Investigating Solar Coronal Temperatures Through GOES-U Observations

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Abstract

This project aims to investigate the phenomena that is the significant discrepancy between the solar corona's high temperatures compared to the effective temperature of the Sun. As we approach the solar maximum of cycle 25, NASAs GOES-19 mission provides the new data on adverse solar events such as solar flares, which are hypothesized to contribute to the high coronal temperatures. Utilizing data from GOES-19, COR3, and COR2, we attempt to conduct an analysis on the relationship between solar radiation emissions in the form of X-Ray flux and measured coronal temperatures via electron density profiles. We unfortunately fail to produce a proper analysis due to the rarity of data necessary to conduct such a calculation. We test the correlation of solar activity via the fluctuations of X-ray activity, the change in sun spots, and the proton density.

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1 Introduction

The stellar corona is one of the least understood phenomena in the study of astrophysics. Although there are multiple satellites observing and taking measurements of our very own Sun and its corona, we cannot explain with certainty what causes the discrepancy between the effective temperature of the Sun's surface and the temperature of its corona, which is between 1-2 million K [1]. With such high temperatures, the corona is expected to be an extremely bright region; however, the low density causes it to be visible only during a total eclipse. Stellar parameters important in testing activity level includes "stellar age, mean stellar rotation rate, depth of convection zone, and stellar surface characteristics such as surface effective temperature, effective gravity, and elemental abundances" [2].

This project seeks to explore the hypothesis that solar flares contribute significantly to coronal heating by examining X-ray emissions during flare events of varying magnitudes to evaluate their contribution to the observed temperature of the corona. To test the possible correlation between flare activity and coronal temperature, we searched the literature in an attempt to calculate the solar coronal temperature using electron density. A very interesting method conducted by Lemaire [3]. In their work they test the scale-height-method, hydrostatic equilibrium method, and the hydrodynamic method of coronal temperature calculations using electron density profiles. They primarily focus on the effects of three factors of the hydrodynamic method, ultimately claiming that the hydrodynamic method is the most useful diagnostic tool for determining the coronal heating rate at its maximum. Although the work is impressive it is also heavily relies on models, which is not quite what we are aiming for our work here.

We then found the impressive work done by Telloni et. al [4] where they report the FIRST observational estimate of the heating rate in the slowly expanding solar corona. Telloni et. al exploit the fortuitous contemporaneous observations from NASA's Parker Solar Probe (PSP) [5] and ESA's Solar Orbiter [6] of the same coronal plasma volume, relying on the basic solar wind magnetohydrodynamic equations, similar to what was done by Lemaire but with the utilization of real data. We attempt to produce evidence and correlation between solar activity (flares, sun spots, etc.) and coronal temperature measurements from proton density.

The Geostationary Operational Environmental Satellites (GOES-U) are well-equipped for this study, with instruments capable of measuring solar X-ray flux and monitoring solar weather. By analyzing GOES-U X-ray data and its correlation with flare magnitudes and other solar parameters, we aim to advance the understanding of coronal heating mechanisms and their implications for space weather.

2 Background

2.1 Solar Dynamo

The solar cycle is approximately 11 years, resulting in the Sun's magnetic field pole reversal. This phenomenon is attributed to the strong magnetic field wound up by the differential rotation of the Sun. The α-effect describes the twisting of the magnetic field lines caused by the Sun's rotation, while the ω-effect refers to the stretching and winding of the magnetic field lines around the Sun. These effects create magnetic stresses that reorient the poloidal dipole field. [7]

2.2 Sunspots and Solar Flares

Sunspots are the concentrated and tangled magnetic field lines appearing on the sun's surface. Sunspots are a product of the α-effect, which twists magnetic field lines into localized magnetic "knots." These knots disrupt the convective flow from the solar interior, creating cooler regions on the Sun's surface. The number of sunspots is also correlated with the phase of the solar cycle, with the number being higher during increased solar activity such as solar flare events.

Sunspots can cause the Sun's magnetic field lines to loop outward, connecting to sunspots of opposite polarity. This process, known as a solar flare, generates significant magnetic energy, emitting high energy signals in the form of radiation such as X-rays and energetic ultraviolet radiation (EUV). X-rays and EUV are absorbed as heat by Earth's upper atmosphere. Similar to how the ions in the Earth's atmosphere absorb high energy signals as heat, we suspect that a similar process happens in the sun's atmosphere as well. These events are key factors in explaining the high temperatures of the solar corona.

