The Coronal Heating Problem of the Sun

Pranav Jain

Department of Robotics Engineering, Worcester Polytechnic Institute

100 Institute Road, Worcester, Massachusetts 01609, USA

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Abstract:

The coronal heating of the Sun still remains a mystery, which focuses on the coronal atmosphere of the Sun being significantly hotter than the surface of the Sun. This goes against the general understanding that the temperature drops as one goes away from the heat source. This literature review would synthesize the current understanding and prevailing theories about coronal heating, including wave heating, reconnection of magnetic lines, and nanoflares. This review would analyze data from various spacecrafts to better comprehend these theories. Recent improvements in high-resolution imaging and spectroscopy have given us new insights into the corona's fine structure and dynamic processes. However, there are still many unanswered questions, especially about how energy is spread out and used up in the corona. This review highlights the need for ongoing observations and improved models to solve the coronal heating mystery.

1 Introduction:

The Sun is the closest star to Earth, being about 1 Astronomical Unit or 149.6 Gm away from Earth. It is made up of several layers, each with distinctive properties and behaviors. Among these layers, the corona – the Sun's outermost layer – which is roughly 26000 km away from the Sun's interior [1] presents one of the most perplexing mysteries in astrophysics: the coronal heating problem. Observations indicate that the core of the Sun exceeds temperatures of 15.7 million Kelvin which cool down to 6,000 Kelvin by the time the energy reaches the photosphere, the Sun's surface; however, the corona reaches temperatures of over a million Kelvin, which is much hotter than the Sun's surface [2]. This extreme temperature difference contradicts the expectations based on the principles of heat transfer, where temperatures typically decrease as an object moves away from the heat source.

The coronal heating problem has been a topic of intense research and debate for several decades. Scientists have proposed various mechanisms to explain this phenomenon, including wave heating, magnetic reconnection, and nanoflares [3]. Each theory offers different insights into how energy is transported and dissipated in the corona, yet none has provided a definitive solution.

This literature review aims to synthesize the current understanding of coronal heating by examining recent observational data and theoretical models. By analyzing findings from key spacecraft missions such as the Solar and Heliospheric Observatory (SOHO), the Transition Region and Coronal Explorer (TRACE), and the Parker Solar Probe [4], this review will better understand the current knowledge about the heating of the coronal region of the Sun.

Understanding the mechanisms behind coronal heating is not only crucial for solar physics but also for broader astrophysical phenomena. By understanding the Sun's corona, we can gain insights into the behavior of other stars and improve our astronomical models, giving humans the ability to more accurately forecast space events, especially those that would impact the Earth.

2 Theory:

Towards the end of the 19th century, spectroscopy of the Sun showed the presence of a coronal "green line" in the coronal spectrum [5]. This new element didn't match with any known element on Earth and was named coronium, an element that only existed in the Sun's atmosphere [5]. In the 1900s, Grotrian and Edlén figured that the "green line" was actually emitted by iron, calcium and nickel during high states of ionization [5]. This suggested that the corona was very high in temperature, even more so than the temperature of the Sun's surface itself [5].

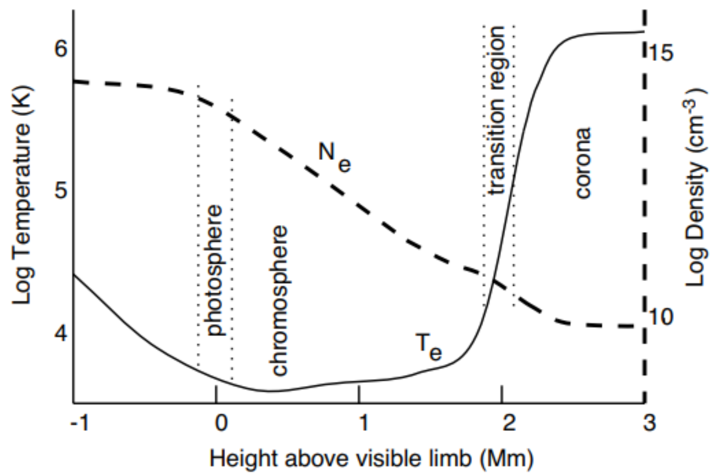

Figure 1: "Sketch of the variation of electron temperature Te and density Ne with height for an average model solar atmosphere" [5]

Figure 1 shows the change in temperature and density as the distance from the surface of the Sun increases. This clearly shows an extreme change in temperature, especially in the transition region between the chromosphere and the corona.

