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Solar Plasma Temperature and Interplanetary Magnetic Field Variability during the Minima and Maxima of Solar Cycle 24

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Abstract
Solar wind is the stream of charged particles that the Sun keeps sending out into space, carrying its magnetic field along with it. This field, once it leaves the Sun, is called the interplanetary magnetic field (IMF), and it travels outward in a spiral shape known as the Parker spiral. This paper looks at two things together: how the temperature of this solar plasma changed, and how the IMF changed, across Solar Cycle 24 (2009-2019) — one of the weakest cycles recorded in over a century. Hourly and monthly data from NASA's OMNIWeb service were used, and a Continuous Wavelet Transform (CWT) was applied along with a $\mu \pm 3\sigma$ statistical boundary, so that real fluctuations could be separated from background noise. Three periods were studied closely: 2009 (the first minimum), 2014 (the maximum), and 2019 (the second minimum), along with the complete cycle. The temperature results show that plasma temperature stayed low during the two minima and rose during the maximum, following sunspot number fairly closely overall, though the years with the sharpest temperature spikes (2015 and 2017, with nine peaks each) actually came after the 2014 peak rather than during it. The IMF results tell a similar story but even more clearly: the year with the single greatest IMF variability across the whole cycle was not 2014, but 2015; one year later, with fifteen significant peaks compared to just nine in 2014 itself. Both findings point to the same idea — that the Sun's response to its own activity peak is somewhat delayed, and this delay matters for how space-weather forecasts are built around solar maxima.

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I. Introduction

The solar wind carries electrons and protons away from the Sun at speeds close to 400 km/s, and it is hot — around a million degrees Celsius near the Sun. Roughly 100 tons of this material leaves the Sun every single day. Once this plasma reaches Earth, it compresses the magnetosphere, and some of its energy leaks into the near-Earth environment, raising temperatures and driving geomagnetic activity. Geomagnetic storms themselves are graded by how negative the Dst index gets: weak storms fall between −30 and −50 nT, medium storms between −50 and −100 nT, strong storms between −100 and −250 nT, and anything beyond that counts as very strong.

Solar Cycle 24 began around January 2008 and stayed unusually quiet well into 2010. It has been described as the weakest cycle of the space age, comparable in some ways to the historically weak Cycle 14 from the early 1900s. Two solar wind properties are of particular interest here — plasma temperature and the interplanetary magnetic field. Temperature and wind speed tend to move together: faster streams run hotter, slower streams run cooler. The IMF, meanwhile, is shaped by the Sun's own magnetic field as it is dragged outward by the solar wind, and it plays a direct role in triggering storms — a southward-pointing IMF that stays in contact with Earth's field for long enough is one of the more reliable storm triggers known.

Chapters 2 and 3 of the source thesis, which covered sunspot/geomagnetic behaviour and proton density respectively, have already been published (Badgotra & Raghuwanshi, 2025a, 2025b). This paper instead focuses on the two remaining, still-unpublished parts of that work — plasma temperature and IMF — and asks a fairly simple question: do these two parameters peak exactly when the sunspot number peaks, or is there a lag?

II. Data and Methodology

Temperature data came from NASA's OMNIWeb service at hourly resolution; the raw thermal-speed values were converted into Kelvin for analysis. IMF data, also from OMNIWeb, was used at monthly resolution, covering January 2009 through December 2020. Both datasets were run through a Continuous Wavelet Transform, using the Morlet wavelet, which is well suited to signals whose frequency content changes over time. On top of this, a $\mu \pm 3\sigma$ boundary (mean plus/minus three standard deviations) was used to mark out which fluctuations counted as genuinely significant rather than background noise.

Three reference periods were examined in detail: 2009, representing the first solar minimum of the cycle; 2014, the solar maximum; and 2019, the second minimum. The full 2009-2019 span was also analysed as one continuous record, so that year-by-year peak counts could be compared across the whole cycle.

III. Solar Plasma Temperature Results

In 2009, temperature showed its clearest changes in February, March, August, and November. During the 2014 maximum, the notable months shifted to January, November, and December, with the single highest reading recorded in January, right at the start of that year. By 2019, the pattern of activity had spread across February, July, August, September, and October, with September in particular showing continuous, sustained changes rather than isolated spikes.

