EXPLORING THE DYNAMICS OF GEOMAGNETIC ACTIVITY: A COMPREHENSIVE ANALYSIS OF LINEAR, NONLINEAR, AND TIME-LAGGED CORRELATIONS WITH SOLAR WIND PARAMETERS

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PLASMA PHYSICS END OF PERIOD

TABLE OF CONTENT

WHAT SPARKED MY INTEREST

Fundamentals of Plasma physics
Bittencourt

What Bittencourt said

In chapter 1 under the occurrence of Plasma in nature Bittencouort wrote,” the progress made in astrophysics and in theoretical physics during the last century, it was realized that most of the matter in the known universe, with a few exceptions such as the surface of cold planets (the Earth, for example) exists as a plasma.”

What I understood by that

Most of the stuff in the universe is in the form of plasma. Plasma is like a gas, but with its particles charged (like ions and electrons). This is different from the solid, liquid, or gas forms we see often on Earth. In space, stars (including our Sun), the space between stars, and even the space between galaxies are mostly filled with plasma. So, while on Earth we see things as solids, liquids, and gases, in the vast universe, plasma is actually the most common form of matter.

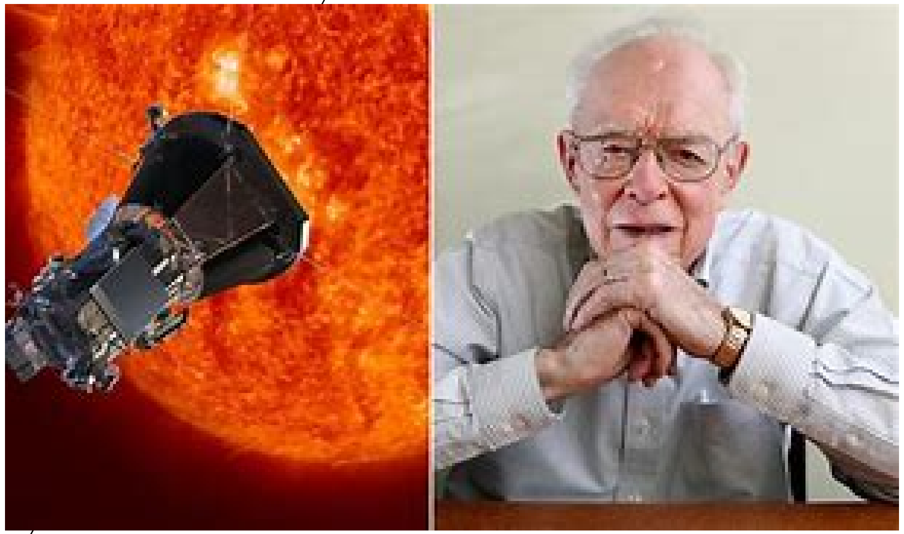
Aha moment!

Human-made plasmas are common in technologies such as fluorescent lights and plasma TVs and in the medical fields for surgeries.

Unlike natural plasmas found in stars or space, these plasmas are generated under controlled conditions on Earth

INTRODUCTION

Since Eugene Parker's model in the 1950s, which strongly suggested that a stream of plasma originated from the hot solar corona and was later verified by the first spacecraft measurements of the solar wind, significant progress has been made in accurately predicting the space plasma environment near Earth. This progress has been fueled by advancements in computing, models, remote observations, and in situ measurements. Scientific curiosity and society's growing reliance on devices vulnerable to space weather phenomena are the driving forces behind these breakthroughs.(Bunting & Morgan, 2023).



PLASMA

Criteria for Plasma definition

$$n_i \approx n_e \qquad (1)$$
$$L \gg \lambda_D \qquad (2)$$
$$\lambda_D^3 n_e \gg 1 \qquad (3)$$
$$\omega_{pe}\tau > 1 \quad where\ \tau = {}^{1}/_{v_{en}} \qquad (4)$$

(1)Quasi neutral, (2) system much larger than the Debye length so that the plasma may behave like quasi neutral, (3) we want large number of a particles inside the Debye length, (4) so that the basic behaviors of plasma is controlled by the Electromagnetic forces and not by Hydrodynamic.

Production

Photoionization: Using high energy photons(x-ray or UV light) to knock electrons out of atoms or molecules thereby ionizing them

Gas discharge: involves passing electric current through a gas. The electric current provides energy to the gas molecules or atoms causing them to ionize.

Collective effects: Charge to Charge interactions

$$\vec{F} = \frac{1}{4\pi\varepsilon_o}\frac{qQ}{r^2}\hat{r}$$

Ampere Maxwell's Addition and Magnetic Induction

A charge in motion is associated with the Amperes and Max Law.

$$\nabla \times B = u_o J + u_o \varepsilon_o \frac{\partial E}{\partial t}$$
$$\vec{B} = u_o H$$

