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Investigations of Solar Flare Events During Solar Cycle 24

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Abstract: ***Solar cycle 24 is the most recently completed solar cycle, the 24th since 1755, when extensive recording of solar sunspot activity began. It began in December 2008 with a minimum smoothed sunspot number of 2.2 and ended in December 2019. Activity was minimal until early 2010. It reached its maximum in April 2014 with a 23 months smoothed sunspot number of 81.8. This maximum value was substantially lower than other recent solar cycles, down to a level which had not been seen since cycles 12 to 15 (1878-1923). In this paper, the solar flare events of solar cycle 24 have been thoroughly examined according to the solar activity.***

Keywords: Solar Activity, Solar Flares, Solar Cycle 24, Coronal Mass Ejection

1. Introduction

Solar activity rises and falls with an 11-year cycle, which is called the Solar Cycle, that affects us in many ways. Increased solar activity includes increase in the number of solar flares and coronal mass ejections (CMEs) which in turn affects sensitive instruments in space by energetic particles accelerated in these events. Every part of the solar activity is strongly modulated by the solar magnetic cycle[1]. Solar flares are intense localized eruption of electromagnetic radiation from the Sun's atmosphere. Flares occur in active regions and are mostly accompanied by CMEs, solar particle events, and other solar phenomena. The occurrence of solar flares varies with the 11-year solar cycle. Solar cycle 24 is the most recently completed solar cycle. It began in the end of 2008 or beginning of 2009, with a minimum smoothed sunspot number of 2.2, and ended in 2019[2]. Solar activity for this solar cycle was minimal until early 2010. It reached its maximum in April 2014. This maximum value was substantially lower than previous solar cycles, down to a level which had not been seen since Dalton minimum (1790-1830)[3]. Solar flares are thought to occur when stored magnetic energy in the Sun's atmosphere accelerates charged particles in the surrounding plasma. This results in the emission of electromagnetic radiation across the electromagnetic spectrum.

Here, an analysis has been done on the solar flare events occurred in each year of the solar cycle 24. The solar cycle was not generating sunspots and solar flare events in the expected manner. Sunspots did not begin to appear immediately after the last minimum in 2008 and although they started to reappear in late 2009, they were at significantly lower rates than anticipated.

2. Solar Flare Events

2.1. Rising Phase of Cycle 24 (2008-2010)

In the beginning or rising phase of Solar Cycle 24, solar activity remained extremely low throughout 2009. No M-class flares were observed in 2009. On 19 January 2010, active region AR11041 produced an M2.3-class flare, the first flare of cycle 24 above M-class. It was followed by an M1.7-class flare and four consecutive M-class flares the next day. Among the four flares, the strongest reached a strength of M3.4. On 12 February 2010, active region AR11046 produced an M8.3-class flare. Later in the month, active regions AR11045 and AR11046 unleashed a total of nine M-class flares. On 5 April 2010, the first coronal mass ejection (CME) of cycle 24 erupted at an active region causing a G3 (strong) geomagnetic storm on Earth. The Kp index, which quantifies disturbances in the horizontal component of Earth's magnetic field, reached a value of 7[4,5]. On 14 August 2010, a C4.4-class flare produced the first solar radiation storm of cycle 24. On 6 November 2010, active region AR11121 emitted an M5.4 flare.

Table 1 shows the solar flares and related events occurred during the rising phase of solar cycle 24 (2008-2010). It is clear from the table that there were no M or X-class flares in 2008 and 2009. In 2010, only 3 M class flares occurred but there was no Geo-Magnetic storm. Therefor the solar activity during that phase of the cycle 24 was very low. Figure 1 depicts the solar flare events occurred in the rising phase of solar cycle 24 (2008-2010). C-class flares are marked in yellow and M-class flares are marked in brown. It is evident from the figure that no X-class flares occurred and only a few M-class flares were recorded during this period. It is clear that the solar activity in the rising phase of this cycle 24 was very low.

Table 1: The strongest solar flares of Solar Cycle 24 for the years 2008-2010 (above M5.0-class) and related events

Year	*Date*	*Class*	*Sunspot region*	*Radio B.*	*SR Storm*	*CME*	*GM Storm*
2008	-	-	-	-	-	-	-
2009	-	-	-	-	-	-	-
2010	Feb 7	M6.4	1045	R2	-	Yes	-
	Feb 12	M8.3	1046	R2	-	Yes	-
	Nov 6	M5.4	1121	R2	-	No	-

