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EVOLUTION AND FLARE ACTIVITY OF CARRINGTON-CLASS SOLAR ACTIVE REGION NOAA 13664 AND ITS IMPACT ON THE EARTH

N.M. Kondrashova, M.M. Pasechnik, S.M. Osipov, M.I. Pishkalo

Main Astronomical Observatory of the NAS of Ukraine,
Kyiv, Ukraine

kondr@mao.kiev.ua; rita@mao.kiev.ua; osipov@mao.kiev.ua; pish@mao.kiev.ua

ABSTRACT. We have analyzed the temporal and spatial evolution and the flare activity of the active region (AR) NOAA 13664 and its impact on the Earth. The large group of sunspots that formed it definitely belonged to the Carrington class. The region appeared in the southern hemisphere of the solar disk on 2024 May 1. The number of sunspots was growing rapidly and its area increased from 40 to 2400 millionths of the solar hemisphere. The AR had a complex multipolar configuration of the magnetic field beginning on May 7. On May 8, solar flares of intensity X1.0, M8.7 and M9.9 took place in it, which caused coronal mass ejections (CMEs). These CMEs reached the Earth on May 10, causing strong and extreme geomagnetic storms with bright and very long-lasting auroras. The event was classified as a G5 geomagnetic storm, making it the most intense storm since 2003. On May 9-11, flares of intensity X2.3, X1.5, X4, and X5.8 occurred, each of which caused a CME. The radiation from the X5.8 flare caused a deep shortwave radio blackout over the Pacific Ocean. On May 14, an X8.7-class flare occurred on the western limb of the Sun, the most powerful in solar cycle 25 at that time. The CME that formed caused a short-wave radio blackout over America.

On May 9 during observations at the Ernest Gurtovenko solar horizontal telescope of the Main Astronomical Observatory of the National Academy of Sciences of Ukraine the X2.3 flare spectrograms in its main phase were obtained.

The active region 13664 passed beyond the solar disk and returned on May 29. It has been renumbered as NOAA 13697. On May 31 and June 1 AR produced three X-flares: X1.1, X1.4, and X1.0. Each of them formed CMEs, which reduced the power of shortwave transmissions at all frequencies below 30 MHz. Radiation from M9.8-class flare on June 8 ionized the upper part of the Earth's atmosphere, causing a deep shortwave radio blackout in the western Pacific Ocean.

On June 24 AR13664 returned again. This was its 3rd trip across the solar disk. It was renamed as NOAA 13723. Although the sunspot region was already fragmented to a fraction of its former size, its magnetic component continued to produce powerful solar flares. On June 23, M9.3-class flare occurred in AR, CME from which caused a moderate shortwave radio blackout in Western Europe and Africa.

In total, AR13664 produced 198 C-class, 87 M-class, and 17 X-class flares during its three passes across the Sun's disk.

By studying in detail the evolution of this hyperactive region NOAA 13664 and its impact on Earth, we are improving our ability to predict solar activity and warn of the extreme space weather events it causes.

Keywords: active regions, sunspots, solar flares, coronal mass ejections, geomagnetic storms.

АНОТАЦІЯ. Ми проаналізували часову та просторову еволюцію та спалахову активність активної області (АО) NOAA 13664 та її вплив на Землю. Велика група сонячних плям, яка її утворила, безумовно належала до класу Керрінгтона. Область з'явилася в південній півкулі сонячного диска 1 травня 2024 р. Кількість сонячних плям швидко зростала, їх площа збільшилася від 40 до 2400 мільйонних частин сонячної півкулі. Починаючи з 7 травня АО мала складну мультиполярну конфігурацію магнітного поля. 8 травня в ній відбулися сонячні спалахи інтенсивністю X1.0, M8.7 і M9.9, які викликали корональні викиди маси (КВМ). Ці КВМ досягли Землі 10 травня, спричинивши сильні та екстремальні геомагнітні бурі з яскравими та дуже тривалими полярними сяйвами. Ця подія була класифікована як геомагнітна буря G5, що робить її найсильнішою бурею з 2003 року. 9-11 травня відбулися спалахи інтенсивністю X2.3, X1.5, X4 та X5.8, кожен з яких викликав КВМ. Випромінювання від спалаху X5.8 спричинило глибоке короткохвильове радіозатемнення над Тихим океаном. 14 травня на західному лімбі Сонця відбувся спалах класу X8.7, на той момент найпотужніший у 25-му сонячному циклі. КВМ, яке утворилося, спричинило короткохвильове радіо-затемнення над Америкою.