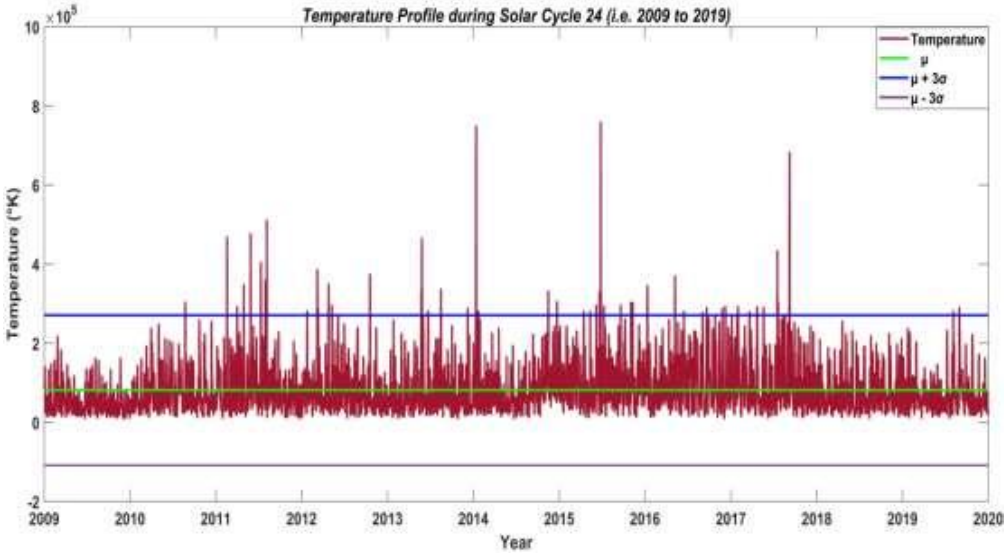

Fig. 1 — Solar plasma temperature profile across the complete Solar Cycle 24, with μ, μ+3σ, and μ−3σ bounds (source: thesis Fig. 4.10).

Looking at the whole cycle together, the number of significant CWT peaks per year came out as follows: none in 2009, seven in 2011, five in 2012, four in 2013, three in 2014, nine in 2015, seven in 2016, nine again in 2017, none in 2018, and two in 2019. What stands out immediately is that the two busiest years, 2015 and 2017, both come after the 2014 sunspot maximum rather than during it — so temperature does not simply spike exactly when sunspot activity is at its highest.

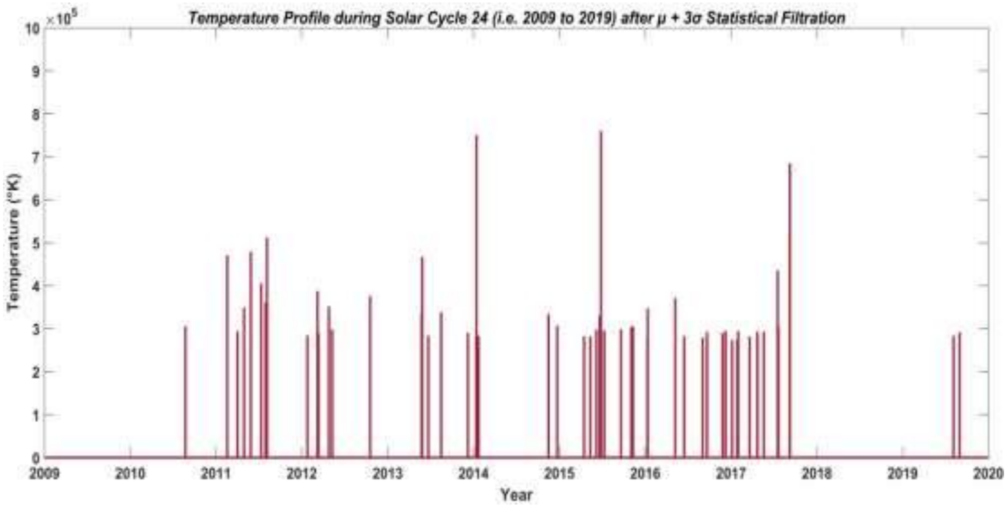

Fig. 2 — Solar plasma temperature profile after μ+3σ filtration, showing the yearly spread of significant peaks (source: thesis Fig. 4.11).