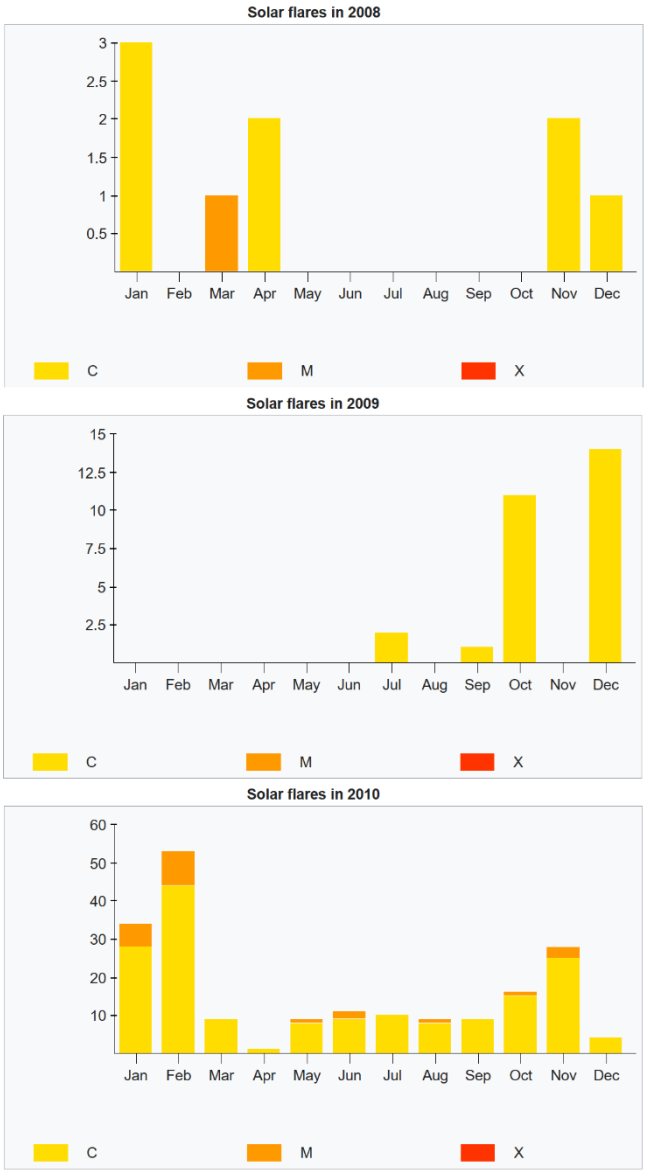


Figure 1: Solar Flare Events for the years 2008-2010

2.2 Active Phase I of Cycle 24 (2011-2012)

From 2011, the sun became much active. On February 15, 2011, sunspot group 1158 produced an X2.2-class solar flare, which is called the Valentine's Day solar event by the scientific community. It was the first X-class level flare in Solar Cycle 24. 2 days before, on February 13, sunspot group 1158 had unleashed an M6.6-class solar flare. 13 M-class bursts were registered in February 2011[6]. On March 9, active region 1166 erupted in an X1.5 flare. The related CME caused a G2 geomagnetic storm two days later[7]. 21 M-class flares were registered this month. In July 2011, a Sunspot 1260 produced an M9.3-class solar flare on July 30, 2011[8]. On August 9, 2011, sunspot 1263 produced a massive X6.9-class solar flare, the third X-flare of Solar Cycle 24 and one of the most powerful. There was also a CME associated with this burst. Although the flare was not Earth-directed, radiation created waves of ionization in Earth's upper atmosphere, briefly disrupting communications at some VLF and HF radio frequencies[9]. In September 2011, Sunspot 1283 erupted with an M5.3-class solar flare on September 6. The burst was Earth-directed. On the very day, an X2.1-class flare – some four times stronger than the earlier flare – erupted from the same sunspot region. The combined CMEs of these bursts arrived at Earth on September 9, provoking a G3 (strong) geomagnetic storm. On the next day, September 7, an X1.8-class solar flare erupted from sunspot 1283, producing an S1 solar radiation storm[10-11]. Then, on September 22, an X1.4-class solar flare erupted out of sunspot 1302. The blast produced a significant CME, but that was not Earth directed. Two days later, an X1.9-class flare, was unleashed out of the same sunspot. A G4 (severe) geomagnetic storm was reported on September 26[12-13]. In total, the Sun produced four X flares and 31 M flares in September 2011, one of the most active months of Solar Cycle 24. In October 2011, The Sun unleashed eight M-class flares, being the strongest the M3.9 event, followed by an Earth-directed CME, produced by sunspot 1305 on October 2[12]. In November 2011, on November 3, 2011, active region 1339 unleashed an X1.9-class solar flare. The related CME was not headed for Earth. 13 M-class flares were registered this month[13]. The monthly sunspot count was nearly 100 (96.7) in this month. In December 2011, Solar activity increased again in late December, with the Sun unleashing eight M-flares. The most intense flare, produced by sunspot 1385, was an M4.0 event on December 25. The year 2011 ended up with 111 M-class and 8 X-class solar flares[14].