Where B is the magnetic induction and H is the magnetic field

The occurrence of Plasma in nature

The sun and its atmosphere

The solar wind

The magnetosphere and the Van Alen Radiation Belts

The Ionosphere

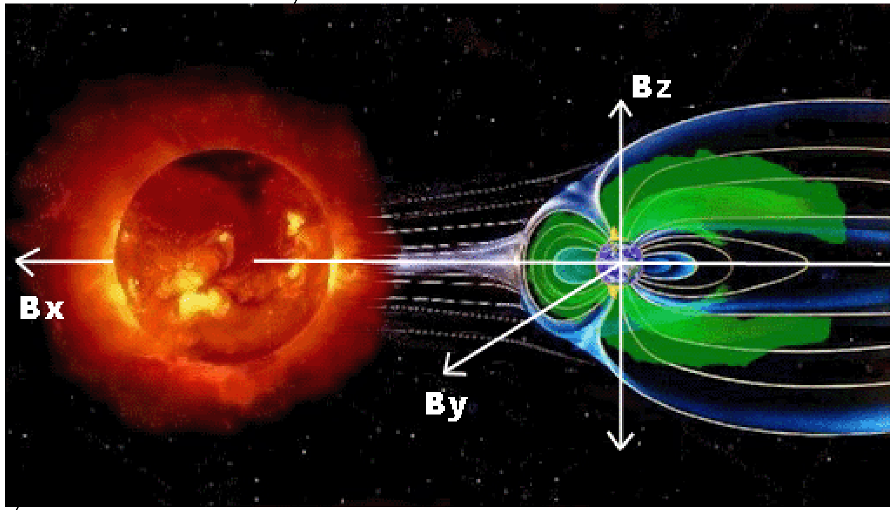
Plasmas beyond the Solar System

SOLAR WIND

The solar wind, a stream of ionized plasma from the solar corona, is pivotal in shaping heliospheric conditions. The solar wind composed mainly of protons and electrons, is continuously emitted by the sun at very high speeds into interplanetary space, as a result of the supersonic expansion of the hot solar corona.

Solar wind has different parameters but some of the solar wind parameters are Proton Density and Proton Speed.

The extension of the coronal magnetic field, carried into interplanetary space by the solar wind, is known as the interplanetary magnetic field (IMF)



GEOMAGNETIC ACTIVITY

The term "geomagnetic activity" describes the fluctuations in the Earth's magnetic field that occur naturally as a result of interactions between the magnetosphere the area surrounding the Earth that is dominated by its magnetic field and the solar wind, a stream of charged particles released by the Sun.

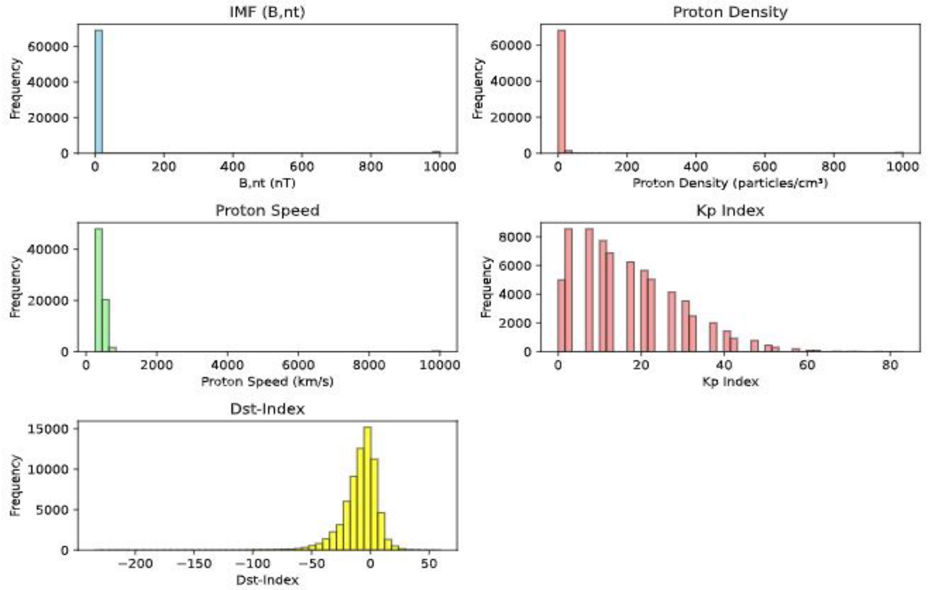
The degree of solar activity-induced disruption of the Earth's magnetic field is quantified using geomagnetic activity indices.(Yin et al., 2023). The highest deviation of the Earth's magnetic field over a three-hour period is measured by the Kp index.

The Earth's magnetosphere's ring current strength is gauged by the Dst index. There are two geomagnetic indices: Kp and Dst. To describe global magnetic activity, 13 magnetic observatories spread throughout important subpolar latitudes worldwide provide magnetic perturbations at 3-hour intervals, which are the basis for the Kp index.(Feng et al., 2023)

DATA

Solar wind and Geomagnetic Index

Parameter	Count	Mean	Std	Min	25%	Median	75%	Max
B	70152	19.33	117.11	0.5	3.7	4.8	6.4	999.9
Proton Density	70152	12.14	74.69	0.1	3.3	5.1	8.1	999.9
Proton Speed	70152	456.44	585.01	259	349	401	478	999.9
Kp index	70152	16.57	12.56	0	7	13	23	83
Dst Index	70152	-8.98	15.53	-234	-16	-6	1	59



OMNI NASA DATA

2015 TO 2023

The data was gotten from the NASA OMNI data server. A period of 8 years was downloaded consisting on IMF magnetic B, proton density and speed, kp and Dst Index