9 травня під час спостережень на сонячному горизонтальному телескопі імені Ернеста Гуртовенка Головної астрономічної обсерваторії НАН України отримано спектрограми спалаху X2.3 у його головній фазі.

Активна область 13664 вийшла за межі сонячного диска і повернулася 29 травня. Вона була перенумерована як NOAA 13697. 31 травня та 1 червня AR створила три X-спалахи: X1.1, X1.4 і X1.0. Кожен з них утворив КВМ, які зменшили потужність короткохвильових передач на всіх частотах нижче 30 МГц. Радіація від спалаху класу M9.8 8 червня іонізувала верхню частину земної атмосфери, спричинивши глибоке короткохвильове радіозатемнення в західній частині Тихого океану.

24 червня AR13664 знову повернулася. Це була її третя подорож по сонячному диску. Її перенумерували на NOAA 13723. Хоча АО вже була фрагментована до частки свого колишнього розміру, її магнітний компонент продовжував створювати потужні сонячні спалахи. 23 червня в АО стався спалах M9.3, КВМ від якого спричинив помірне короткохвильове радіовимкнення в Західній Європі та Африці.

Загалом AR13664 під час своїх трьох проходів по диску Сонця створила 198 спалахів класу C, 87 спалахів класу M і 17 спалахів класу X.

Детально вивчаючи еволюцію цієї гіперактивної області NOAA 13664 та її вплив на Землю, ми вдосконалюємо нашу здатність прогнозування сонячної активності та попереджати про екстремальні явища космічної погоди, які вона викликає.

Ключові слова: активні області, сонячні плями, сонячні спалахи, викиди корональної маси, геомагнітні бурі.

1. Introduction

The Carrington Event in early September 1859, a solar flare with an associated geomagnetic storm, is considered one of the most extreme space weather events in observed history and the first direct evidence of a connection between the Sun and Earth's environment. The Carrington flare has become a benchmark as the earliest and brightest solar flare ever recorded. The flare's power estimate from ≈X80 to ≈X14 on the GOES X-ray scale, obtained by scientists using different methods, is given in the paper (Hayakawa et al., 2023). On September 1, british astronomers R. Carrington and R. Hodgson independently observed this flare (Carrington, 1859; Hodgson, 1859), which caused a large coronal mass ejection (CME). It reached Earth after 18 hours. On September 1-2, the largest geomagnetic storm in history began, which caused the failure of telegraph systems throughout Europe and North America. The magnetometers went off the scale. The aurora borealis has been seen all over the world, even by people in Cuba, Jamaica and Hawaii who have never seen anything like it before. The Carrington event became a benchmark of space weather impact on our planet. The Carrington event is certainly one of the most extreme space weather events, but it is not unique. Research indicates that Carrington-class storms occur every 40 to 60 years. The NOAA 13664 active region studied in this paper was one of the largest and most active solar regions observed in the current 25th solar cycle. It rivaled the Carrington sunspot group in size. AR produced many powerful flares that caused strong magnetic storms on the Earth (Hayakawa et al., 2024; Romano et al., 2024). In present paper we analyze the evolution and flare activity of this active region and its impact on Earth. Studying the properties of such regions can be useful for improving methods for predicting solar activity and extreme space weather events.

2. Observational data

The magnetograms, continuum images and EUV-images were provided by the Solar Dynamics Observatory (SDO) the Helioseismic and Magnetic Imager (HMI) and the Atmospheric Imaging Assembly (AIA). The X-ray data were obtained at Geostationary Operational Environmental Satellite (GOES). Data on the solar flares are taken from the site https://www.lmsal.com/solarsoft/latest_events_archive.html and data on SMEs and their impact on Earth from the site https://www.swpc.noaa.gov. NOAA's Space Weather Prediction Center (SWPC) is a division of the National Weather Service. The spectrograms for X2.3-class flare were recorded on 2024 May 9 with the Ernest Gurtovenko solar horizontal telescope at the Main Astronomical Observatory in Kyiv. The Hα line profiles were obtained.