3 Methods

This study focused on data collected from the GOES-19 satellite, which is in geostationary orbit approximately 22,236 [8] miles above Earth's equator. GOES-19 is equipped with advanced instruments for monitoring solar activity, including an X-ray irradiance sensor, an ultraviolet imager, and sensors for detecting protons and electrons. These instruments enable the observation of key parameters such as X-ray flux, particle density, and UV emissions, which are critical for understanding solar flare activity and its effects on the solar corona.

The analysis began by identifying and examining solar flare events captured by GOES-19 during periods of high solar activity. To establish a baseline for comparison, data from "solar normal" conditions—periods of lower solar activity without significant flares—were analyzed. This baseline was then compared to mid-levels of activity and high activity. This approach allowed us to distinguish the effects of flare events on X-ray flux and coronal temperatures from the background solar environment.

In addition to analyzing the X-Ray flux over time periods of varying levels of solar activity, the sunspot numbers were also compared. This was computed with the same source of X-ray flux data, but instead of a short period, X-ray flux was calculated as a mean per month. These are compared to average sunspot number to the corresponding month for 24 months. While we attempted to compute for the entire solar cycle 25, the operation was computationally too expensive and was canceled after 412 minutes.

Data processing involved accessing NOAA's GOES database and using the `Sun.py` library, an open-source Python package for solar physics, was used to preprocess and analyze the data. This included tasks such as time-series extraction, visualization of X-ray flux trends, and filtering data to isolate specific flare events.

In addition to GOES-19 data, coronagraph observations were obtained from other satellite missions, including the COR2 and COR3 instruments aboard the STEREO spacecraft. These coronagraphs provided another perspective of measurements of the solar corona during periods of elevated solar activity.

4 Results

Our first analysis was an attempt to determine a correlation between proton density and measured x-ray flux, we query the GOES-19 X-ray flux database from the dates of January 18th-January 23rd to compare the a calculated proton temperature of the corona determined by [9]. Unfortunately, we are missing X-ray data for January 19th.

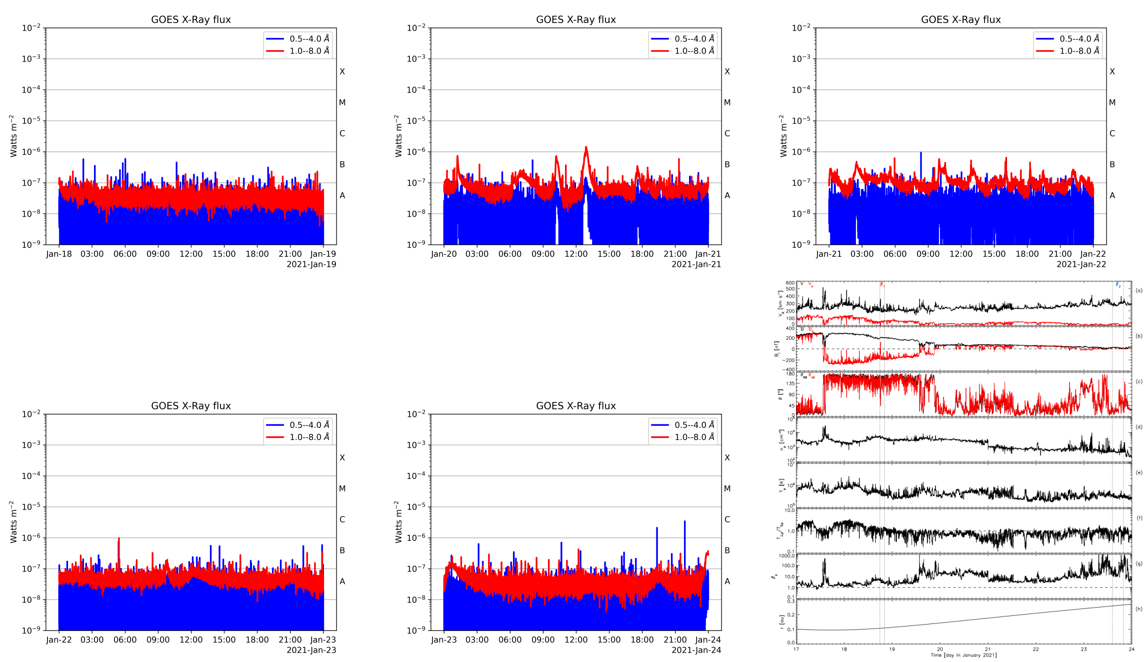

Figure 1: From left to right: Comparison between the observed X-ray flux on the days in January 2021 on the 18th, 20th, 21st, 22nd, 23rd, and the last plot obtained from [9] of the calculated proton temperature in the corona. The coronal proton temperature is shown as the