Preprocessed Data

Inconsistency

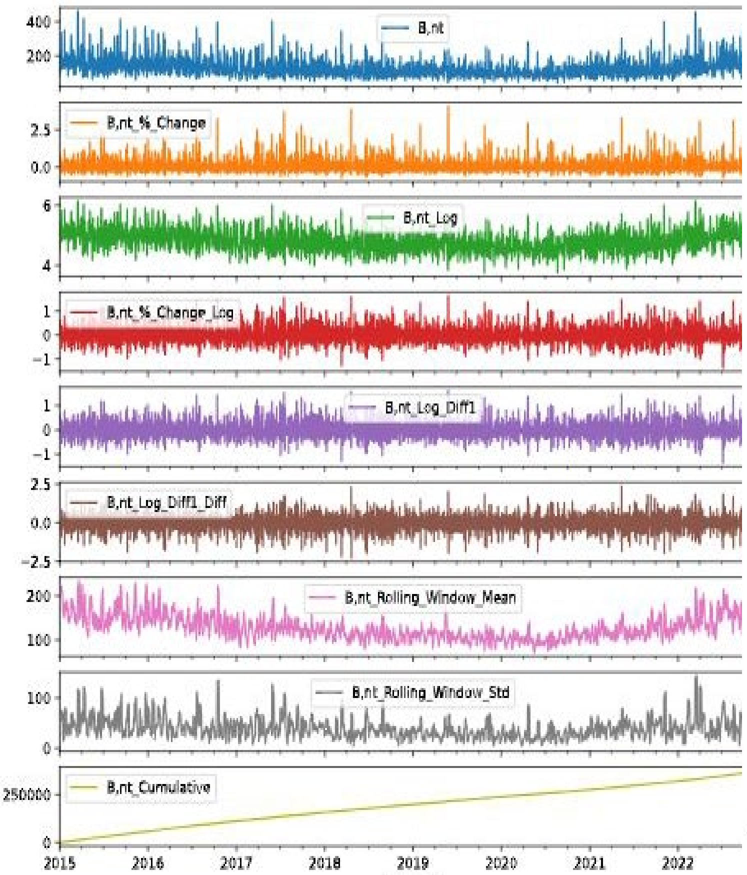
The data was preprocessed by interpolating and the python script can be accessed with the link.

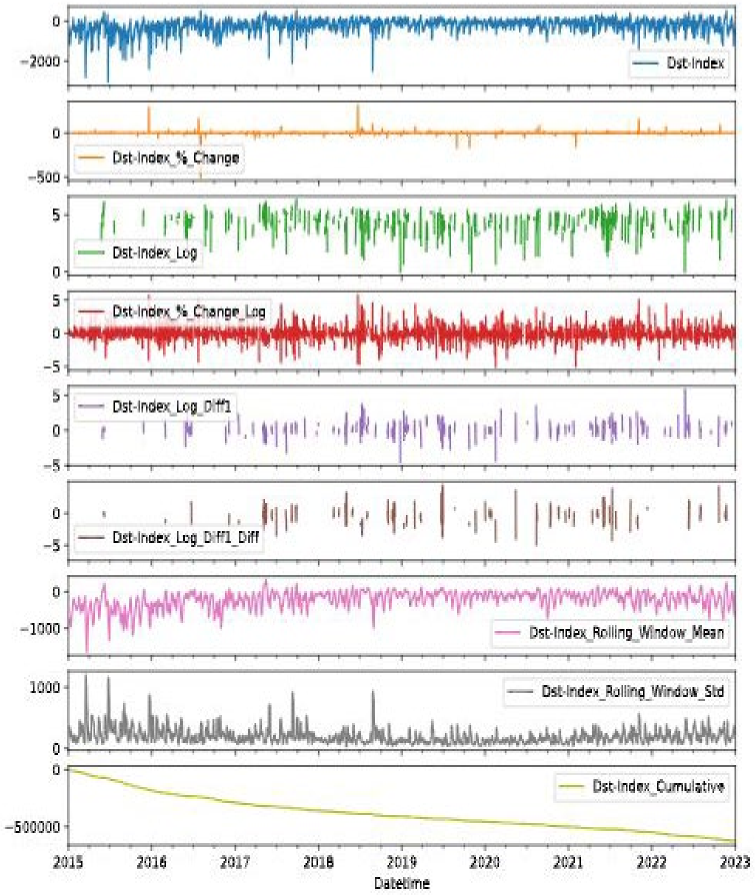
Analysis

Time series &Time lagged

We did time series, time lagged and correlation Analysis with the data to explore the relationship between the parameters

