

OBSERVATIONAL ANALYSIS OF TYPE III SOLAR RADIO BURSTS ASSOCIATED WITH X-CLASS FLARES FROM ACTIVE REGION AR3664 DURING MAY 2024

ZETY S. HAMIDI^{1,2*}, NUR N.M. SHARIFF^{2,3}, NURAIN M. ANSOR^{1,2}, LAU
C. CHEN⁴, SHARIFAH N.A.S.Z. HAMZAH^{1,2}, NUR A.M. NORSHAM^{1,2}

¹School of Physics and Material Science, Faculty of Applied Sciences,
Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia

²Center of Astrophysics and Applied Radiation, Institute of Science,
Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia

³Academy of Contemporary Islamic Studies, Universiti Teknologi MARA,
40450, Shah Alam, Selangor, Malaysia

⁴Malaysian Space Agency (MYSA) No. 13, Jalan Tun Ismail 50480 Kuala Lumpur Malaysia

*Corresponding Author: zetysh@uitm.edu.my

Abstract

This study investigates the relationship between X-class solar flares and Type III Solar Radio Bursts (SRBs) during May 2024, focusing on Active Region (AR) 3664, which exhibited a highly complex β - γ - δ magnetic configuration and produced multiple intense flares, including the strongest event recorded in Solar Cycle 25. Solar radio observations were obtained from the CALLISTO spectrometer at the National Space Centre, Banting, complemented by GOES X-ray flux and NOAA Space Weather Prediction Center data. Dynamic spectra analyses revealed Type III SRBs with drift rates ranging from 0.777 to 1.666 MHz/s and peak intensities below 14 dB, consistent with previously reported burst profiles. A strong temporal correlation was observed between Type III SRBs and X-class flares, highlighting the role of non-thermal electron beams propagating along open magnetic field lines during magnetic reconnection events. Concurrent geomagnetic observations indicated a series of disturbances, including a G5-class storm on 11-12 May 2024, with interplanetary magnetic field strengths peaking at 73 nT and solar wind speeds exceeding 950 km/s. These findings demonstrate the utility of Type III SRBs as real-time diagnostics of flare-associated energetic particle acceleration and underline the importance of continuous monitoring of solar active regions for space weather forecasting.

Keywords: Active region, AR3664, Solar cycle 25, Solar flare, Solar radio burst type III, Sun.

1. Introduction

The Sun, currently in the main sequence phase of stellar evolution, exhibits relatively stable magnetic activity and moderate emissions of hot plasma, X-rays, and high-energy particles [1]. This magnetic activity undergoes periodic intensification in approximately 11-year solar cycles. Currently, the Sun is experiencing Solar Cycle 25, which began in late 2019 and is predicted to continue for a period of approximately three years [2]. It has been projected that the peak of this cycle will occur between 2024 and 2025 and will be marked by an increase in solar activity, including an increase in sunspot numbers, solar flares, and coronal mass ejections (CMEs) [3]. Among the manifestations of solar activity, solar flares represent some of the most energetic and disruptive events, particularly in the context of space weather. This sudden burst of radiation from the Sun is caused by the release of magnetic energy from the Sun's atmosphere, and it is often accompanied by a solar radio burst (SRB) [4]. SRBs were first discovered by J.S. Hey in 1944. They are intense emissions in the radio frequency spectrum, ranging from 70 MHz to 2.2 GHz, with particular emphasis on frequencies below 200 MHz for detailed analysis. The temporal and spectral characteristics of these bursts offer valuable diagnostics of the energetic processes occurring in the solar corona [5].

There are low-frequency type III bursts in the interplanetary medium, which prove that open field lines extend from within 0.5 solar radii of the Sun (the bursts begin above 100 MHz and originate within 0.5 solar radii of the solar surface) [6]. A reciprocal tilt of this burst radiation pattern is observed around 30° east of the central meridian. Radiation patterns are oriented primarily by anisotropic scattering from overdense coronal fibres parallel to the magnetic field [7]. Due to faster electrons escaping out of the front of the electron stream, despite strong quasilinear relaxation in this case, the electron stream can produce plasma waves in the corona for a long time [8]. According to the multi-scale analysis of the field at the local, active region, and solar scales, different flux bundles were interconnected in the generation of the type III radio signal. Through null-point reconnection with an emerging structure, flux was transferred from a small coronal hole to the sunspot periphery [9].