Here we observe a very weak correlation between X-ray activity and the calculated coronal proton temperature [9]. Unfortunately, during the time of these calculations and in situ observations, the solar activity of the sun seems to be at a minimum, as seen in the X-ray data queried from GOES with flare activity being at the baseline. A better comment on the correlation could be made if more coronal proton temperature calculations could be made on varying days, but unfortunately contemporaneous observations between the solar orbiter and the PSP are very few.

Our initial analysis using proton density data faced challenges due to the lack of simultaneous remote and local observations.

We then analyzed X-ray flux data over higher periods of solar activity, which offered more comprehensive datasets. The most recent geomagnetic storm on 11/10/2024 revealed a correlation between increased X-ray emissions and flare events.

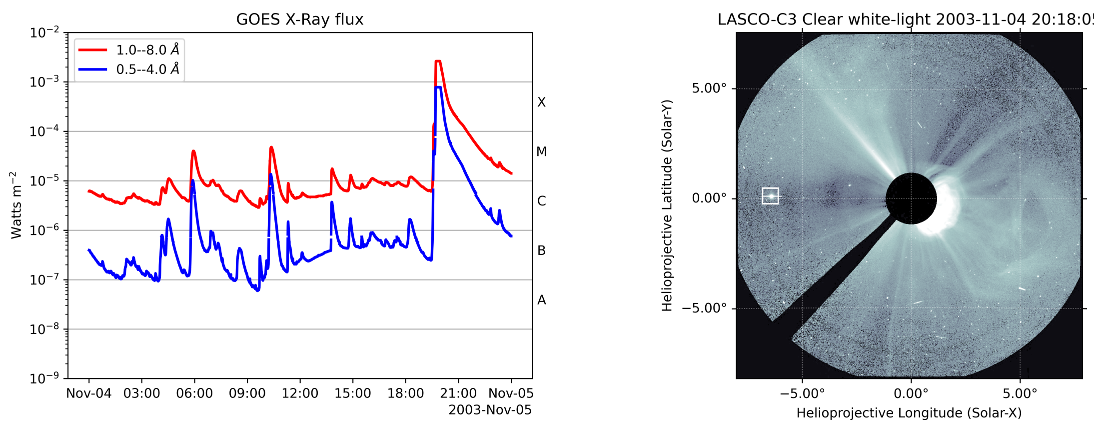

Figure 2: Left: X-ray flux on November 4, 2003 obtained by GOES-19. The solar flare occurred at a time of approximately 20:18:00, recording a solar flare strength of X40+, one of the strongest recorded solar flares in modern time. Right: Contemporaneous data from the COR3 coronograph, displaying the solar flare.