IMF B and Kp Index

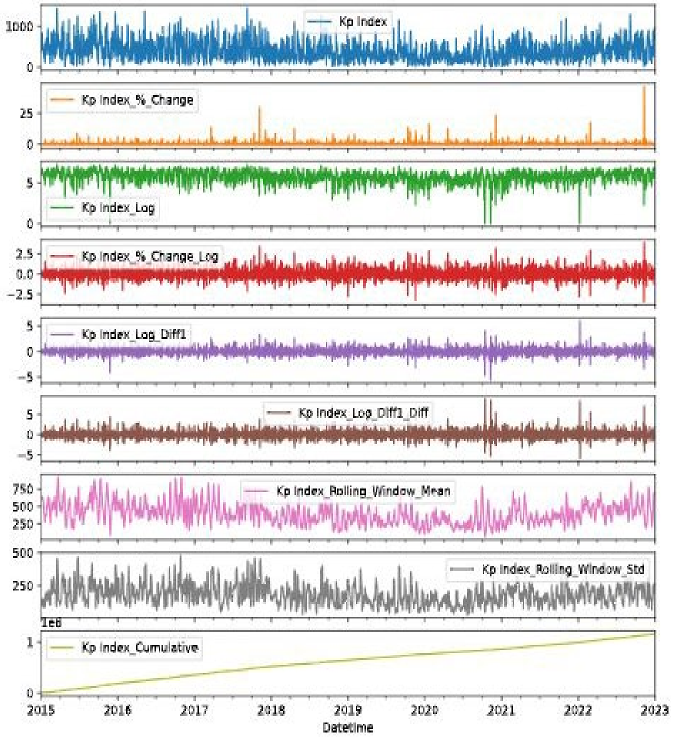


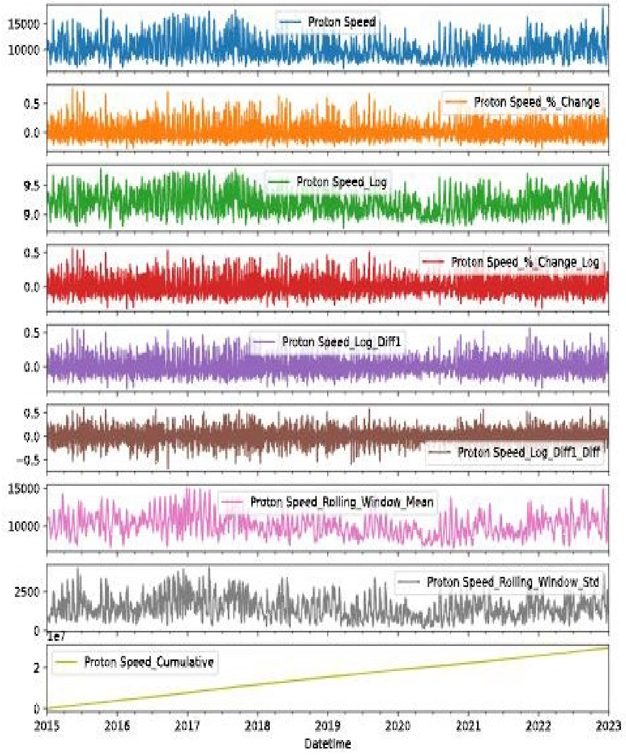


The raw data shows variability, with a slight cumulative increase over time, indicating a gradual strengthening of the magnetic field. The rolling window mean is relatively flat, suggesting that any long-term trends are subtle and overshadowed by short-term fluctuations.

The raw data shows episodic spikes indicating geomagnetic storms. The cumulative line trends downward, which could suggest an overall increase in geomagnetic activity, as lower Dst values indicate stronger disturbances.

Kp and Proton speed



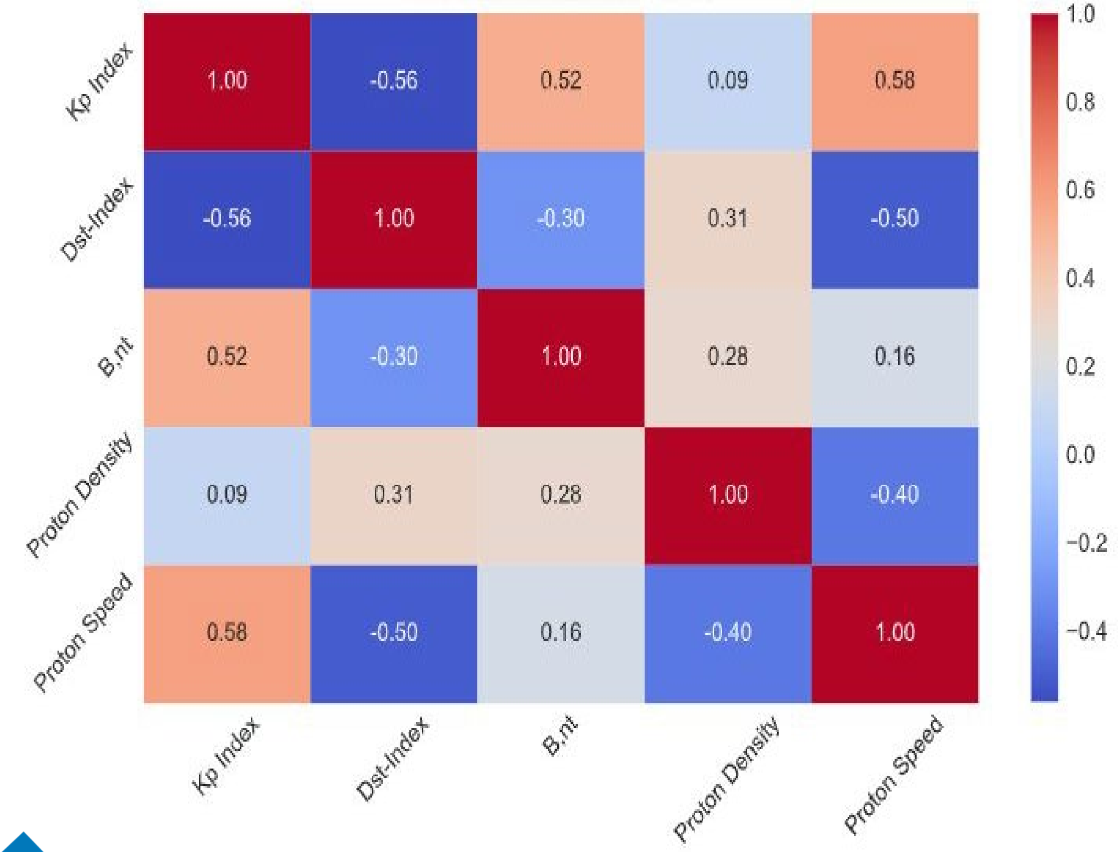


the Kp Index, which is a planetary index representing the intensity of global geomagnetic effects. The Kp index data follows a similar pattern to the Dst index with spikes that suggest geomagnetic storms. The cumulative value does not show a strong trend, indicating that there hasn't been a significant long-term change in geomagnetic activity levels based on the Kp index.

The Proton Speed shows a considerable degree of variability. The cumulative graph shows an upward trend, suggesting an increase in the speed of protons over time. This could be related to solar cycle progression or changes in the solar wind flow characteristics.