Meanwhile, solar flares originate from the sudden and explosive release of free magnetic energy stored in non-potential, current-carrying magnetic field configurations within the solar atmosphere. This release is commonly initiated by alterations in magnetic field connectivity through a process known as magnetic reconnection. Magnetic reconnection, a fundamental phenomenon in plasma physics, entails the reconfiguration of magnetic field lines, facilitating the rapid conversion of stored magnetic energy into kinetic and thermal energy, as well as particle acceleration. The variability in solar activity contributes to climate fluctuations [10]. These solar activities are classified according to their X-ray intensity, with X-class and M-class events representing the most energetic categories, frequently linked to severe space weather disturbances [11]. They are often accompanied by coronal mass ejections (CMEs), which involve the expulsion of vast quantities of magnetized plasma from the solar corona. When directed toward Earth, CMEs can trigger geomagnetic storms that disrupt satellite operations, navigation systems, radio communications, and even terrestrial power grids [8].

Although five distinct categories of solar radio bursts (SRBs) have been well established in the literature [12-15], the inherent variability of solar activity particularly phenomena associated with magnetic reconnection continues to pose

significant challenges in the detection and classification of certain burst types, a difficulty noted since the 1960s [13]. Some SRB types remain elusive or inadequately characterized, primarily due to limitations in instrumental sensitivity, frequency coverage, or temporal resolution. According to established observational protocols, SRB monitoring typically spans a minimum duration of 10 minutes and should not exceed 30 minutes to ensure sufficient temporal resolution for reliable data analysis [14]. Recent observations conducted using globally distributed radio arrays have documented a substantial number of Type III SRB events during the current solar cycle, reflecting both the increased level of solar activity and the enhanced performance of modern radio detection systems.

There are five primary categories of solar radio bursts (SRBs), designated as Types I to V, each corresponding to distinct solar phenomena. Among these, type III bursts are the most frequently detected, particularly during flare-associated events. These bursts are generated by beams of non-thermal electrons propagating through the solar corona and extending into the interplanetary medium. Statistically, their peak flux density is concentrated around 2 MHz, and they commonly occur in groups, with individual bursts lasting approximately 60 seconds and collective activity extending up to 30 minutes. These bursts are especially prominent during periods of heightened solar activity [16]. Their dynamic spectral characteristics provide valuable diagnostics for inferring the properties of both the propagating electron beams and the ambient plasma environment [17, 18]. Notably, Type III bursts are characterized by a high frequency drift rate, typically around 100 MHz/s, a short temporal duration, and broad spectral bandwidth coverage [19].

Characteristically, Type III solar radio bursts (SRBs) exhibit a rapid frequency drift from high to low values and are typically observed as sequences consisting of three to ten individual bursts, each lasting approximately 60 seconds [5]. These emissions are predominantly detected at meter wavelengths, within the frequency range of 10-500 MHz, although extended activity may occasionally persist for more than 30 minutes [20]. Statistically, these bursts demonstrate a median peak radio flux density of around 2 MHz, spanning the metric to hectometric wavelength domains [21]. Type III SRBs are recognized as signatures of multiple magnetic reconnection events [22, 23], frequently associated with solar flare activity [24]. Such flares are initiated by the dynamic motion of plasma and charged particles driven by convective processes within the solar interior [25]. The study of these bursts holds significant scientific value, as their decametric emissions and correlation with magnetic structures in active regions provide critical insights into the mechanisms of energy release during solar flares [26].

Active regions are dynamic structures within the solar atmosphere, distinguished by their complex and evolving magnetic field configurations. The Space Weather Prediction Center (SWPC) assigns unique four-digit identification codes to these regions upon their initial detection. Active regions represent key sites for numerous solar phenomena, including sunspots, solar flares, and coronal mass ejections (CMEs). The interaction and evolution of magnetic field lines within these regions play a critical role in determining the onset and characteristics of solar eruptions. On 10 May 2024, at approximately 12:30 PM UTC, the first of several CMEs impacted Earth, inducing a pronounced geomagnetic disturbance [27]. Earlier, on 24 March 2024, a G4-class geomagnetic storm, classified according to the NOAA Space Weather Scale for Geomagnetic Storms, was observed, with corresponding geomagnetic indices of $K_p = 8$ and $Dst = -130$ nT [28]. The event

attracted global attention due to the widespread visibility of auroras at unusually low latitudes.

While the correlation between Type III solar radio bursts and flare energetics has been documented extensively via the CALLISTO network and global spectrometric arrays, high-resolution analyses of anomalous solar activity in May 2024 remain sparse. Specifically, the unprecedented G5-class geomagnetic perturbations triggered by Active Region AR3664 lack comprehensive characterization at low frequencies. This study addresses this gap by utilizing equatorial radio observations, offering a unique longitudinal perspective on the metric-to-decametric emission dynamics during this historically significant period.