3. Active region NOAA 13664

We analyzed the temporal and spatial evolution and flare activity of the active region 13664 and its impact on Earth. The region appeared in the southern hemisphere of the solar disk on May 1, 2024 of the current 25th cycle of solar activity. This AR attracted attention because its structure was rapidly changing (Fig. 1). Figure 2 shows how the spots number and its area changed during the first passage of the region across the Sun's disk. It can be seen that the maximum number of spots (N=81) in AR was observed on May 10, and the area occupied by them reached a maximum (S=2400 millionths of the solar hemisphere) on May 11. In a few days the active region not only increased significantly in size (up to ≈ 20 Mm), but its magnetic structure also became significantly more complex. Figure 3 shows AR magnetograms obtained by SDO/HMI on May 3 and 7. Starting from May 7, AR had a complex (βγδ) multipolar configuration of the magnetic field. It contained powerful and entangled magnetic fields, which allowed it to produce a series of moderate and strong solar flares that began on May 8. On May 8, solar flares of intensity X1.0, M8.7, X1.02 and M9.9 took place in AR, which caused powerful coronal mass ejections (CMEs) towards the Earth. When the CME reaches Earth, it can cause powerful effects on its magnetosphere, causing various space weather effects. Among the possible effects are aurora borealis, magnetic storms, malfunctions of electrical equipment, deterioration of radio wave propagation conditions. The three CMEs that formed on May 8 reached Earth on May 10, causing the strongest and most extreme geomagnetic storms in nearly 20 years. The event was classified as a G5 geomagnetic storm, making it the most intense storm since 2003. In 2003, the most powerful flare on record took place, estimated at about X18+. It created long-lasting radiation storms. The geomagnetic storm of May 10–11, 2024 was so strong (on

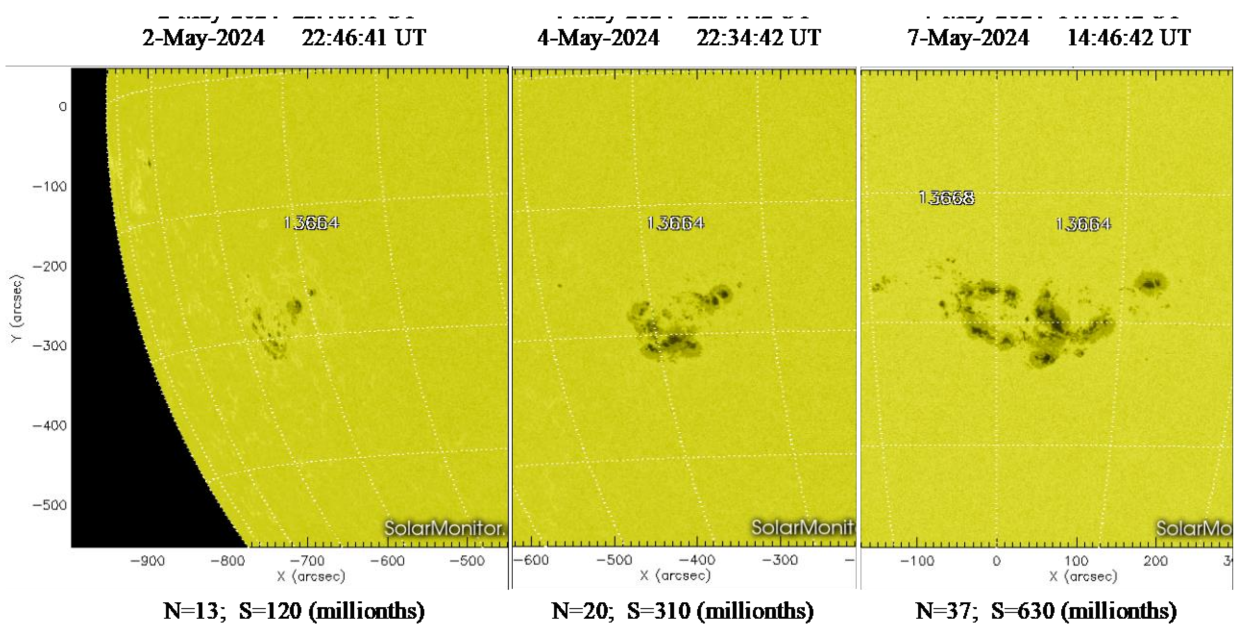

Figure 1: Change in the structure of the active region NOAA 13664.