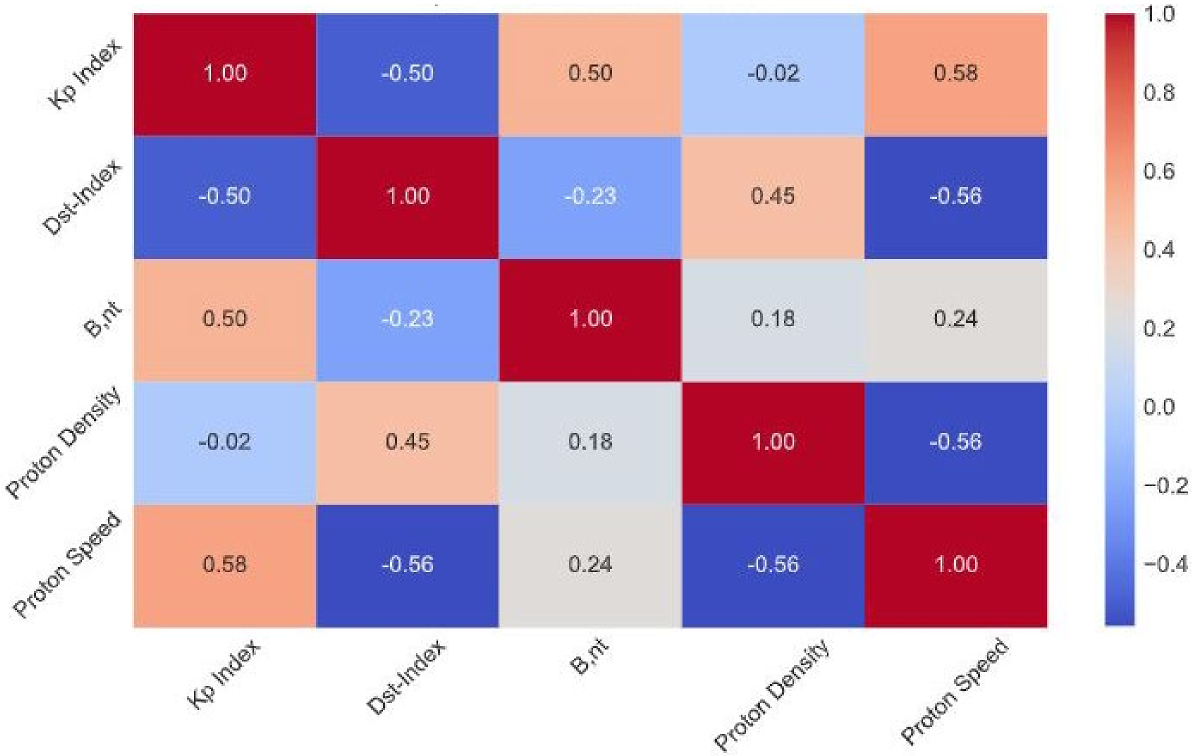
LINEAR CORRELATION

PEARSON CORRELATION



Over view of the linear relationship between the parameters. We had some interesting results like how the Kp and Dst have a negative correlations , which may indicate that these indices react differently to variations in solar and IMF conditions.

The Pearson Correlation coefficient r measure the linear relationship between two continuous variables. It assesses how well a linear equation describes the relationship between two variables, with a value of +1 indicating a perfect positive linear relationship, -1 indicating a perfect negative linear relationship, and 0 indicating no linear relationship at all.



NON-LINEAR CORRELATION

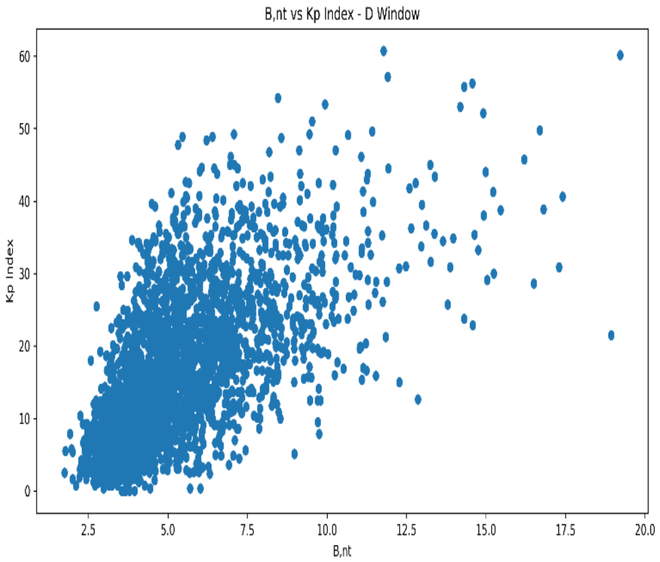
SPEARMAN CORRELATION

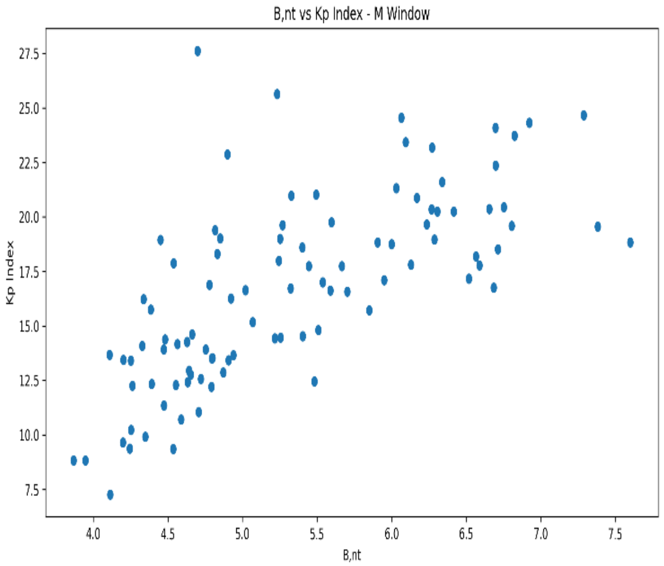
Over view of the non- linear relationship between the parameters. We had some interesting results like how the Kp Index has a moderate negative correlation with Dst Index (-0.50), indicating that higher values of Kp Index tend to coincide with lower values of Dst Index..