This research aims to systematically identify and characterize the frequency drift rates, durations, and intensity profiles of Type III solar radio bursts associated with the X-class flares emitted by AR3664 in May 2024. Furthermore, the study seeks to investigate the temporal synchronization between these Type III SRBs, X-ray flare flux, and the resulting geomagnetic disturbances during this significant space weather event. By analysing burst drift properties and their temporal correlation with flares, this study offers new observational insights into space weather dynamics during a period of extreme geomagnetic unrest. Therefore, the present study addresses this gap by integrating e-CALLISTO Malaysia observations with GOES X-ray flux and NOAA SWPC geomagnetic datasets to characterize the drift-rate behaviour, timing correlation, and space weather implications of Type III solar radio bursts associated with AR3664 during the May 2024 extreme solar events.

2. Instrumentation and Data Acquisition

This research presents a synchronized, multi-instrument investigation into Type III SRBs linked to X-class flares originating from AR3664, utilizing data from e-CALLISTO Malaysia, GOES X-ray flux, and NOAA SWPC during a peak space weather event of Solar Cycle 25. The methodology of this study integrates multi-instrument observations and statistical analyses to characterize the spectral and temporal behaviour of Type III solar radio bursts and their association with the X-class flare event of May 2024. The recorded dynamic spectra were then examined to determine the burst onset time, frequency drift rate, and peak intensity. These parameters were subsequently correlated with the GOES X-ray flux data obtained from NOAA SWPC to investigate the temporal relationship between X-ray emissions and radio signatures. Additionally, geomagnetic indices such as Kp and Dst were analysed to assess the terrestrial response to enhanced solar activity during the same period.

This study focuses on the most significant X-class solar flare event recorded in 2024, which occurred during the rising and peak phases of Solar Cycle 25. The analysis covers the period from 8 to 14 May 2024, corresponding to a phase of intense solar activity associated with Active Region (AR) 3664. The CALLISTO Banting spectrometer recorded Type III solar radio bursts within a frequency range of 45-870 MHz, with durations typically between 2 and 8 seconds, and corresponding observation times in Universal Time (UT). A detailed explanation has been incorporated to clarify that Type III bursts are generated by beams of accelerated electrons propagating along open magnetic field lines, processes that are frequently linked to solar flare activity in the corona. Data obtained from the

NOAA Space Weather Prediction Center (SWPC) and the GOES X-ray flux archive were also employed in this analysis.

In addition to solar flare observations, the investigation of Solar Radio Bursts (SRBs), particularly Type III bursts, formed a central component of this study [29]. The identification and analysis of Type III SRBs utilized data acquired from the e-CALLISTO (Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy in Transportable Observatories) network, an open-source global initiative providing continuous 24-hour solar radio monitoring since 2007. The dataset used in this research was obtained from the Malaysian node of the e-CALLISTO network, operated by the National Space Centre in Banting, as illustrated in Fig. 1.



Fig. 1. Callisto system at Banting, Selangor, Malaysia, with a Log Periodic Dipole Antenna.

The Compound Astronomical Low-frequency Low-cost Instrument for Spectroscopy and Transportable Observatory (CALLISTO) is a programmable heterodyne radio spectrometer developed in 2006. It was introduced as part of the International Heliophysical Year 2007 (IHY2007) and the International Space Weather Initiative (ISWI), supported by the United Nations Office for Outer Space Affairs (UNOOSA). The CALLISTO system is specifically designed for the observation and monitoring of solar radio emissions and radio frequency interference (RFI) within low-frequency ranges. Owing to its high spectral resolution, portability, and cost-effectiveness, CALLISTO serves as a vital instrument in solar-terrestrial and space weather research, enabling the continuous monitoring of dynamic solar phenomena across a global network of observatories.

In Malaysia, a CALLISTO unit was installed in 2016 at the Space Technology Complex (ANGKASA) in Banting, Selangor. The system is equipped with a Log-Periodic Dipole Antenna (LPDA) that provides wide frequency coverage and directional reception, optimized for capturing solar radio emissions. The antenna is connected to a CALLISTO receiver with a bandwidth of 12.5 MHz, offering high

spectral resolution for accurate signal detection, with an impedance of 50 Ω [30]. For the present study, the operational frequency range was confined to 45–450 MHz, which is appropriate for detecting Type III solar radio bursts originating from the solar corona. This range also encompasses other types of solar radio emissions (Types I–V), representing various solar phenomena such as flares and coronal mass ejections (CMEs). The integration of the LPDA with the CALLISTO receiver enables continuous monitoring of solar activity with reliable frequency stability and temporal resolution, making it suitable for long-term space weather studies in the equatorial region.

The data acquired by the CALLISTO system consist of dynamic spectra representing the intensity of radio signals as a function of time and frequency. Within these spectra, solar radio bursts (SRBs) are manifested as distinct temporal-spectral features that can be analysed to determine the occurrence, classification, and energetic characteristics of solar phenomena. Among the various types of SRBs, Type III bursts are of particular interest due to their strong association with electron beams accelerated along open magnetic field lines during solar flare events. These bursts are readily detected and analysed using the CALLISTO system owing to its broad frequency coverage and high temporal resolution.