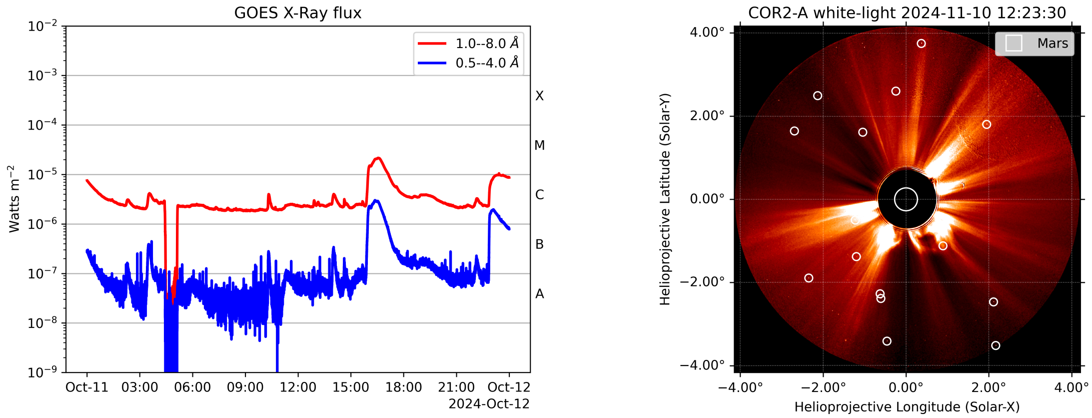

Figure 3: Left: X-ray flux on October 11, 2024 obtained by GOES-19. The solar flare occurred at a time of approximately 12:23:00, recording a moderate solar flare strength of M magnitude. Right: Contemporaneous data from the COR2 coronograph, displaying the solar flare.

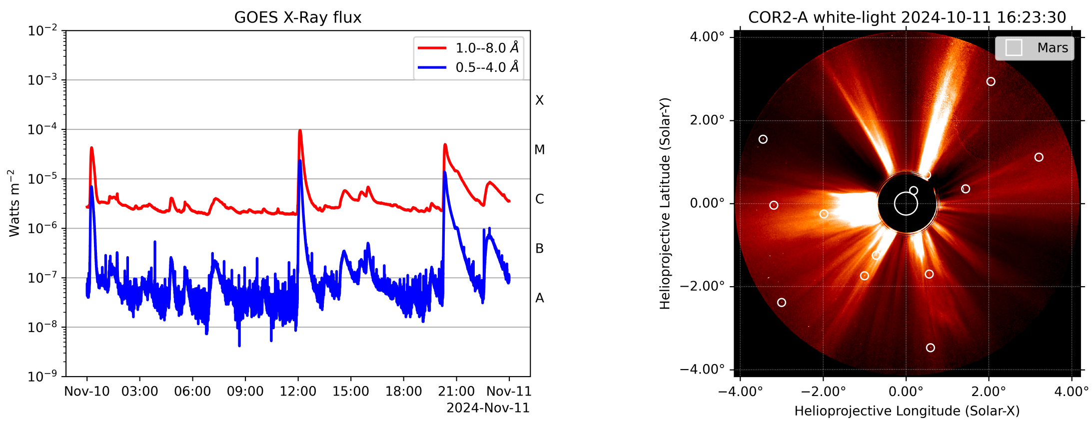

Figure 4: Left: X-ray flux on November 10, 2024 obtained by GOES-19. The solar flare occurred at a time of approximately 16:23:00, recording a strong solar flare strength of M10, possibly X1, magnitude. Right: Contemporaneous data from the COR2 coronograph, displaying the solar flare.

We also show the average X-ray flux values compared to the average sunspot number per month. The data is from January 2023. While more data points would prove stronger correlation, it is important to note that there is a potential correlation to more sun spot numbers resulting in higher X-ray flux values as shown.

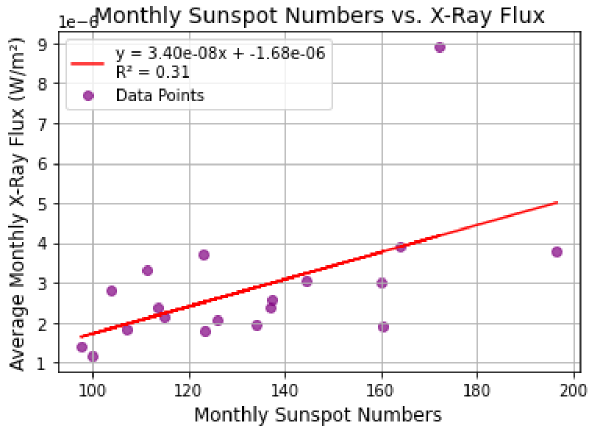

Figure 5: Monthly X-Ray flux compared to monthly sunspot numbers, showing possible correlation.

5 Discussion

The results of this study suggest a potential relationship between solar flare activity and coronal heating, as evidenced by the observed increase in X-ray flux during flare events. This aligns with the hypothesis that solar flares, driven by intense magnetic reconnection events, release substantial energy that contributes to the elevated temperatures of the corona. However, while the trends observed in the GOES-19 data are promising, several limitations need to be addressed to establish a more robust correlation.