For the year 2012, solar activity continue to rise. Sunspot 1402 erupted a long-duration M8.7-class flare, followed by a CME, on January 23, 2012. According to NOAA, the flare's radiation storm was ranked as S3 (strong)[15]. On January 27, sunspot region 1402 unleashed an X1.7-class flare and an S2 (moderate) Solar Radiation Storm. In March 2012, active region 1429 erupted an X1.1-class flare on March 5. The wave of high energy electromagnetic rays, caused an R3 (strong) radio blackout[16-17]. On March 7, after releasing up to nine M-class flares in only one day, the active region 1429 erupted a powerful X5.4-class flare. The related CME impacted the Earth on March 8, causing a G3 (strong) geomagnetic storm. Active Region 1429, generated an M6.3-class flare on March 9, an M8.5 flare one day later and an M7.9 flare on March 13. The first wave of plasma impacted the magnetosphere on March 12, causing a G2 (moderate) geomagnetic storm. March 2012 became one of the most active months of Solar Cycle 24, ended up with 19 M-class and three X-class flares. Solar activity increased again in May 2012, with 12 M-class flares ejected, the strongest being an M5.7 flare produced by

active region 1476 on May 10[18]. 11 M-class solar flares were observed this month, the largest being an M3.3 flare in June 2012. An X1.1-class flare erupted from sunspot 1515 on July 6, generating an R3 (strong) radio blackout and an S1 (minor) solar storm. Six days after, sunspot 1520, unleashed an X1.4-class flare. The related CME caused a G2 (moderate) geomagnetic storm, following an R3 radio blackout and an S1 solar storm[19]. The Sun emitted a moderate solar flare on July 19, 2012. The flare was classified as an M7.7 flare. Other M-class flares registered this month included an M6.9 (July 8), an M6.1 (July 5), an M6.1 (July 28), an M5.6 (July 2) and an M5.3 (July 4). The month ended up with 45 M-class flares and 2 X-class flares[20]. The Sun released an M9.0 flare on October 20. This was followed three days later on October 23 by a very impulsive flare, peaking as an X1.8-class event[21]. Both flares came from active region 1598. 14 M-class flares were registered in November, 2012, the strongest being an M6.0 flare, which erupted on November 13[22]. Solar activity decreased significantly in December 2012. For first time in two years (since December 2010), no X or M-class flares were emitted by the Sun. The year 2012 ended up with 129 M-class and 7 X-class solar flares[23].

Table 2 shows the most powerful X-class solar flares and related events occurred during the active phase I of solar cycle 24 (2011-2012). It is clear from the table that there were 8 X-class flares in 2011 and 7 X-class flares in 2012. The X6.9 flare occurred on August 9, 2011 was strongest in 2011 and in 2012, it was a X5.4 flare on March 7 2012. Figure 2 shows the solar flare events occurred in the active phase I of solar cycle 24 (2011-2012). Here the C-class flares are marked in yellow, M-class flares are marked in brown and the X-class flares are marked in red colour.

Table 2: The strongest solar flares of Solar Cycle 24 for the years 2011-2012 (X-class) and related events

Year	*Date*	*Class*	*Sunspot region*	*Radio B.*	*SR Storm*	*CME*	*GM Storm*
2011	Feb 15	X2.2	1158	R3	-	Yes	G1
	Mar 9	X1.5	1166	R3	-	Yes	G2
	Aug 9	X6.9	1263	R3	S1	Yes	-
	Sep 6	X2.1	1283	R3	S1	Yes	G3
	Sep 7	X1.8	1283	R3	S1	Yes	G1
	Sep 22	X1.4	1302	R3	-	Yes	-
	Sep 24	X1.9	1302	R3	S1	Yes	G4
	Nov 3	X1.9	1339	R3	-	Yes	-
2012	Jan 27	X1.7	1402	R3	S2	Yes	-
	Mar 5	X1.1	1429	R3	-	Yes	G2
	Mar 7	X5.4	1429	R3	S3	Yes	G3
	Mar 7	X1.3	1430	R3	S3	No	-
	Jul 6	X1.1	1515	R3	S1	Yes	G1
	Jul 12	X1.4	1520	R3	S1	Yes	G2
	Oct 23	X1.8	1598	R3	-	No	-