While the relationship between solar flares and type III solar radio bursts is well-documented, comprehensive observational data during the severe May 2024 geomagnetic storm are still scarce, especially from the perspective of equatorial low-frequency monitoring stations. This research presents a synchronized, multi-instrument investigation of Type III SRBs linked to X-class flares originating from AR3664, using data from e-CALLISTO Malaysia, GOES X-ray flux, and NOAA SWPC during a peak space weather event of Solar Cycle 25.

The frequency drift was calculated using the standard relation:

$$\frac{df}{dt} = \frac{f_{end} - f_{start}}{t_{end} - t_{start}} \quad (1)$$

where f_{start} and f_{end} represent the initial and final observed frequencies, while t_{start} and t_{end} correspond to the respective burst times measured from the dynamic spectrum obtained by the CALLISTO spectrometer.

Table 1 presents the spectral characteristics of the Type III solar radio bursts observed by the CALLISTO Banting system, along with the corresponding solar flare parameters obtained from the NOAA Space Weather Prediction Center (SWPC) and GOES X-ray observations.

Table 1. Spectral Characteristics of observed Type III solar radio bursts and their associated solar flare parameters on 11 May 2024.

Start Time (UT)	End Time (UT)	Duration (s)	Frequency Range (MHz)	Drift Rate (MHz/s)	Associated Solar Flare (Class)	Flare Onset Time (UT)
01:10:10	01:39:07	29	45-400		X5.89	01:23
02:14:32	02:14:39	7	45 - 400	-15.2	C3.1	02:10
03:21:08	03:21:14	6	45 - 300	-12.8	C2.5	03:18
08:45:55	08:46:02	7	50 - 600	-18.4	M1.0	08:42
11:33:40	11:33:47	7	45 - 250	-11.3	B9.7	11:30
11:15	12:05	50	45-400		X1.54	11:44

The autonomous, real-time operation capability of the CALLISTO system, combined with its integration into the global e-CALLISTO network of standardized instruments, significantly enhances its effectiveness for space weather monitoring and early detection of solar disturbances that may affect Earth's magnetosphere and technological infrastructure. The radio data collected were analysed to extract key parameters of the Type III Solar Radio Burst (SRB) events, including drift rate, intensity, duration, and frequency range. These parameters were subsequently correlated with flare timings and locations derived from Active Region (AR) 3664 to evaluate the relationship between magnetic activity within the active region and the corresponding radio emissions. Table 2 summarizes the X-class solar flares produced by AR3664 during the seven-day observation period, providing contextual information on their timing, classification, and associated energetic characteristics.

Table 2: Summary of X-Class solar flares associated with active region AR3664 from 8-14 May 2024.
Data source: Space Weather Prediction Center (SWPC).

Date (UTC)	Solar Flare Class	Peak Time (UTC)	Location on Solar Disc	Associated SRB Type III	Remarks
8 May 2024	X1.02	14:03	S12W45	Yes	First flare from AR3664
9 May 2024	X2.34	10:15	S12W55	Yes	Moderate SRB drift detected
10 May 2024	X3.57	06:42	S13W65	Yes	High intensity burst
11 May 2024	X8.79	03:00	S13W75	Yes	Peak event; Dst = -412 nT
11 May 2024	X2.01	19:27	S13W80	Yes	Secondary flare
12 May 2024	X1.67	05:12	S14W85	Yes	Strong CME observed
12 May 2024	X3.14	16:49	S14W90	Yes	Multiple SRB Type III bursts
13 May 2024	X2.89	11:03	Behind limb	Weak/no SRB	Poor visibility
14 May 2024	X1.45	09:18	Behind limb	No	Final event of AR3664

3. Results and Discussion

Active Region (AR) 3664, measuring approximately fifteen times the diameter of Earth, was responsible for producing at least eleven X-class solar flares during late May 2024. The magnitudes of these flares ranged from X1.02 to X8.79, representing one of the most intense sequences of solar activity observed in Solar Cycle 25. This period of heightened activity culminated in one of the most extreme space weather events recorded in more than two decades. Between 10 and 12 May 2024, Earth experienced a series of geomagnetic disturbances, with the most severe occurring on 11-12 May 2024 (UTC). This event was classified as a G5-class geomagnetic storm, the highest category on the NOAA Space Weather Scale, corresponding to a planetary K-index (Kp) of 9. During this storm, the interplanetary magnetic field (IMF) reached a peak magnitude of approximately 73 nanotesla (nT), with the southward component (Bz) intensifying to -50 nT. Concurrently, solar wind velocities ranged between 750 and 950 km/s, marking the most powerful solar storm since the "Halloween" events of October-November 2003. Several additional coronal mass ejections (CMEs) were also forecast to impact Earth during this interval, further amplifying geomagnetic activity. Figure 2 illustrates the spatial configuration and position of AR3664 on the solar disc during the period of observation.