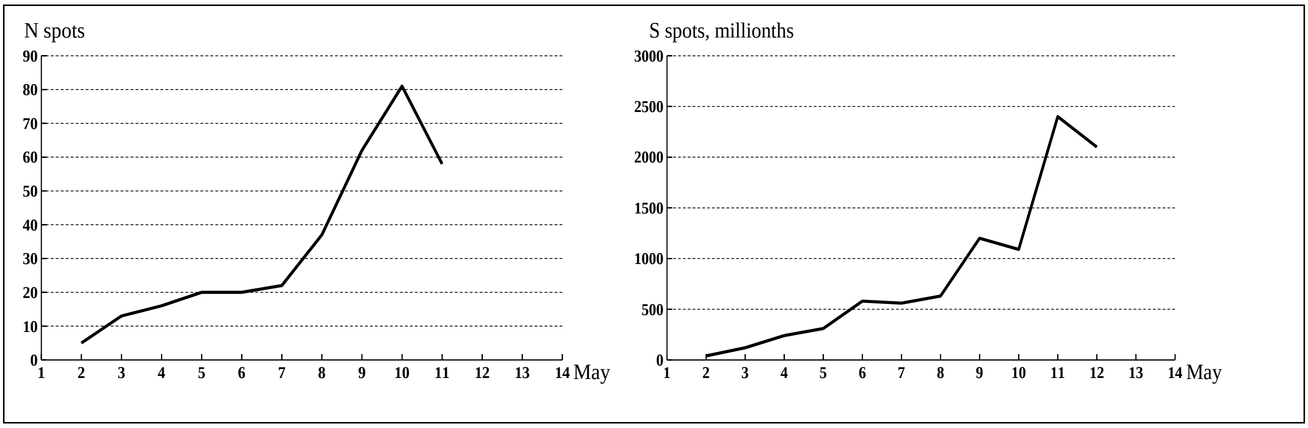

Figure 2: Change in the number of sunspots (N) and the area occupied by them (S, millionths) during the first passage of AR13664 across the Sun's disk.