To explain this phenomenon, several theories have been developed to help understand the reasons behind the extremely high temperature observed in the corona compared to those on the Sun's surface. The most prominent theories include wave heating, magnetic reconnection, and nanoflares.

2.1 Wave Heating:

The Sun's photosphere is a convective zone which causes the magnetic fields to be compressed into strong flux tubes where the magnetic field strength is about 0.1 – 0.3 Tesla [6]. As the pressure reduces in the chromosphere, these tubes spread out into a roughly horizontal canopy of the field with individual flux tubes merging above [6]. Hence, the corona has lots of magnetic field lines with a magnetic field strength of about 0.001 – 0.01 Tesla [6].

Magnetohydrodynamic (MHD) waves are characterized by oscillations of both the magnetic field and the plasma particles. As the plasma beta is very small in the corona, being about 1 – 10%, the magnetic field controls the heating [6]. Alfvén waves are a type of MHD wave that was discovered by Alfvén in 1942 [7]. These waves travel along magnetic field lines using the magnetic tension as their restoring force [7]. Researchers soon realized that the Alfvén waves could propagate along these magnetic field lines and carry substantial energy from the lower photosphere to the corona [6]. However, as the coronal magnetic field cannot directly be measured, it becomes difficult to prove this theory [6].

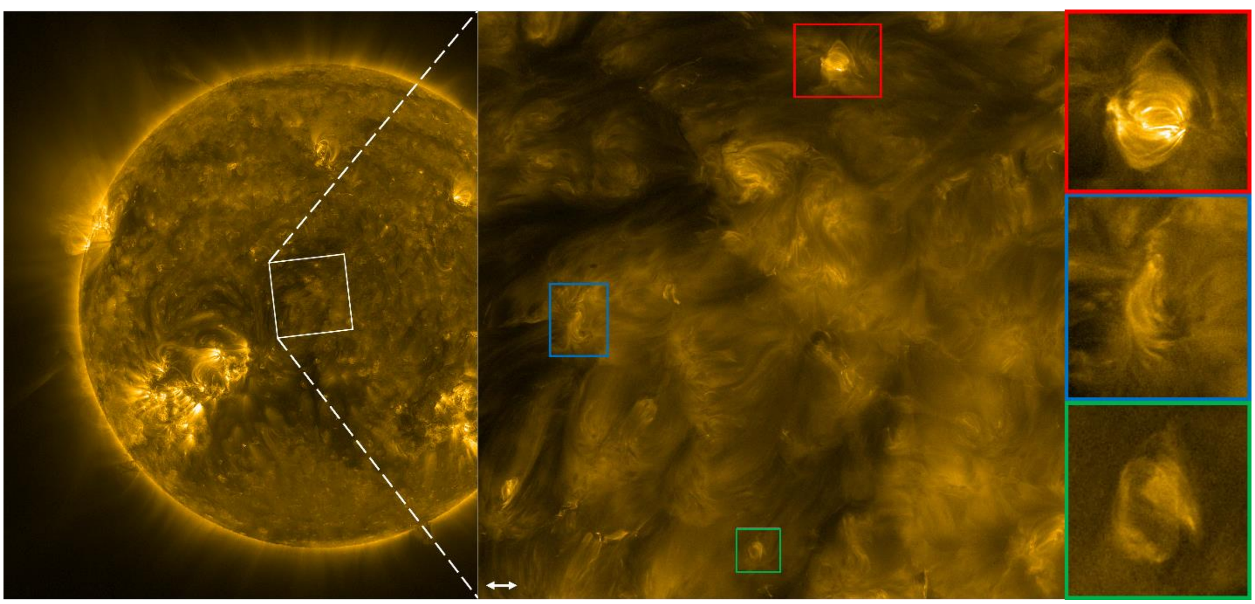

Figure 2: "Full Sun observation taken on October 12, 2022 by EUI's Full Sun Imager (FSI) and a zoom on the center of the Sun taken by its High-Resolution Imager (HRI). The white arrow corresponds to a distance of about 10 000 km. Three smaller structures highlighted with red, blue, and green boxes, show magnetic waves that appear as a transverse motion." [19]

After the energy reaches the corona by the Alfvén waves, there are various processes through which this energy could be dissipated, including resonant absorption and phase mixing.