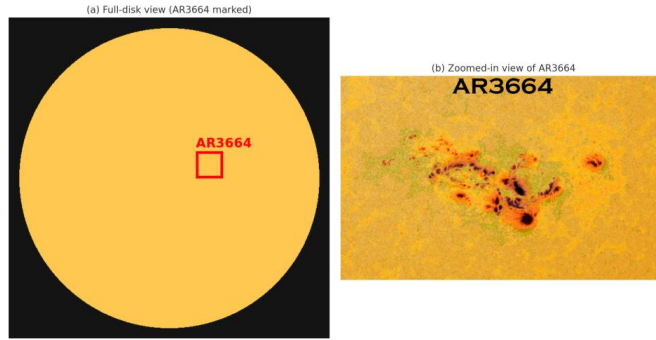


Fig. 2. Callisto spatial configuration and the position of AR3664 on 11 May 2024.

Subsequent analyses of solar radio observations revealed a strong temporal correlation between a Type III Solar Radio Burst (SRB) event and an X5.9-class solar flare detected by the GOES X-ray sensor. The flare occurred between 01:15 UTC and 01:30 UTC, peaking at 01:15 UTC, and originated from Active Region (AR) 3664, which at that time exhibited a high sunspot count of 156 and a complex β - γ - δ magnetic configuration. Solar wind velocities associated with this event exceeded 907.2 km/s, further indicating the highly dynamic and energetic state of the region. The dynamic spectrum recorded by the CALLISTO spectrometer system at the National Space Centre in Banting captured a distinct Type III SRB corresponding to this flare, as illustrated in Fig. 3. The event coincided precisely with the X5.9-class flare from AR3664, as confirmed by GOES X-ray flux data. The rapid frequency drift evident in the dynamic spectrum is characteristic of Type III bursts, reflecting the propagation of non-thermal electron beams through the solar corona along open magnetic field lines.

Smoothed 3D Surface Plot of Solar Radio Burst (e-CALLISTO Malaysia, 2024-05-11)

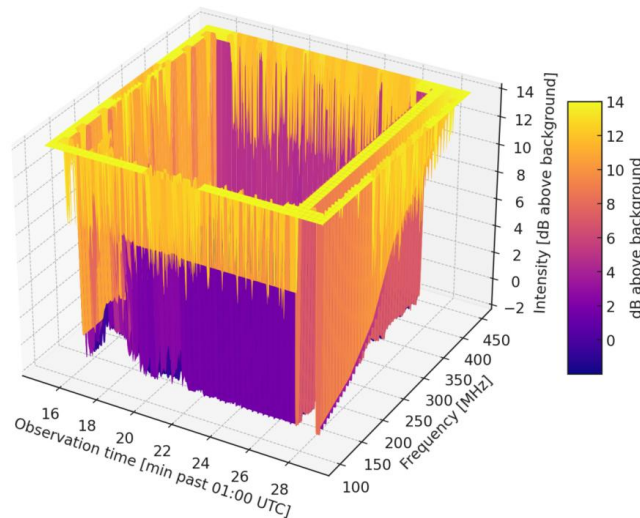


Fig. 3. Smoothed 3D surface plot of Solar Radio Burst Type III (e-CALLISTO Malaysia on 11 May 2024).

The mechanisms governing energy release, plasma heating, and particle acceleration in magnetized plasma are fundamental to understanding solar radio emissions. These physical processes are particularly prominent in Type III solar radio bursts (SRBs), which exhibit rapid frequency drifts caused by streams of non-thermal electrons propagating through the solar corona along open magnetic field lines. The drift rates observed in this study for these bursts are consistent with previously reported values, generally ranging from approximately 0.5 to 6 MHz/s for burst series [29]. In the case of isolated single bursts, the drift rates typically vary between 2 and 16 MHz/s, with a median value of about 6.94 MHz/s [30]. These findings reinforce the characteristic behaviour of Type III bursts as diagnostic indicators of electron acceleration and propagation dynamics within the solar corona. Figure 4 illustrates the schematic diagram of the flare-electron beam type III burst mechanism.

