score by a factor of 1.93, indicating as expected that IMF orientation has a stronger relationship with substorms than eclipses.

Results from conditioning the eclipse/substorm PMI by IMF northward turnings ($B_{S\rightarrow N}$) are presented in Table 4. The nPMI scores for both the presence and absence of northward turnings are combined in each combination of eclipse and substorm variables to compare the results to the previous table and identify the impact of the conditioning variable. Once again, the scores when an eclipse is absent are two orders of magnitude less than those when the eclipse is present. Additionally, the sign of the scores (and therefore likelihood compared to random chance) remains unchanged. Interestingly, the magnitude of the scores increase when a northward turning is absent, and slightly shrink in its presence. This would indicate there is a stronger dependence in the absence of the northward variable, which is to be expected if the IMF has a strong mutual dependence with substorms (i.e., there is more ambiguity about the dependence between substorms and eclipses when northward turnings occur). The mutual information score for eclipses and substorms under this conditioning method is $I(X;Y|Z) = 3.144 \times 10^{-5}$. The interaction information as defined above is therefore negative, $1.248 \times 10^{-5} - 3.144 \times 10^{-5} = -1.896 \times 10^{-5}$.

4. Discussion

The results of Table 2 indicate that it is more likely than random chance that during an eclipse, a substorm will occur. Similarly, it is less likely than random chance that a substorm does not occur during an eclipse. Table 3 shows a stronger mutual dependence between northward turnings and substorms, with their simultaneous occurrence and absence more likely than random chance, with an equal magnitude but negative score describing times when one occurs without the other. After conditioning the results of the eclipse-substorm relation with northward turnings, the overall trends remain the same, however the magnitude of the dependence relation increased by approximately a factor of two. The reinforcement of these trends after conditioning is evidence that the dependence is not influenced by this particular external variable, but it remains the possibility that a different controlling variable exists.

Table 3
Normalized Point-Wise Mutual Information Scores—Northward Turnings

$B_{S\rightarrow N}$	Substorm	nPMI score
N	N	1.145×10^{-1}
N	Y	-1.540×10^{-1}
Y	N	-1.348×10^{-1}
Y	Y	1.270×10^{-1}

Comparison of the information scores before and after conditioning yields a negative value for the "interaction information" defined earlier. This is because the conditioned results have a larger mutual information score than the unconditioned set. In this case of negative interaction information, it is notable that in the absence of northward turnings, the original consensus is reinforced. However, the addition of the conditioning variable results in the opposite dependence relation and of a smaller magnitude. This is likely due to the relatively stronger mutual dependence between substorms and

Table 4
Normalized Conditional Point-Wise Mutual Information Scores

Eclipse	Substorm	$B_{S\rightarrow N}$	nPMI score	(combined)
N	N	N	1.391×10^{-4}	(1.244×10^{-4})
N	N	Y	-1.475×10^{-5}	
N	Y	N	-1.736×10^{-4}	$-1.587 \times 10^{-4})$
N	Y	Y	1.495×10^{-5}	
Y	N	N	-3.720×10^{-2}	$-3.265 \times 10^{-2})$
Y	N	Y	4.556×10^{-3}	
Y	Y	N	5.472×10^{-2}	(5.963×10^{-2})
Y	Y	Y	-4.905×10^{-3}	

solar wind energy accumulation by the magnetosphere. If a stronger driver is present during an eclipse period, then the eclipse effect is mitigated. In the case where the conditioning variable is absent, the dependence between eclipses and substorms is more apparent. This is consistent with the condition of negative interaction information, which indicates that the conditioning variable enhances the dependence between the original variables.

It is perhaps useful to evaluate some more common statistical parameters of this data set for ease of interpretation. The structure of this investigation lends itself readily to computing χ^2 and a p-value. However, performing this calculation with the windowed event lists would result in counting each eclipse 120 times over (corresponding with a 2 hr window). It is therefore reasonable to scale the event counts by dividing each category by 120. With this scaling factor in mind, the unconditioned PMI study yields a $\chi^2 \approx 1.625$ and $p \approx 0.444$. When conditioning with the solar wind variable, the degrees of freedom increase to 2, and $\chi^2 \approx 4.359$, $p \approx 0.113$. The p-values reported here represent the probability of attaining these particular results given the null-hypothesis is true and eclipses and substorms are independent events.

The use of northward turnings as a proxy for solar wind driven substorms is admittedly contentious. It is especially so in the manner presented herein, where we make no efforts to isolate windows where the northward turning occurs specifically prior to the identified substorm onset. Accounting for this error in follow on studies is expected to influence the magnitude of the PMI scores, but the sign of the scores (and therefore conclusion) is likely to remain the same. Similar conditioning of the eclipse-substorm relation has been completed with polar cap indices, stock market valuations, and other variables not presented (because they do not influence the conclusion) to gain insight into the robustness of the result, all of which retain the general trend (at least for conditioned eclipse-substorm PMIs). It is therefore presented that these results are statistically significant and robust, but they are not necessarily indicative of a strong dependence.