2.1.1 Resonant Absorption:

Resonant Absorption occurs when the frequency of the Alfvén wave matches the natural frequency of the coronal plasma [8]. At the natural frequency, the magnetic and kinetic energy values increase significantly [8], suggesting some sort of localized heating. This is particularly effective in regions with varying density or magnetic field strength [8].

2.1.2 Phase Mixing:

In 1983, phase mixing was proposed by Heyvaerts and Priest as a method to heat the corona atmosphere [9]. In this process, Alfvén waves traveling along neighboring magnetic field lines can have slightly different speeds due to variations in the local plasma conditions [9]. This difference causes the waves to become out of phase over time, leading to an increase in the gradients of the wave field [9]. These gradients enhance the dissipation of wave energy through viscosity and resistivity, converting wave energy into heat [9].

2.2 Magnetic Reconnection:

Magnetic reconnection is a process where oppositely directed magnetic field lines break and reconnect, producing jets of hot plasma and Alfvén waves in the corona, which causes the release of stored magnetic energy as heat and kinetic energy [10]. During reconnection, large electric currents, shock waves and filamentation are formed in localized regions called current sheets [11]. The dissipation of these currents through the plasma's resistivity generates heat, known as Ohmic heating, especially in regions of high magnetic shear where reconnection may be more likely to occur [12]. Additionally, the rapid energy release during magnetic reconnection can generate shock waves that propagate through the plasma, compressing and heating it as they travel, thus converting kinetic energy into thermal energy [12]. Reconnection sites can also accelerate particles to high energies with their intensity increasing by 10 – 100 times, and as these energetic particles collide with denser regions of the corona, they lose energy through collisions, resulting in heating of the ambient plasma [11]. This process is often observed in solar flares, where accelerated electrons produce X-ray emissions [11].

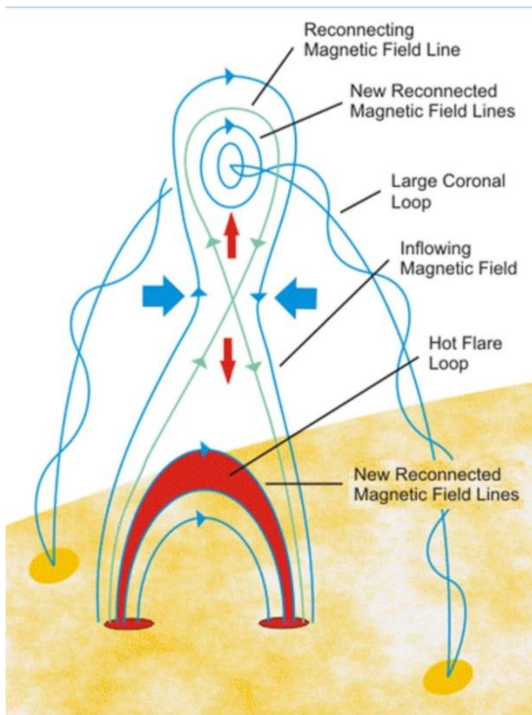

Figure 3: "An illustrated model of magnetic reconnection on the sun" [20].

2.3 Nanoflares:

Nanoflares, or small flares, were discovered by Parker in the corona and have 10^9 times less energy than large flares that are present on the Sun's surface; however, they could heat the corona if multiple of these flares occurred at the same time [12]. These tiny, frequent bursts of energy are caused by small-scale magnetic reconnection events throughout the corona [12]. Each nanoflare generates localized electric currents, and the dissipation of these currents through the plasma's resistivity leads to heating in small regions, similar to a larger reconnection event [12].