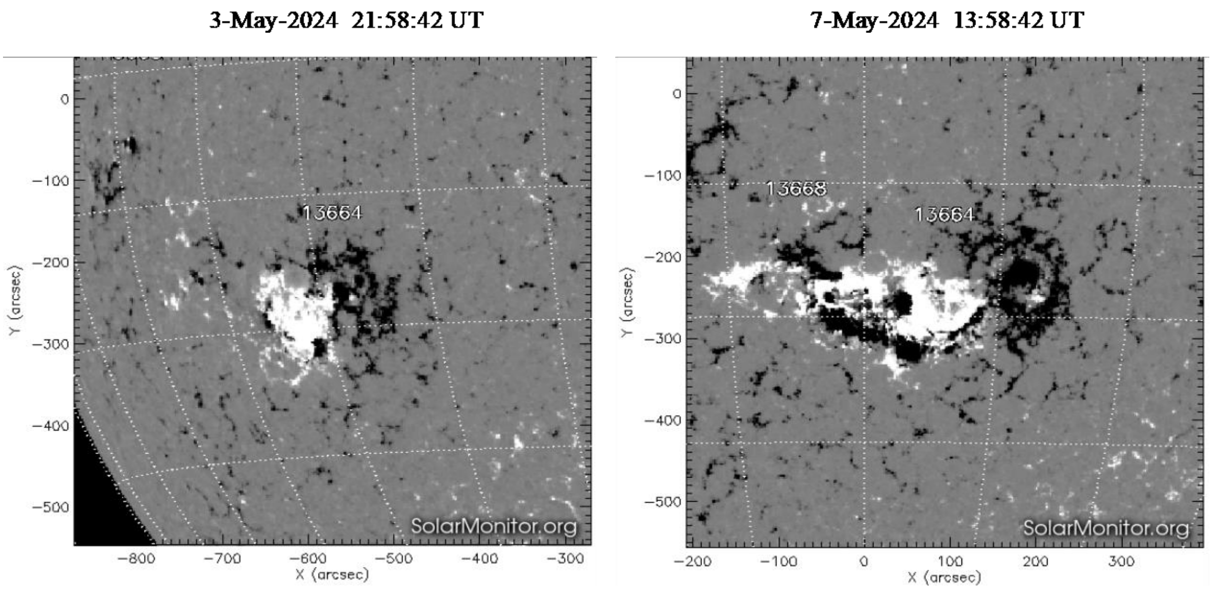

Figure 3: AR13664 magnetograms obtained with the SDO/HMI instrument on May 3 and 7, 2024. The positive and negative polarities are indicated by white and black colours, respectively.

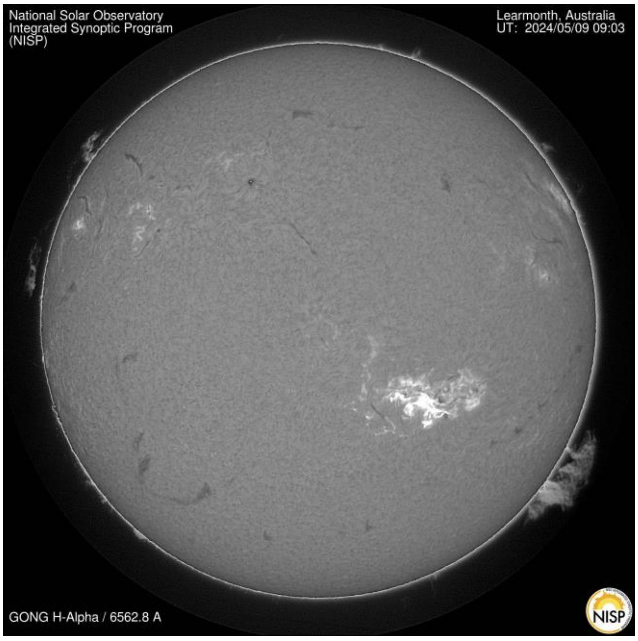

Figure 4: AR13664 May 9, 2024, flare X2.3.

May 11, the Kp index reached 9) that the US National Oceanic and Atmospheric Administration (NOAA), which predicts solar storms and their impact on our planet, issued for the first time in almost two decades storm warning After receiving the warning, NASA put at least one of its satellites, ICESat-2, into safe mode. Geomagnetic storm caused auroras across Europe, Asia, Mexico, and all 50 US states, even in Hawaii. Many people around the world saw the aurora borealis for the first time in their lives, for example, such as the residents of Puerto Rico at 18.1° north latitude. The Northern Lights were also observed in many regions of Ukraine at this time. Usually, such a phenomenon can be observed at a distance of 20–35° from the Earth's magnetic poles, and Ukraine is located at a latitude of 52°–44°, which makes the northern lights a rare phenomenon here.

On May 9, there were flares of intensity X2.3 (Fig. 4) and X1.1, each of which caused a CME. Spectrograms during the main phase of the X2.3 flare were recorded on May 9 at the Ernest Gurtovenko solar horizontal telescope of the Main Astronomical Observatory in Kyiv by observers S.M.Osipov and M.I.Pishkalo. The observation interval was 09:14:44 – 09:33:28 UT. The Hα line profiles show a strong emission during the flare main phase. Figure 5 shows examples Hα-spectra and Hα line profiles obtained for this flare.