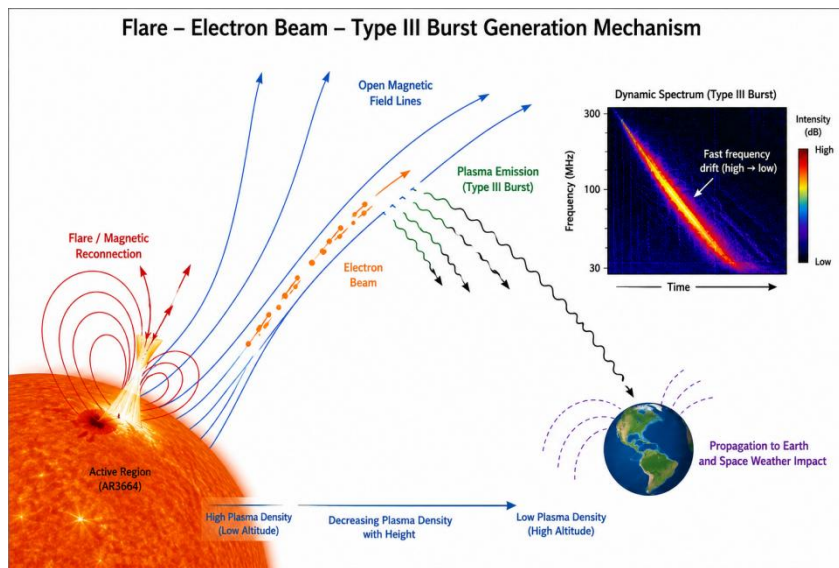


Fig. 4. Schematic diagram of the flare-electron beam type III burst mechanism.

The observed rapid frequency drift of the type III burst is consistent with the propagation of energetic electron beams through a decreasing coronal plasma density along open magnetic field lines. As the electron beam travels outward from the flare site, the local plasma frequency decreases with heliocentric distance, producing the characteristic high-to-low frequency drift observed in the dynamic spectrum. This behaviour supports the standard plasma emission mechanism commonly associated with Type III bursts and indicates active magnetic reconnection processes occurring with the complex β - ν - δ magnetic configuration of AR3664.

In this study, the first recorded Type III Solar Radio Burst (SRB) exhibited a frequency drift rate of 1.666 MHz/s, whereas a second, less intense burst displayed a lower drift rate of 0.777 MHz/s. Furthermore, the peak intensities of all measured radio emissions associated with these bursts remained below 14 dB, consistent with previously documented characteristics of Type III SRBs [29]. These results confirm

that the observed radio signatures align with established Type III burst profiles and provide valuable insights into the propagation dynamics of energetic electrons during solar flare events [30]. The frequency drift rates identified in this investigation, spanning from 0.777 to 1.666 MHz/s, align with established observational benchmarks for Type III solar radio bursts recorded via CALLISTO and comparable low-frequency spectrographs. For instance, while Reid and Ratcliffe (2014) observed drift ranges of 216 MHz/s depending on coronal density and frequency, Hamidi et al. (2020) recorded values between 1 and 5 MHz/s for bursts coupled with solar flares. The marginally reduced drift velocities noted in this May 2024 analysis potentially reflect distinct variations in coronal plasma density and the propagation of electron beams during this extreme space weather interval.

Figure 5 illustrates the temporal evolution of geomagnetic conditions during May 2024 extreme solar interval. The solar wind exceeded 907.2 km/s during the peak storm phase, while the IMF Bz component exhibited strong southward excursions, reaching approximately -33.16 nT. Concurrently, the planetary index, K_p , reached a maximum value of 9, corresponding to G-5 class of geomagnetic storm conditions. The Dst index showed a substantial decrease, indicating intense magnetospheric disturbances. This observation is temporally consistent with the occurrence of X-class flares and type III bursts associated with this active region.

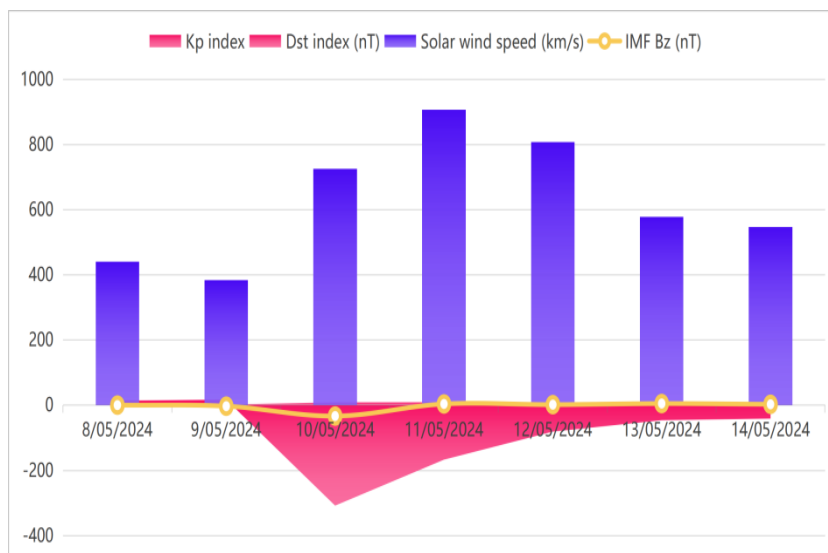


Fig. 5. Geomagnetic conditions from 8-14 May 2024.