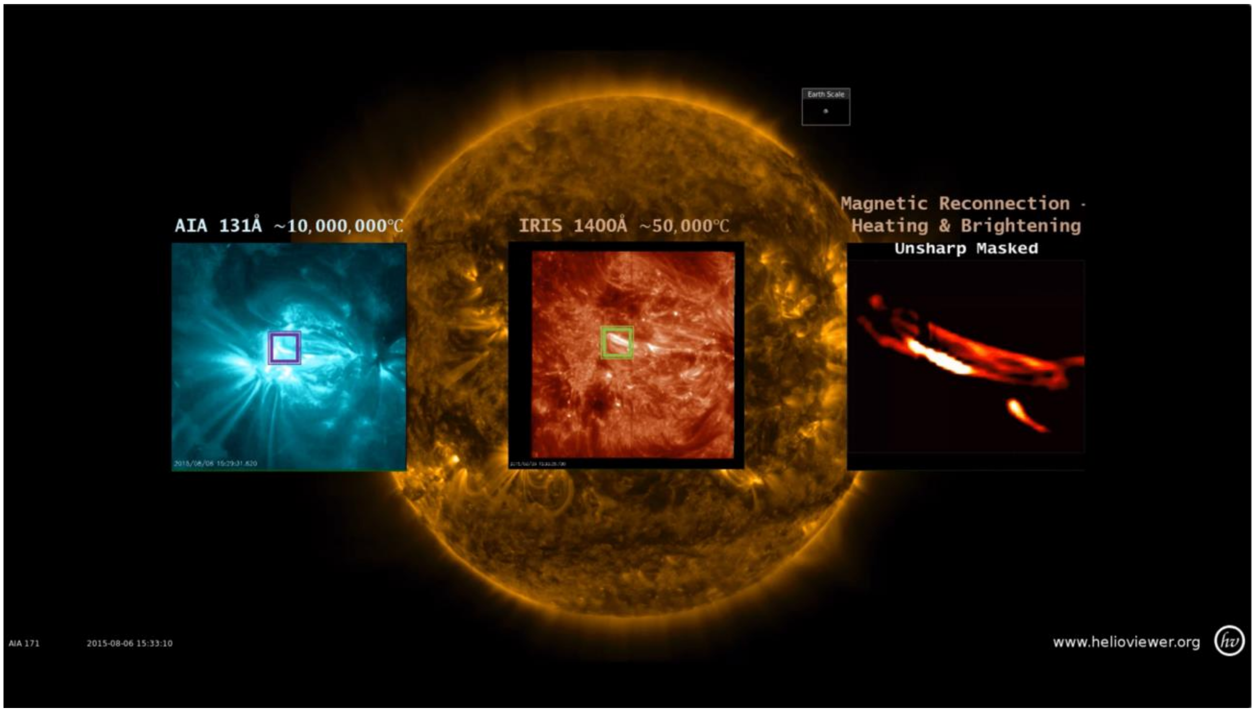

Figure 4: "A close-up of one of the loop brightenings studied in the article. Each inset frame zooms in to the selected region in the frame to its left. The frame on the far right is the most zoomed in, showing the putative nanoflare." [17]

3 Observations:

Hence, to understand and research the Sun, we shall understand the observations made by SOHO, TRACE, and Parker Solar Probe related to the coronal heating problem.

3.1 SOHO:

SOHO was launched on December 2nd, 1995 [13]. It was sent to collect information about the Sun – from its interior to its corona [13]. It found evidence of magnetic energy travelling from the Sun's surface to the corona [13]. It found that the Sun's atmosphere contains multiple isothermal, highly dynamic loop structures that could carry energy from the Sun's surface to the corona and be responsible for coronal heating [13]. These loops often appeared to be significantly hotter than the surrounding area, suggesting some form of localized heating process [13]. One of the interesting results from SOHO suggested highly ionized elements such as oxygen and magnesium in the corona [13].

SOHO had also observed various types of waves in the solar corona, including Alfvén waves and magnetohydrodynamic (MHD) waves [13]. The detection of these waves supports the theory that wave heating is a significant mechanism for coronal heating.

Moreover, SOHO also captured evidence of magnetic reconnection events in the corona, including nanoflares [13]. The energy released during these reconnection events is believed to contribute to the heating of the corona.