Heading toward the western edge of the Sun, AR continued to produce powerful M- and X-class flares. On May 10 an X4.0 flare occurred in this AR. May 11, NASA's Solar Dynamics Observatory recorded a bright X5.8 flare. The radiation from this flare caused a deep shortwave radio blackout over the Pacific Ocean. Loss of signal at frequencies below 30 MHz was observed within an hour after the peak of the flare. A solar-proton storm of intensity S1 also occurred in the region. May 12 AR produced flare of intensity X1. There was a geomagnetic storm that began on May 10, but it was minor (G1). On the May 13, AR which was approaching the western limb of the Sun, i.e. was already leaving the zone of influence on the Earth, created a series of M-class flares that ejected CMEs into space. May 14 AR produced flares of intensity X1.2, X1.7, X8.7. Since the AR was beyond the edge of the solar disk, the strongest flare of the current solar cycle, the X8.7, was partially eclipsed and probably even stronger than it appeared (Fig. 6). The extreme ultraviolet radiation from the flare ionized the upper part of the Earth's atmosphere, resulting in signal loss at all frequencies below 30 Mhz. May 15 AR produced flare of intensity X3.5.

Figure 7 shows how many flares of different classes occurred in the AO during its first passage across the Sun's disk from May 1 to 15. In total, AR3664 produced 48 C-class, 55 M-class and 12 X-class flares in the first half of May. AR turned out to be one of the most powerful among all observed on the Sun in recent years.

4. Active region NOAA 13697

Active region 13664 went beyond the edge of the solar disk and returned on May 29 and was renumbered as NOAA 13697. AR was collapsing: the number of sunspots (maximum N=42) and the area occupied by them (maximum S=420 millionths of the solar hemisphere) were decreasing. But during its exit, the AR had an unstable magnetic field of the βγδ Hale class, which contained the energy for powerful flares (Fig. 8). On May 27, it created a X2.9 class flare at the eastern edge of the solar disk. After it came into view, it also produced X1.4 class flare on May 29. From May 31 to June 1, it produced three X-flares: X1.1, X1.4 and X1.0. Each caused a radio blackout on the Earth day side, with almost all longitudes affected by one or more flares. Although AR13697 was losing power, it produced another very strong M9.8 solar flare on June 8, ejecting a large CME into space. Radiation from the flare ionized Earth's upper atmosphere, causing a deep shortwave radio blackout in the western Pacific Ocean. The flare also caused a radiation storm category S2. On June 10, just beyond the sun's western limb, an X1.6 flare occurred in the AR, which was partially obscured by the Sun edge. As a result, it was not very geoeffective. In total, AR13697 produced 127 C-class, 30 M-class, and 6 X-class flares during its second pass across the Sun's disk from May 27 to June 10.

5. Active region NOAA 13723

Hyperactive AR13664 returned on June 24 again. This was its rare 3rd trip across the solar disk. It was renamed as NOAA 13723. It became much smaller compared to the previous ones, the maximum N=12 and their area S=210 millionths of the solar hemisphere were observed on June 26. Although the sunspot region was already fragmented to a fraction of its former size, its magnetic component continued to produce powerful solar flares (Fig. 8). On June 23, M9.3-class flare occurred in AR. It caused moderate