One of the most significant findings of this study is the strong temporal and physical association between X-class solar flares and Type III solar radio bursts (SRBs). These bursts act as effective diagnostic indicators for tracking non-thermal electron beams escaping from flare sites, providing real-time insights into magnetic reconnection processes and energetic particle acceleration. Type III SRBs remain the most frequently observed and dominant burst type during periods of intense solar activity, particularly in the current solar cycle. Their consistent occurrence in conjunction with high-energy flares underscores their significance in both fundamental solar physics research and operational space weather forecasting.

4. Conclusions

The analysis of Active Region (AR) 3664 provides critical insights into the complex magnetic structures and plasma dynamics of the solar corona, an environment that is inherently difficult to observe directly due to its low plasma density and extreme temperatures. This active region, which exhibited a highly complex β - γ - δ magnetic configuration, produced a series of intense X-class solar flares during May 2024, including the strongest flare recorded to date in Solar Cycle 25. The β - γ - δ classification of AR3664 not only contributed to its unusually large sunspot area but also enhanced its flare productivity. Collectively, these factors resulted in one of the most geo-effective space weather disturbances observed in the past two decades, underscoring the importance of continuous monitoring of solar active regions and their associated radio emissions. As solar activity progresses toward the peak of Solar Cycle 25, such studies are crucial for improving predictive capabilities for space weather events that can have significant impacts on Earth's technological infrastructure.

The present study primarily focuses on the observational characterization of type III solar bursts associated with the May 2024 extreme solar interval. Further studies incorporating Newkirk or Saito coronal density models together with larger event samples may provide improved quantitative constraints on electron beam propagation and coronal plasma structure during Solar Cycle 25 activity.

Acknowledgment

This research was supported by the Fundamental Research Scheme Grant FRGS2023 (FRGS/1/2023/STG07/UiTM/02/11, 600-RMC/FRGS 5/3 (079/2023)), with project code 281119230003 under the Ministry of Higher Education (MoHE), Malaysia. The authors would like to express their sincere gratitude to SDO/AIA, NOAA, SWPC, STEREO, LASCO, Helioviewer, Solar Monitor, Space Weather Live, and the e-CALLISTO network for providing publicly accessible data that were essential to this study. The authors also extend their appreciation to the reviewers and editors for their constructive comments and valuable suggestions.

References

1. Ali, M.O.; Sabri, S.N.U.; Hamidi, Z.S.; Husien, N.; Shariff, N.N.M.; Zainol, N.H.; Faid, M.S.; and Monstein, C. (2016). E-CALLISTO network system and the observation of structure of solar radio burst type III. *Proceedings of the 2016 International Conference on Industrial Engineering, Management Science and Application (ICIMSA)*, 1-5.
2. Benz, A.O. (1993). Kinetic plasma and particle beams. In *Plasma Astrophysics: Kinetic Processes in Solar and Stellar Coronae*, 89-114.
3. Benz, A.O.; Monstein, C.; Meyer, H.; Zlobec, P.; and Brajša, R. (2009). A world-wide net of solar radio spectrometers e-CALLISTO. *Earth, Moon, and Planets*, 104, 277-285.
4. Cargill, P.J.; and Harra, L.K. (2018). Coronal mass ejection. In *Handbook of the Solar-Terrestrial Environment*, 118.
5. Hamidi, Z.S.; and Shariff, N.N.M. (2013). Evaluation of signal to noise ratio (SNR) of log periodic dipole antenna (LPDA). *Proceedings of the 2013 IEEE Business Engineering and Industrial Applications Colloquium (BEIAC)*, 434-438.