It is important to remember that the results of the mutual information analysis are not directly suggestive of a causal relationship between the dependent variables. For instance, it is certainly well known that substorms do not require the occurrence of an eclipse to manifest. However, it is not beyond reason to speculate on how an eclipse might accelerate the development of a substorm. In fact there are a number of compelling explanations that can be made to fit the popular substorm models. We explore two types of causal mechanisms herein: a dayside-to-nightside wave interaction model and a substorm instability acceleration model.

The primary impact of an eclipse on the coupled magnetosphere-ionosphere system is the dramatic reduction of the dayside ionospheric conductivity. Model results from previous studies have shown that conductivity can be reduced by nearly half under the region of totality. This rapid modification of conductivity on the dayside has been associated with magnetosphere-ionosphere waves observed in both hemispheres during a high latitude eclipse (Coyle et al., 2023). It is possible that these dayside magnetosphere waves couple to a fast-mode wave that travels toward the magnetotail. A similar but reversed mechanism for coupling activity in the magnetotail to the dayside region has been proposed in Ohtani et al. (2021) and Elhawary et al. (2023). This wave coupling method could be detected by spacecraft magnetometers, but it would likely require an intentional observation campaign to place them appropriately. It is likely that future modeling work may give us an insight into the plausibility of coupling energy from the dayside to the nightside in a manner that can trigger a substorm.

Coyle et al. (2023) presented a case study of an Antarctic total solar eclipse and used event data to simulate the amount of energy diverted from the ionosphere in a simple circuit model as in Boström (1974). This analysis yielded a result similar to the energy supposed by Akasofu (2021) necessary to initiate a substorm onset. It is therefore possible that simply by hampering the ionospheric current sink, the conditions for substorm development in the tail manifest more rapidly than otherwise. In terms of the "tippy bucket" model (Akasofu, 1985), it could be imagined that the bucket has a steady drip into the ionosphere that becomes plugged during an eclipse. This accelerates the rate at which the bucket fills, and shortens the time before it tips. Further, assuming the dayside currents are driven by a quasi-static potential, the decrease in conductivity necessarily reduces the current flowing in those regions. Modeling this as an anti-parallel current, the resultant magnetic field variation will alter the reconnection rate and therefore directly alter solar-wind-magnetosphere coupling as a result.

It is noted that substorm occurrence is not always preceded by the maximum of the eclipse. Sometimes it happens that a coincident substorm occurs after the eclipse starts but before it reaches the maximum obscuration point. This seems to support the idea that an eclipse related conductivity change may simply accelerate the development of an otherwise developing substorm. Again, because substorms also occur during periods without an eclipse, this seems to be the most plausible explanation for any mutual dependence.

It is also possible that the observed dependency relies on an entirely different coupling mechanism, or even that no direct causal relationship actually exists. In the latter case, an unknown driver may exist that explains the association. Clearly there is a need for expanded observational support to answer this question. One readily available avenue for investigating the link between these events is through the use of coupled geospace models. Ideally each of these eclipses can be simulated with realistic solar wind driving, but even a basic set of runs with constant solar wind driving and a realistic eclipse modulated ionosphere may provide sufficient insight.

5. Summary and Conclusion

We have presented herein the results of a mutual information analysis of substorm onset and solar eclipse maximum occurrence for the period between January 2001 and December 2021. By dividing that period into overlapping 2-hr long segments and analyzing the occurrence rates of each event, it is found that the nominal substorm rate of 40% increases to 67% during periods centered on eclipse maxima. Based on the normalized mutual information scores presented above, it is more likely than random chance that a substorm will have occurred during the same 2 hr interval in which an eclipse has reached maximum obscuration. It is also less likely than random chance that an eclipse will occur without a coincident substorm. When accounting for the occurrence of a 20 min period of southward IMF followed by a northward turning, this trend remains. The mutual information score is greater in magnitude in the absence of a probable substorm trigger, which suggests the mutual dependence of substorms and eclipses is independent of such drivers. This may therefore be the first evidence of an ionospheric "trigger mechanism" (or "accelerating condition") for substorms. Clearly there is a need for greater diagnostic information of both the dayside/nightside magnetosphere in conjunction with ionospheric measurements during an eclipse to substantiate such a claim. Modeling efforts that combine a realistic ionospheric feedback mechanism with magnetospheric dynamics may also provide insight into explanations for the mutual dependence described above.

Data Availability Statement

Eclipse and Solar Wind data are both publicly available and provided online by NASA. JHU/APL provides substorm lists and information online via SuperMAG.

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