The underlying reason for all of this fits together fairly simply. At solar minimum, only a small amount of plasma makes it into the upper atmosphere, so the thermosphere cools down, which shows up as low temperature readings. This period is dominated by high-speed streams from coronal holes — fast but sparse wind, without many disruptive events. At solar maximum, the opposite happens: plasma ejections become more frequent through flares and coronal mass ejections, the thermosphere gains energy and warms, and the whole environment becomes more turbulent because of these transient events. Sunspot number and plasma temperature end up following what looks like a parallel pattern across the cycle, with temperature staying low during the rising phase (alongside low sunspot counts) and reaching its own maximum right around the sunspot maximum. Overall, this cycle's temperature readings came out lower than those of previous cycles, which lines up with Cycle 24's generally lower sunspot number.

IV. Interplanetary Magnetic Field (IMF) Results

The 2009 minimum showed its main IMF changes in January, March, July, and October, with March standing out as the sharpest of these. During the 2014 maximum, the active months were April, August, September, and December, and here the peak value landed in September rather than at the very start of the year. By the 2019 minimum, notable changes appeared in February, May, October, and the early part of November.

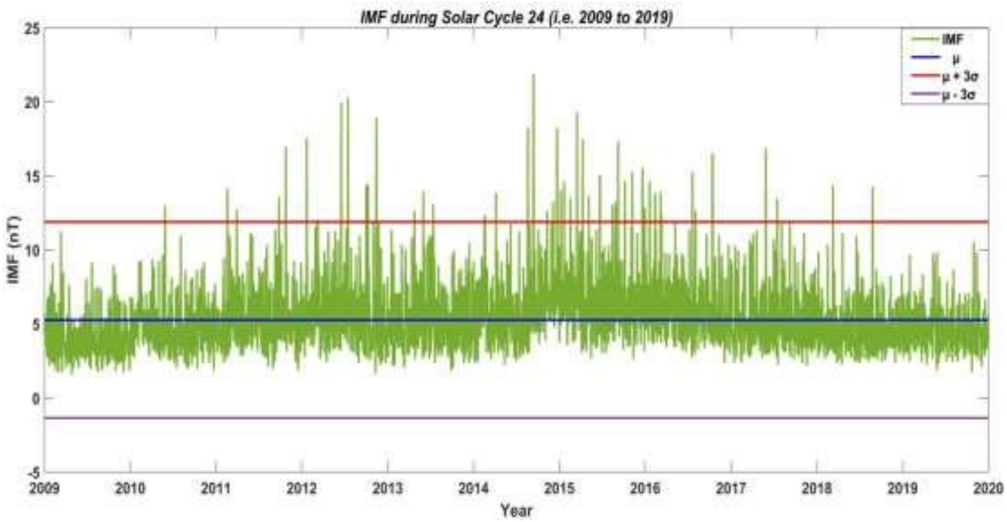

Fig. 3 — IMF profile across the complete Solar Cycle 24, with μ, μ+3σ, and μ−3σ bounds (source: thesis Fig. 5.10).

The full-cycle picture is where this chapter's most interesting result shows up. Year-by-year peak counts ran as follows: one in 2010, four in 2011, eight in 2012, three in 2013, nine in 2014, fifteen in 2015, eight in 2016, and two in 2018, with 2009 and 2019 showing no significant variation at all. The important detail here is that 2015 — not 2014 — had the single highest peak count of the entire cycle, with fifteen significant fluctuations against nine in the actual maximum year. In other words, the IMF's biggest year of change came a full year after the sunspot number itself had already peaked.