The Spearman rank correlation coefficient often donated as ρ can be used to identify nonlinear correlations between variables. It measures the strength and direction of monotonic relationship between two variables. A monotonic relationship is one where the variables tend to change together, but not necessarily at a constant rate.

TIME SERIES

IMF B VS KP INDEX FOR DAY AND MONTH WINDOW



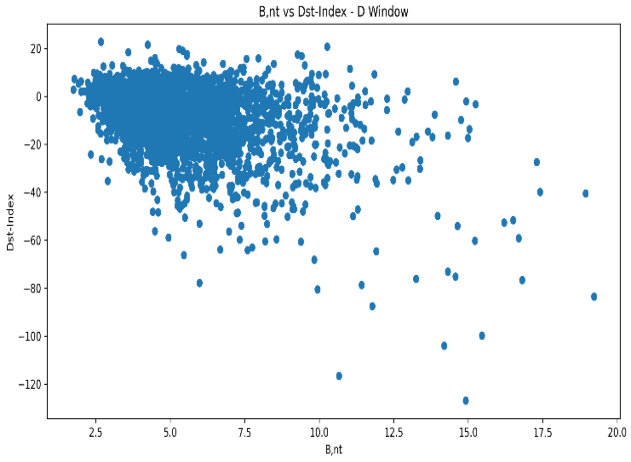


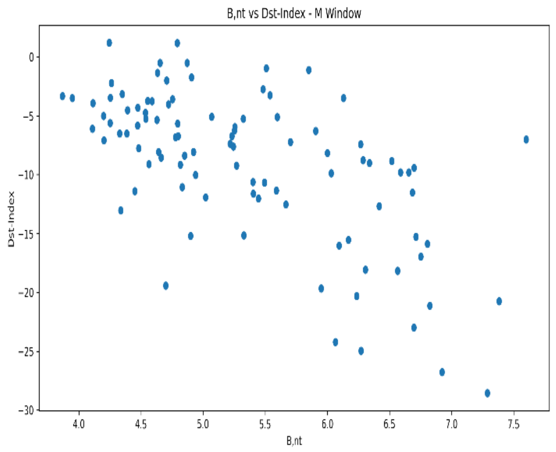
B,nt values are more common, as indicated by the dense clustering of points at the lower end of the B,nt scale. There is increased variability in the Kp index as B,nt values increase, suggesting that higher magnetic field strengths may lead to a wider range of geomagnetic responses.

The more widely spread data points indicate that there is a larger variation in the Kp index and B,nt on a monthly scale, which could reflect more sustained influences on geomagnetic activity. The clustering of points in the middle range of B,nt values might suggest a commonality in the strength of the magnetic field that influences geomagnetic activity.

TIME SERIES

IMF B VS Dst INDEX FOR DAY AND MONTH WINDOW



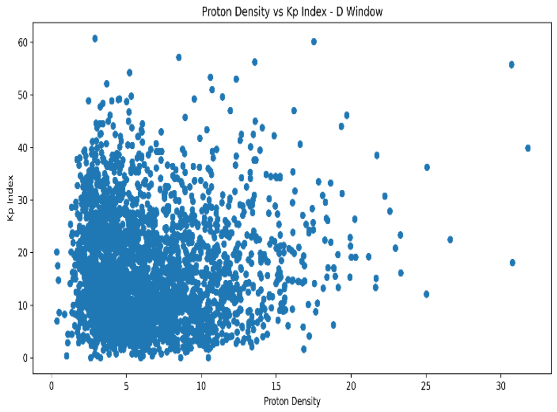


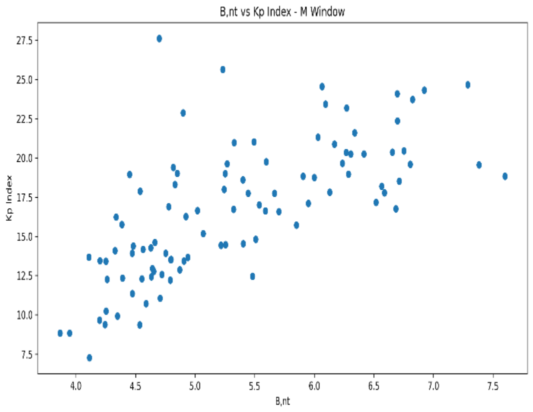
The Dst index primarily takes on negative values, which is characteristic of this index as it measures the intensity of the geomagnetic storm—the more negative the value, the stronger the storm.

The B,nt values are spread between approximately 4.0 to 7.5, with the Dst index ranging from 0 to about -30. This shows the variability of the Dst index in response to changes in B,nt over each month. Most of the Dst index values are negative, which is typical since the Dst index measures the disturbance in Earth's magnetic field, with more negative values indicating stronger disturbances.

TIME SERIES

Proton Density VS kp INDEX FOR DAY AND MONTH WINDOW



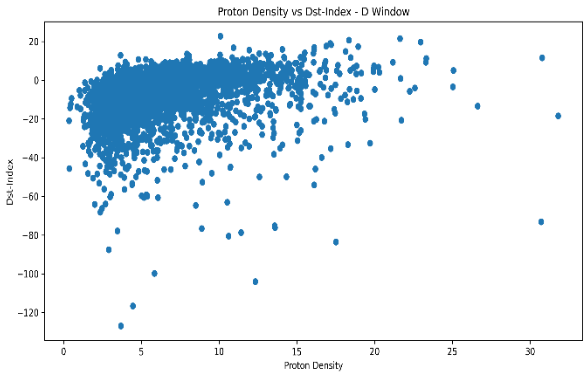


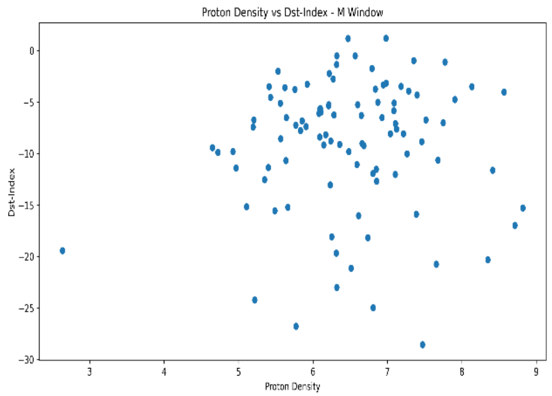
The spread of Kp index values seems to increase with proton density, indicating that higher densities may be associated with a wider range of geomagnetic activity. The scatter plot suggests that on a day-to-day basis, the Kp index has a variable response to changes in proton density.