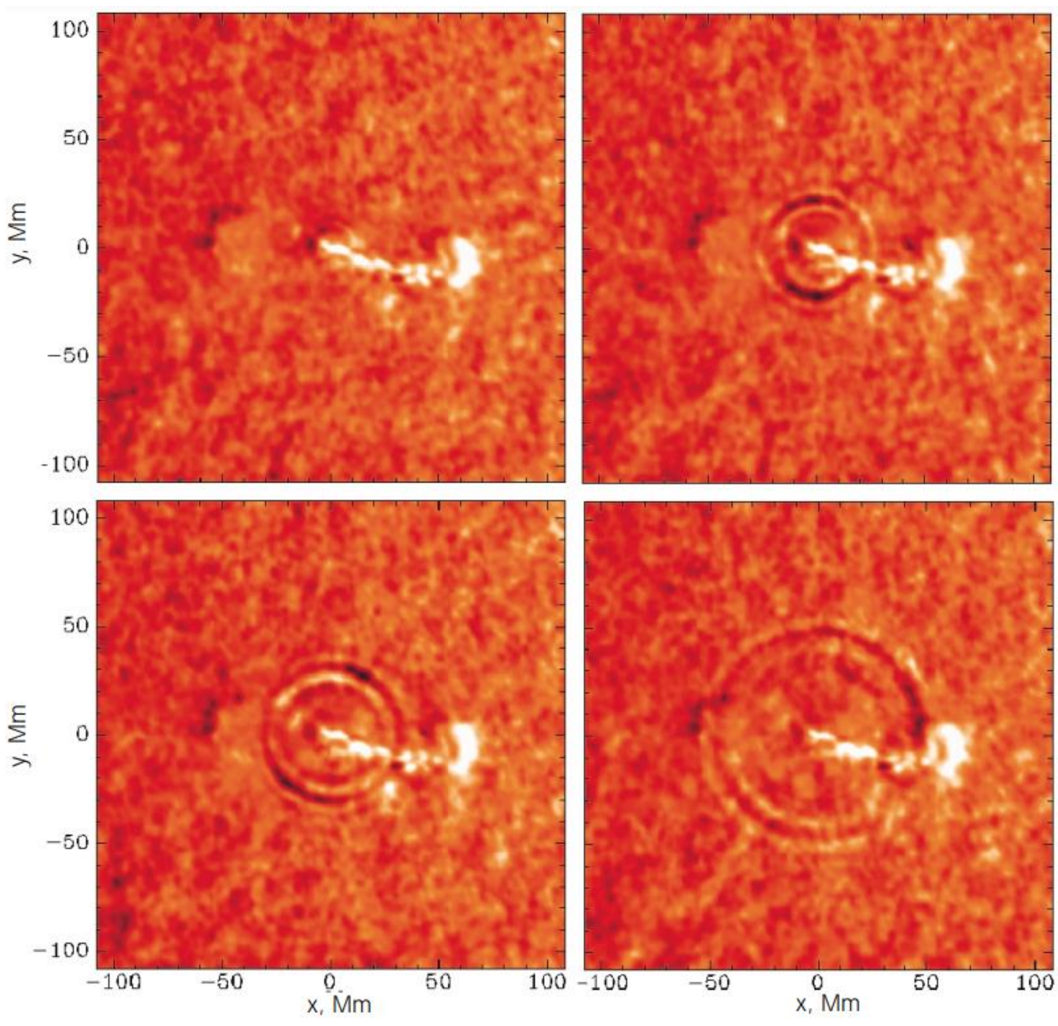

Figure 5: "Seismic waves ('sun quake') produced by a solar flare on 9 July 1996" [13]

3.2 TRACE:

TRACE was launched on April 2nd, 1998 [14]. It was sent to collect information about the solar transition region and the low corona [14]. TRACE observed tiny, frequent bright points in the corona [14], which could suggest the presence of nanoflares. These observations suggest that the cumulative effect of numerous nanoflares could maintain the high temperatures observed in the corona.

It also detected oscillations in coronal loops that have periods of under 3 mins and travel from the Sun's surface to the corona [14]. These waves are consistent with Alfvén waves. The observations of these wave helped to provide valuable data to support the wave heating theories.

Moreover, it observed numerous magnetic reconnection events [14]. Its detailed imaging helped in understanding the spatial and temporal characteristics of these reconnection processes [14].