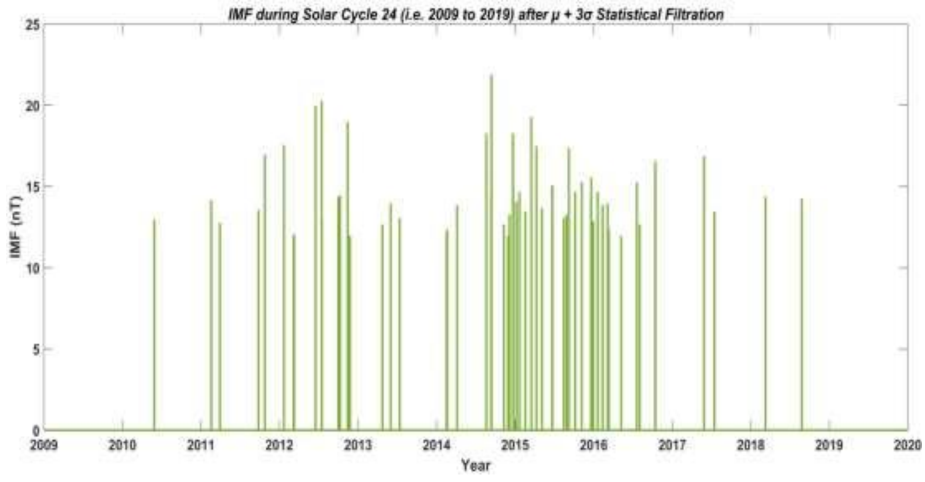

Fig. 4 — IMF profile after μ+3σ filtration, showing the yearly spread of significant peaks — note the concentration of peaks in 2015 (source: thesis Fig. 5.11).

This delay is attributed to how the magnetic field behaves right at the peak of solar activity — the field becomes more diffracted or scattered during the maximum itself, and this effect carries over and shows up more strongly the following year, in a way that still correlates with sunspot number even though it's offset in time. The Bz component specifically (the north-south orientation of the IMF) strengthens during maxima and weakens during minima, and at minimum the interplanetary medium becomes noticeably more complex, sometimes even shifting the IMF's direction back toward the Sun. Since a southward-pointing IMF combined with sustained contact with Earth's field is what actually drives geomagnetic storms, this result connects directly back to the storm patterns already documented for this cycle in earlier work on the same thesis.

V. Discussion

Put side by side, the temperature and IMF results tell a fairly consistent story. Both parameters show their sharpest activity not exactly at the 2014 sunspot maximum, but in the year or two that follow it — 2015 for the IMF specifically, and 2015/2017 for temperature. This isn't really two separate coincidences; both are downstream effects of the same underlying process, since a more complex, more energetic magnetic field at solar maximum takes some time to fully unwind, and that unwinding process is what shows up as continued high variability the following year.

At minimum, by contrast, everything settles into a simpler state together — a dipolar, weak, and stable magnetic field, cooler plasma, and fewer disruptive events, driven mainly by steady high-speed streams from coronal holes rather than by transient eruptions. This gives a fairly clean two-state picture across the cycle, with a delayed transition between the two states rather than an instant one.

From a forecasting point of view, this lag is worth paying attention to. If space-weather models assume that the most disruptive conditions line up exactly with the sunspot maximum, they may under-prepare for the year immediately following it — which, based on this cycle's data, can actually be the more turbulent one for both plasma temperature and the interplanetary field.

This overall picture of Cycle 24 as an unusually weak cycle is also supported by Indian research on the same period. Kakad *et al.* (2019), working at the Indian Institute of Geomagnetism, found that solar magnetic energy density and geomagnetic indices such as Dst and AE all showed a marked decline through Cycles 22-24, with high-latitude Joule heating down by about 31% in Cycle 24 compared to Cycle 23. Separately, Janardhan *et al.* (2018) at the Physical Research Laboratory, Ahmedabad, documented an unusually delayed and weak polar field reversal during this cycle, reinforcing the idea that the Sun's magnetic behaviour was slower to settle during Cycle 24 than in earlier cycles. More directly relevant to the present study, Jain *et al.* (2022) used radio signals from India's own Mars Orbiter Mission, recorded during the 2015 solar conjunction, to show that coronal turbulence in the post-maximum declining phase of Cycle 24 still carried a clear signature of the solar wind acceleration region — independent evidence, from an entirely different technique, that the year or two after the 2014 maximum remained physically active rather than quiet.

VI. Conclusion

This paper looked at solar plasma temperature and interplanetary magnetic field behaviour across Solar Cycle 24, using CWT-based de-noising combined with $\mu \pm 3\sigma$ statistical filtering on OMNIWeb data. Both parameters were found to be generally weaker than in earlier cycles, consistent with Cycle 24's overall low sunspot activity. More notably, both showed their peak variability not during the 2014 solar maximum itself but in the following year — 2015 recorded the highest number of significant IMF fluctuations of the whole cycle (fifteen, against nine in 2014), and temperature's two busiest years (2015 and 2017, nine peaks each) likewise came after the sunspot peak. This delayed response appears to stem from how long it takes the Sun's magnetic field to settle back down after reaching its most complex state at maximum, and it is a detail worth building into space-weather forecasting models that are otherwise calibrated tightly around the sunspot cycle itself.

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