The Kp index values range from about 7.5 to 27.5, suggesting a wide range of geomagnetic activity levels during different months. The plot does not indicate a clear linear correlation between proton density and the Kp index.

TIME SERIES

Proton Density VS Dst INDEX FOR DAY AND MONTH WINDOW



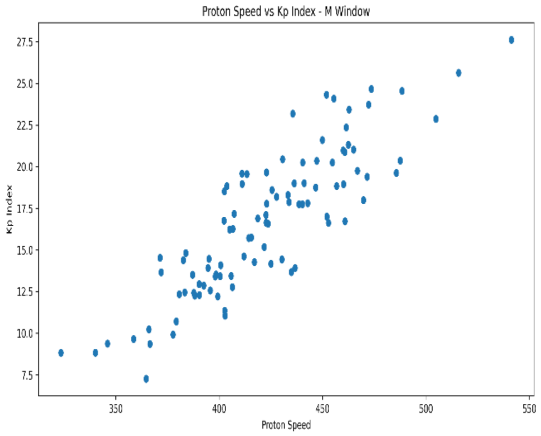


The Dst index varies from slightly positive to significantly negative values. The negative values are indicative of geomagnetic storm conditions, with more negative values pointing to more intense storms. There appears to be a high density of data points at lower proton densities, which suggests that lower proton densities are more common.

The data points are relatively spread out across the range of proton densities, with no apparent dense clustering. This spread suggests variability in the geomagnetic response to different proton densities.

TIME SERIES

Proton Speed VS Kp INDEX FOR DAY AND MONTH WINDOW

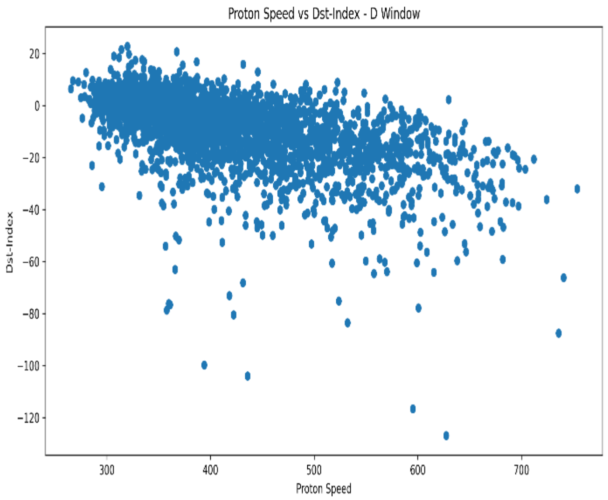


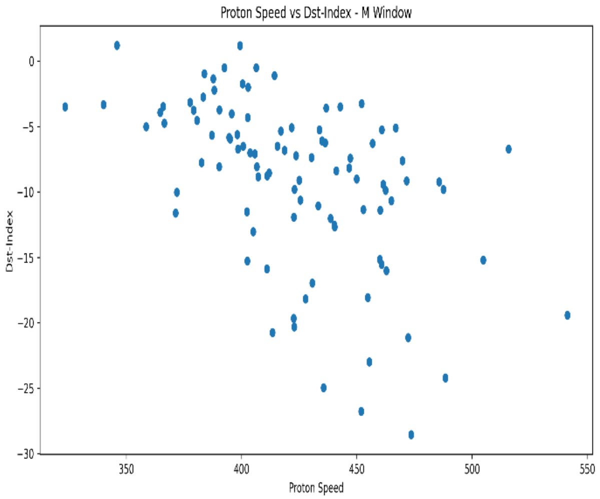
There's a noticeable density of data points at lower proton speeds, which suggests that solar wind speeds in this range are more common. However, the density of points decreases as proton speed increases.

There appears to be an upward trend, where months with higher proton speeds tend to have higher Kp index values. This suggests a correlation where faster solar wind may be associated with increased geomagnetic activity.