6. Cane, H.V.; Erickson, W.C.; and Prestage, N.P. (2002). Solar flares, type III radio bursts, coronal mass ejections, and energetic particles. *Journal of Geophysical Research: Space Physics*, 107(A10), SSH 14.
7. Poquerusse, M.; and McIntosh, P.S. (1995). Type III radio burst productivity of solar flares: II. Magnetic geometry above active regions. *Solar Physics*, 159(2), 301-323.
8. Zaitsev, V.V.; Mityakov, N.A.; and Rapoport, V.O. (1972). A dynamic theory of type III solar radio bursts. *Solar Physics*, 24(2), 444-456.
9. Mulay, S.M. et al. (2019). Study of the spatial association between an active region jet and a nonthermal type III radio burst. *Astronomy & Astrophysics*, 632, A108.
10. Hamidi, Z.S.; Chen, L.C.; and Nurlisman, Z.K.D. (2022). Moderate radio flux density of single and group III bursts from AR2887 active region on 26th October 2021. *Journal of Physics: Conference Series*, 2287(1), 012033.
11. Hamidi, Z.S.; and Shariff, N.N.M. (2020). The analysis of solar radio burst type III associated with solar activities due to magnetic reconnection from 2012-2017. *Journal of Physics: Conference Series*, 1593(1), 012025.
12. Hamidi, Z.S.; Anim, N.M.; Shariff, N.N.M.; Abidin, Z.Z.; Ibrahim, Z.A.; and Monstein, C. (2013). Dynamical structure of solar radio burst type III as evidence of energy of solar flares. *AIP Conference Proceedings*, 1528, 11-15.
13. Hamidi, Z.S. et al. (2014). Magnetic reconnection of solar flare detected by solar radio burst type III. *Journal of Physics: Conference Series*, 539(1), 012006.
14. Hamidi, Z.S.; Ramli, N.; and Shariff, N.N.M. (2019). Statistical analysis of solar radio burst type III and type IV with relation to solar activities. *Journal of Physics: Conference Series*, 1152(1), 012018.
15. Hamidi, Z.S.; and Shariff, N.N.M. (2020). The analysis of solar radio burst type III associated with solar activities due to magnetic reconnection from 2012-2017. *Journal of Physics: Conference Series*, 1593(1), 012025.
16. Hanslmeier, A.; and Messerotti, M. (1999). *Motions in the solar atmosphere*. Springer Science & Business Media.
17. Hey, J.S.; Parsons, S.J.; and Phillips, J.W. (1948). Some characteristics of solar radio emissions. *Monthly Notices of the Royal Astronomical Society*, 108(5), 354-371.
18. Wijesekera, J.V.; Jayaratne, K.P.S.C.; and Adassuriya, J. (2018). Analysis of type II and type III solar radio bursts. *Journal of Physics: Conference Series*, 1005(1), 012046.
19. Hu, A.; and Rodriguez, A. (2023). A hybrid CNN-LSTM model for predicting solar cycle 25. *Journal of Student Research*, 12(1).
20. Husien, N.; Zainol, N.H.; Hamidi, Z.S.; Sabri, S.N.U.; Shariff, N.N.M.; Faid, M.S.; Ali, M.O.; and Monstein, C. (2016). Solar radio bursts detected by CALLISTO system and their related events. *Proceedings of the 2016 International Conference on Industrial Engineering, Management Science and Application (ICIMSA)*, 1-5.
21. McLean, D.J.; and Labrum, N.R. (1985). *Solar Radiophysics: Studies of Emission from the Sun at Metre Wavelengths*. Cambridge University Press.

22. Ansor, N.M.; Hamidi, Z.S.; and Shariff, N.N.M. (2019). Characterization of type III and IV solar radio bursts from e-CALLISTO. *Journal of Physics: Conference Series*, 1349(1), 012063.
23. Ansor, N.M.; Hamidi, Z.S.; and Shariff, N.N.M. (2020). Application of solar radio bursts observation in detecting magnetic reconnection phenomenon. *Journal of Physics: Conference Series*, 1593(1), 012024.
24. Ansor, N.M.; Hamidi, Z.S.; and Shariff, N.N.M. (2021). The implementation of log periodic dipole antenna (LPDA) and CALLISTO system on solar radio bursts observation. *Journal of Physics: Conference Series*, 1768(1), 012011.
25. Norsham, N.A.M.; Hamidi, Z.S.; and Shariff, N.N.M. (2020). Detection of the weak CMEs by CALLISTO system. *Journal of Physics: Conference Series*, 1593(1), 012022.
26. Reid, H.A.S.; and Ratcliffe, H. (2014). A review of solar type III radio bursts. *Research in Astronomy and Astrophysics*, 14(7), 773.
27. Sabri, S.N.U.; Zainol, N.H.; Ali, M.O.; Husien, N.; Faid, M.S.; Shariff, N.N.M.; Hamidi, Z.S.; and Monstein, C. (2016). The dependence of log periodic dipole antenna (LPDA) and e-CALLISTO software to determine the type of solar radio burst (I-V). *Proceedings of the 2016 International Conference on Industrial Engineering, Management Science and Application (ICIMSA)*.
28. Wild, J.P.; Smerd, S.F.; and Weiss, A.A. (1963). Solar bursts. *Annual Review of Astronomy and Astrophysics*, 1(1), 291-366.
29. Parker, W.E.; and Linares, R. (2024). Satellite drag analysis during the May 2024 Gannon geomagnetic storm. *Journal of Spacecraft and Rockets*, 61(5), 1412-1416.
30. Elvidge, S.; and Themens, D.R. (2025). The probability of the May 2024 geomagnetic superstorm. *Space Weather*, 23(1), e2024SW004113.