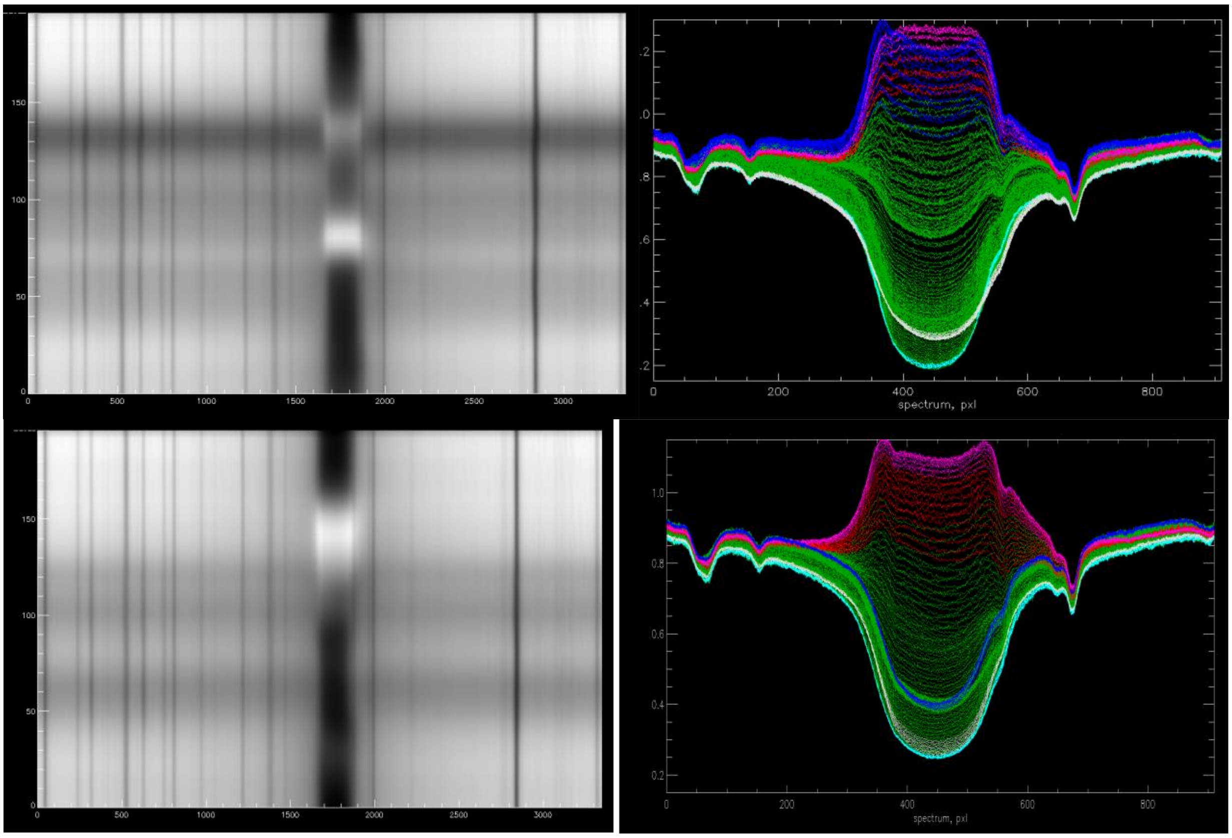

Figure 5: Examples of obtained Hα-spectra and Hα-line profiles for a flare X2.3-class

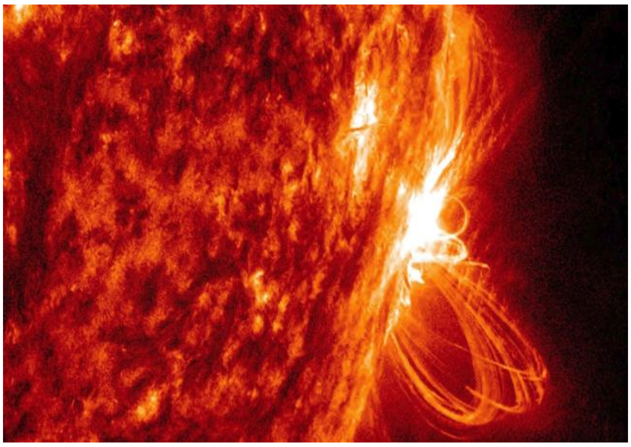

Figure 6: AR13664, flare X8.7.

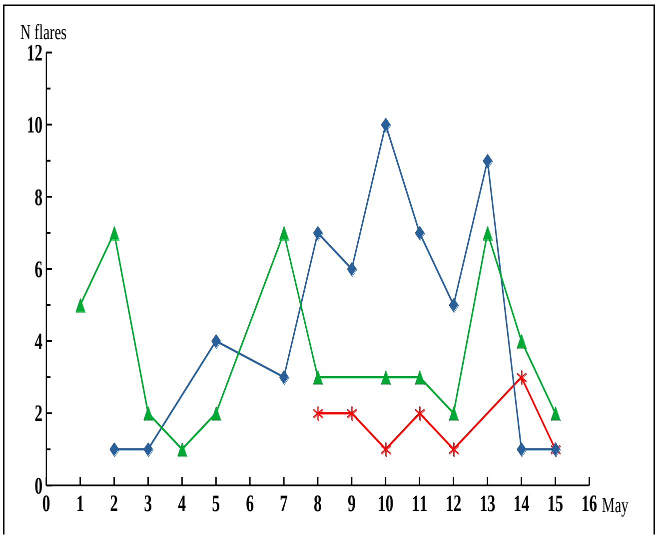

Figure 7: The number of various class flares produced in the AR13664 during its first passage across the Sun's disk. Blue curve – number of C-class flares,
green curve – M-class and red curve – X-class