First, the analysis relied on X-ray flux data as a proxy for flare intensity and coronal heating. While X-ray flux provides valuable insights into the radiation emitted during flare events, it does not fully capture other energy transport mechanisms such as turbulence or magnetic field dissipation. To gain a more comprehensive understanding, future studies could incorporate additional observational datasets, such as extreme ultraviolet (EUV) imaging and spectroscopic data from instruments like the Solar Dynamics Observatory (SDO) or the Parker Solar Probe. These datasets would allow for a more detailed examination of energy distribution and transport in the corona.

Second, the study analyzed flare events in isolation, without considering long-term trends or cumulative effects. Solar flares occur within the solar cycle, and their frequency and intensity vary significantly over time. Developing correlation models for flare activity with other phenomena, such as the number of sunspots, changes in the magnetic field structure, and the solar dynamo process, could help identify underlying patterns and mechanisms that drive coronal heating.

Third, the influence of external factors, such as solar wind and coronal mass ejections (CMEs), was not accounted for in this analysis. These phenomena can interact with flare events and contribute to the complex dynamics of the corona. Future work could incorporate multi-satellite observations from missions like the Solar and Heliospheric Observatory (SOHO) and the STEREO spacecraft to disentangle these effects and provide a clearer picture of the interplay between different solar activities.

Finally, the data processing pipeline used in this study relied heavily on the SunPy library [10] and NOAA's GOES database. While these tools offer significant advantages in terms of accessibility and ease of use, they also introduce potential biases due to data selection and processing algorithms. Developing custom data processing workflows and cross-validating results with other solar data repositories, such as the European Space Agency's Solar Orbiter mission, could improve the accuracy and reliability of the analysis.

Since we are not taking into account external factors like solar wind and coronal mass ejections (CMEs), there may be inconsistencies observed in the X-ray emissions during flare events. This can lead to an overestimation of the flare's role in coronal heating. CME induced geomagnetic storms can also affect satellite instrumentation and data, leading to inconsistent data. Even with these effects, there was still a clear indication of the influence of solar flares on coronal heating. In summary, although the current results provide preliminary evidence of a link between solar flare activity and coronal heating, further refinement and validation are necessary. Expanding the scope of the analysis to include additional datasets, exploring the cumulative and long-term effects of flare activity, and accounting for external influences will be critical steps in establishing a robust and comprehensive understanding of this relationship. This knowledge has significant implications for space weather forecasting and mitigating the impact of solar activity on Earth's technological infrastructure.

6 Conclusion

Our analysis using GOES-19 X-ray flux data has provided insights into the potential relationship between solar flare activity and coronal heating. While our initial attempt to use proton flux density to estimate coronal temperature faced challenges due to the lack of simultaneous local and remote observations, the use of X-ray flux data proved more promising. Data from the geomagnetic storm on November 10, 2024, showed notable increases in X-ray emissions during flare events, supporting the hypothesis that solar flares contribute to the heating of the solar corona. However, further refinement and validation using more comprehensive datasets are required to establish a robust correlation between X-ray flux and coronal temperature.

Beyond coronal heating, our study highlights the broader implications of solar X-ray and EUV radiation. These high-energy emissions ionize the Earth's upper atmosphere, creating the ionosphere, which significantly affects radio wave propagation. Solar flares can lead to increased ionization in the lower D-region of the ionosphere, causing radio blackouts and disruptions to navigation systems. Extreme flares can also disturb satellite communications, increase atmospheric drag on low-Earth orbit satellites, and potentially damage satellite electronics due to charging from high-energy particles. These findings underscore the importance of monitoring solar activity for mitigating risks to critical technological infrastructure on Earth and in space.

Future research could benefit from advanced observational tools like the recently launched CCOR-1 coronagraph and the Parker Solar Probe (PSP). The PSP's closer approaches to the Sun in upcoming years may provide unparalleled data on the Sun's magnetic field, plasma dynamics, and coronal heating mechanisms. With higher-resolution data from these instruments, we hope to further unravel the complexities of coronal heating and improve our understanding of how solar activity influences both the Sun and the near-Earth environment.

7 Contributions

Edin Peskovic: Conceptualization, Data curation, Visualization, Writing – review & editing

Leah Popoolapade: Conceptualization, Data curation, Visualization, Writing – review & editing

Naia Lum: Conceptualization, Data curation, Writing – original draft, Writing – review & editing

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