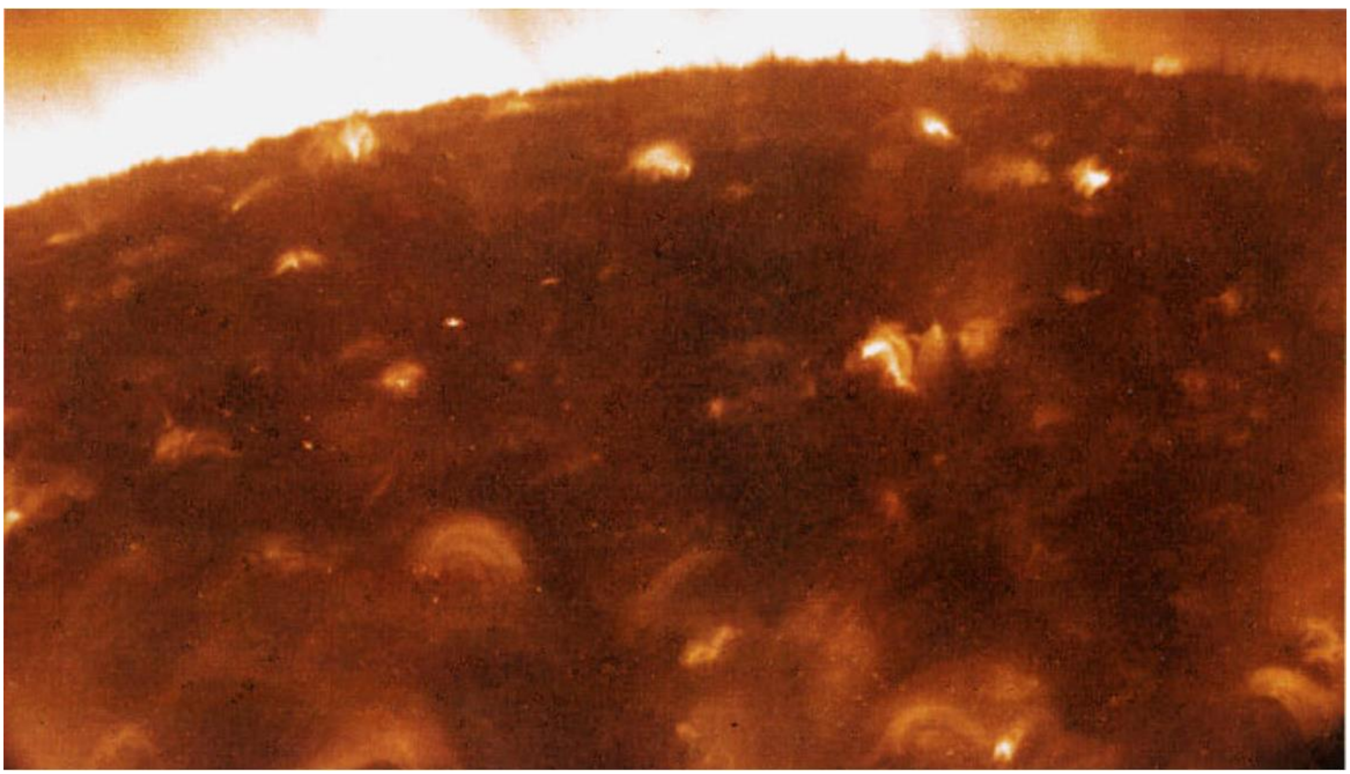

Figure 6: "X-ray bright points resolved into small loops in Fe $_{XII}$; TRACE image, 18 September 1998." [14]

3.3 Parker Solar Probe:

Parker Solar Probe was launched on August 12th, 2018 [15] and studied the Sun from about 24 million kilometers away [16]. It was sent to orbit the Sun 7 times nearer than any spacecraft and collect information about the origin and evolution of the solar wind [15]. One of the most interesting findings from the Parker Solar Probe is the observation of magnetic switchbacks — sudden flips in the direction of the solar wind's magnetic field [16]. The exact mechanism of how these switchbacks contribute to coronal heating is still under study [16].

The probe has collected evidence supporting the occurrence of nanoflares [17]. Observations of rapid, localized heating events suggest that nanoflares could contribute substantially to the heating of the corona [17].

It has also detected a variety of plasma waves in the solar wind, including Alfvén waves [18]. The probe's distance from the Sun allows it to observe these waves with high precision, providing insights into how they propagate and dissipate energy in the corona, potentially contributing to its heating.