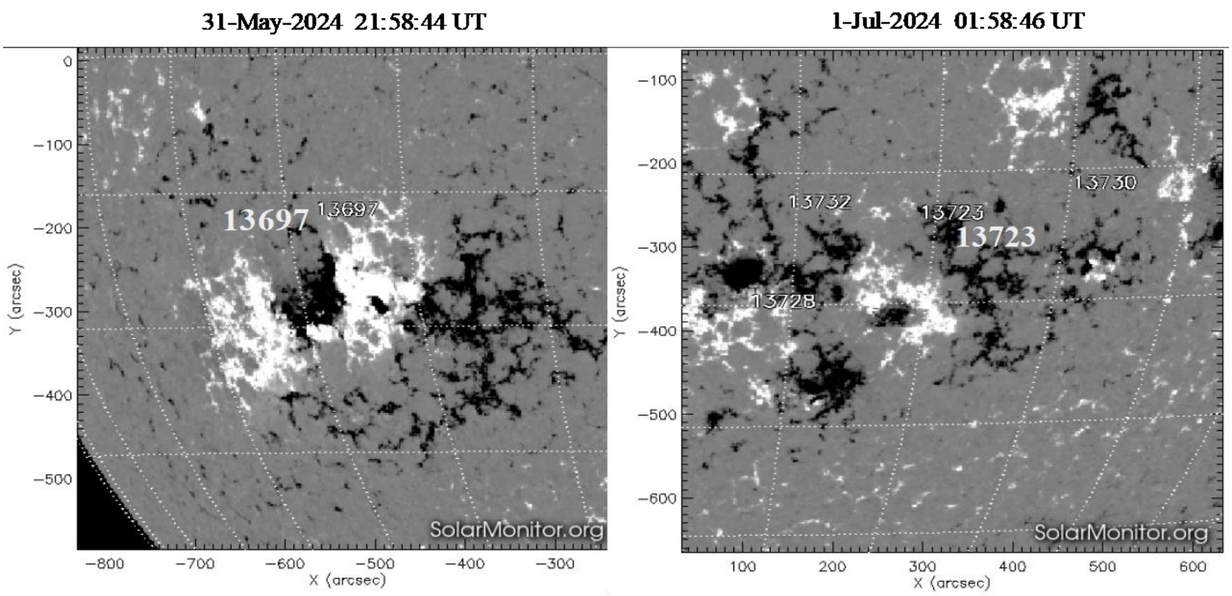

Figure 8: AR13697 and AR13723 magnetograms obtained with the SDO/HMI instrument on May 31 and July 1, 2024, respectively. The positive and negative polarities are indicated by white and black colours, respectively.

shortwave radio outages in Western Europe and Africa. Starting from June 29, AO had β Hale class magnetic field configuration. In total, AR13723 produced 23 C-class and 1 M-class flares during its third pass across the Sun's disk from June 24 to July 6.

6. Conclusion

The AR13664/AR13697/AR13723 belonged to the Carrington class. It was not only one of the largest sunspot groups rivaled Carrington's sunspot of 1859, it turned out to be one of the most powerful among all those observed on the Sun in the current 25th solar cycle. It was the source of the strongest flares M- and X- class, that triggered largest CMEs and associated geomagnetic storms which were very geoeffective and created bright auroras at much lower latitudes than usual, both in the northern and southern hemispheres. The geomagnetic storm of May 10–11, 2024 was the strongest and most extreme in nearly 20 years and classified as a G5.

By studying in detail the evolution of this hyperactive region NOAA 13664 and its impact on Earth, we are improving our ability to predict solar activity and warn of the extreme space weather events it causes, such as powerful geomagnetic storms that affect people's quality of life.

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