TIME SERIES

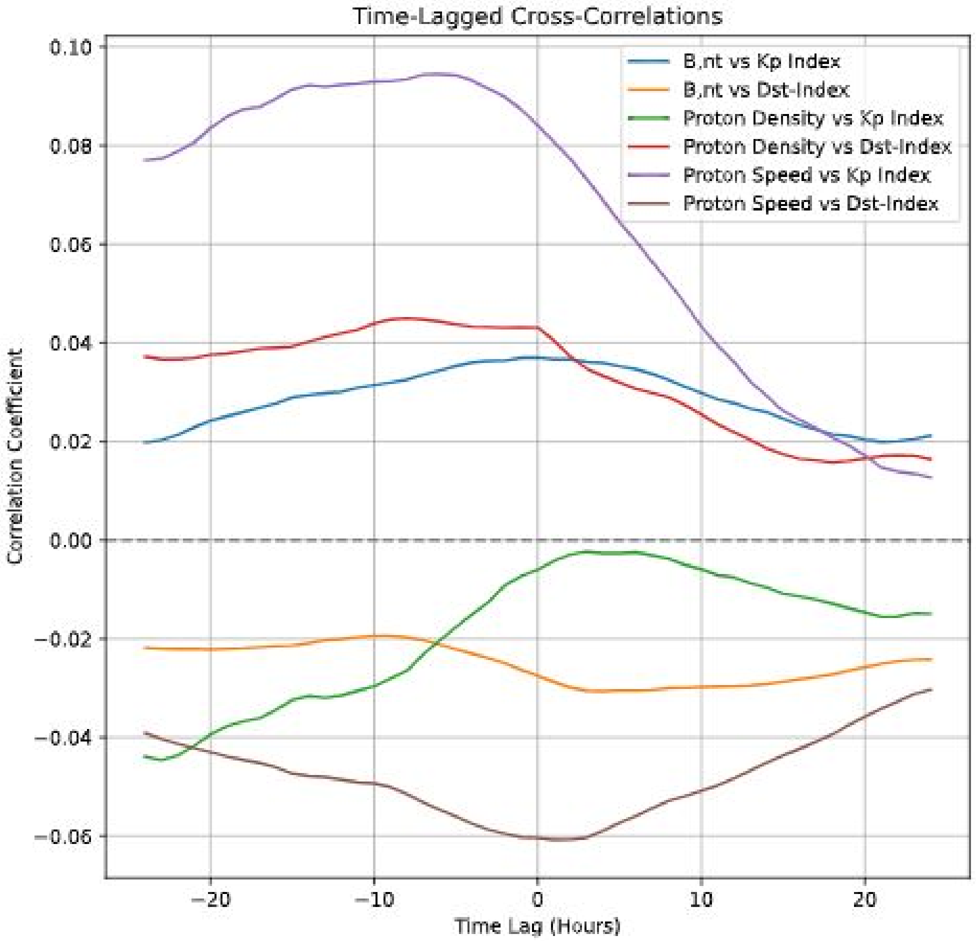
Proton Speed VS Dst INDEX FOR DAY AND MONTH WINDOW





The Dst index ranges from positive values down to less than -100, with negative values indicating geomagnetic storms of varying intensities. There's a dense clustering of points at moderate proton speeds, with the density thinning out at higher speeds. This could suggest that moderate solar wind speeds are more common than very high speeds on a daily basis.

The data points is spread throughout the range of proton speeds, without a clear concentration in any specific area. This suggests variability in the geomagnetic response to different solar wind speeds on a monthly basis.



TIME LAGGED

TIME LAGGED CORRELATION OF THE VARIOUS PARAMETERS AGAINST EACH OTHER

Interestingly, the effects of proton density and speed on geomagnetic conditions are not the same depending on whether these changes happen before or after changes in geomagnetic activity. This suggests different physical processes might be involved in these scenarios. The study also found varying levels of influence from different solar wind parameters on geomagnetic activity. For instance, the magnetic field intensity ('B,nt') seems to have a more direct or stronger influence on geomagnetic conditions compared to proton density or speed. This helps to understand better which aspects of the solar wind have the most impact on geomagnetic activity.

CONCLUSION AND FURTHER WORKS

A study from 2015 to 2023 found a complex link between solar activity and Earth's geomagnetic field. Increases in the solar wind's magnetic field and proton speed were noted, alongside varying geomagnetic activity and storm indicators. Different geomagnetic indices responded uniquely to solar conditions, showing both immediate and delayed effects on Earth's magnetosphere. This highlights the complexity and challenges in predicting space weather.

The study's conclusions are constrained by the limitations inherent in observational data and the specific time period analyzed. Future research could build upon this foundation by exploring additional solar wind parameters, extending the analysis period, or employing more advanced modeling techniques to unravel the causal mechanisms behind these correlations.

Additionally, the research will include examining the relationship between coronal mass ejections (CMEs)—huge expulsions of plasma and magnetic field from the Sun's corona—and geomagnetic storms, which are disturbances in the Earth's magnetosphere caused by these solar events. By overlaying data on solar wind energy with occurrences of CMEs and geomagnetic storms.

REFERENCES

Bandić, M., Verbanac, G., & Živković, S. (2023). Geoeffective interplanetary magnetic field (IMF) from in situ data: Realistic versus idealized spiral IMF. *Scientific Reports*, *13*(1), Article 1. https://doi.org/10.1038/s41598-023-36499-1

Bittencourt, J. A. (2004). *Fundamentals of plasma physics*. New York : Springer. http://archive.org/details/fundamentalsofpl0000bitt

Bunting, K. A., & Morgan, H. (2023). An Empirical Relationship Between Coronal Density and Solar Wind Velocity in the Middle Corona With Applications to Space Weather. *Space Weather*, *21*(3), e2023SW003448. https://doi.org/10.1029/2023SW003448

Svalgaard, L. (1977). *Geomagnetic activity: Dependence on solar wind parameters* (SU-IPR-699). https://ntrs.nasa.gov/citations/19770022104

The Interplanetary Magnetic Field (IMF) | Help. (n.d.). SpaceWeatherLive.Com. Retrieved November 30, 2023, from https://spaceweatherlive.com/en/help/the-interplanetary-magnetic-field-imf.html

Wavelet Analysis of solar, solar wind and geomagnetic parameters—ProQuest. (n.d.). Retrieved November 21, 2023, from https://www.proquest.com/openview/001f9e92e0c51775b2f63ee019c4dd7c/1?pq-origsite=gscholar&cbl=105618

Yin, L., Wang, L., Ge, L., Tian, J., Yin, Z., Liu, M., & Zheng, W. (2023). Study on the Thermospheric Density Distribution Pattern during Geomagnetic Activity. *Applied Sciences*, *13*(9), Article 9. https://doi.org/10.3390/app13095564

THANK YOU

QUESTIONS AND FEEDBACK

HAVE A WONDERFUL
PLASMA DAY