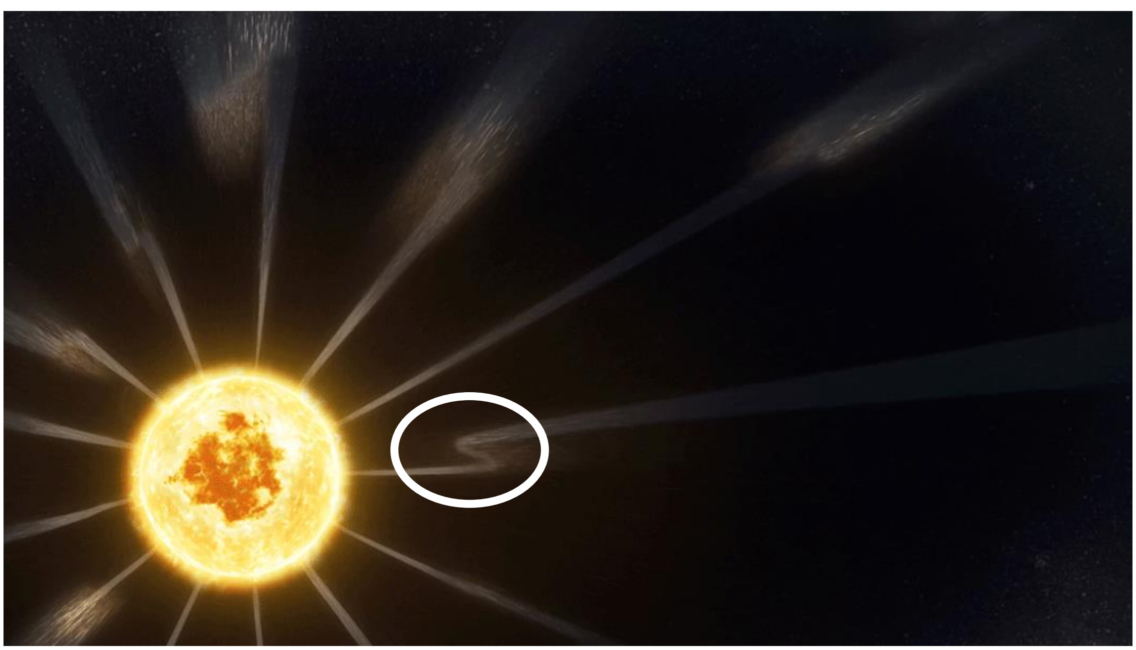

Figure 7: "Parker Solar Probe observed switchbacks — traveling disturbances in the solar wind that caused the magnetic field to bend back on itself — an as-yet unexplained phenomenon that might help scientists uncover more information about how the solar wind is accelerated from the Sun." [21]

4 Conclusion:

The coronal heating problem of the Sun remains a mystery in astrophysics. This literature review has synthesized the current understanding and prevailing theories about coronal heating, including wave heating, magnetic reconnection, and nanoflares. By analyzing data from various spacecraft, such as SOHO, TRACE, and the Parker Solar Probe, this review has provided a comprehensive overview of the mechanisms that may contribute to the extreme temperatures observed in the solar coronal region.

Wave heating, particularly through Alfvén waves, suggests that significant energy can be transported from the Sun’s lower atmosphere to the corona, with resonant absorption and phase mixing as potential dissipation mechanisms. Magnetic reconnection, where the splitting and reconnecting of magnetic field lines release energy in the form of heat, is another form of heat generation. Nanoflares, though individually small, collectively provide a substantial source of energy that could sustain the high temperatures of the corona.

Observations from SOHO, TRACE, and the Parker Solar Probe have provided valuable data supporting these theories. SOHO's detection of isothermal loop structures and various types of waves, TRACE's observations of coronal oscillations and bright points, and Parker Solar Probe's discovery of magnetic switchbacks and plasma waves all contribute to a deeper understanding of coronal heating processes.

Despite these advancements, numerous questions remain, especially concerning the exact mechanisms of energy transport and dissipation within the corona. It is becoming clear that multiple mechanisms might be responsible for the coronal region heating up and that they maybe complementing each other to raise the temperatures in the corona. The need for ongoing observations and improved models is crucial to solving the coronal heating mystery. Continued research and future missions will undoubtedly provide further insights, bringing us closer to understanding the complex and dynamic processes that heat the Sun’s outermost layer. This understanding is not only essential for solar physics but also has broader implications for our knowledge of other stars and astrophysical phenomena.

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