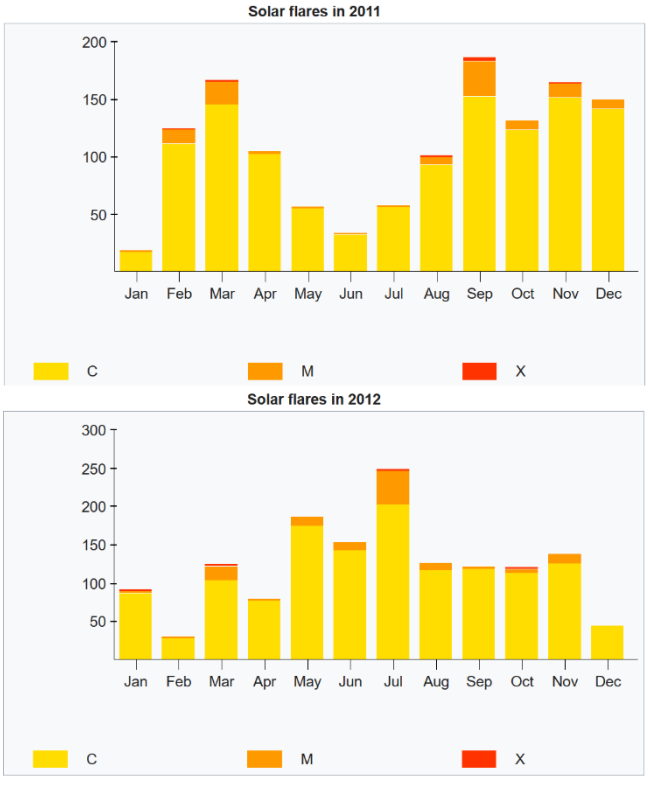


Figure 2: Solar Flare Events for the years 2011-2012

2.3 Active Phase II of Cycle 24 (2013-2015)

The unexpectedly low solar activity continued from January to April 2013. Only 13 M-class flares were reported from December 2012 to April 2013. The strongest was an M6.5 unleashed by active region 1719[24-25]. In May 2013, the solar activity increased rapidly with four consecutive strong flares in two days. These powerful bursts all surged from sunspot AR1748. It emitted the first flare, an X1.7-class, on May 13. This event was quickly followed the same day by an X2.8-class flare. On May 14 the same sunspot emitted an X3.2-class flare. This was followed by an X1.2-class flare on May 15. The four X-ray bursts generated an R3 (strong) radio blackout in the upper atmosphere[26]. In October and November 2013, four X-class flares were erupted from the sun in each month, the largest being an X3.3 flare on November 5, 2013. Figure 3 depicts the 13-15 May, 2013 series of four X-class flares erupted by AR1748: X1.7, X2.8, X3.2 and X1.2, as they were registered by the real-time monitor (3 days, 5-min data) of GOES 15 satellite X-ray Flux[27]. In 2014, the solar activity was moderately high. On January 7, 2014, sunspot region 1944 emitted an X1.2 flare. On February 24, 2014, the sun erupted with an X4.9-class solar flare, the strongest of that year[28]. Then up to May 2014, solar activity was moderate producing an X1.0 flare in March 29 and an X1.3 flare in April 25.

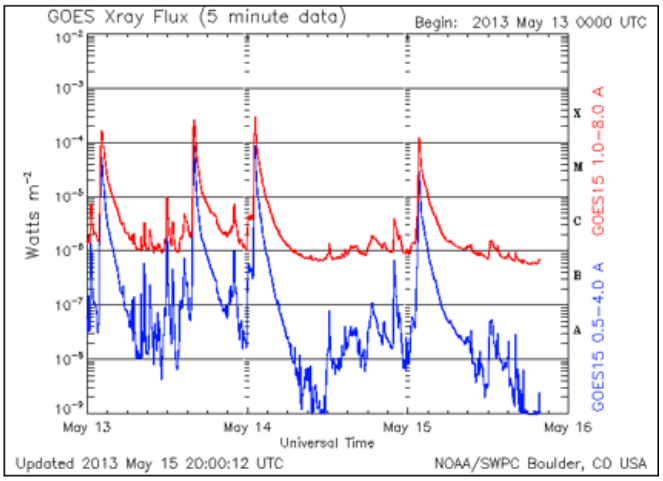


Figure 3: The 13–15 May 2013 series of four X-class flares

Table 3: The strongest flares of Solar Cycle 24 for the years 2013-2015 (X-class) and related events

Year	*Date*	*Class*	*Sunspot region*	*Radio B.*	*SR Storm*	*CME*	*GM Storm*
2013	May 13	X2.8	1748	R3	-	Yes	-
	May 13	X1.7	1748	R3	-	Yes	-
	May 14	X3.2	1748	R3	-	Yes	-
	May 15	X1.2	1748	R3	S1	Yes	G1
	Oct 25	X2.1	1882	R3	-	Yes	-
	Oct 25	X1.7	1882	R3	-	Yes	-
	Oct 28	X1.0	1875	R3	S1	Yes	-
	Oct 29	X2.3	1875	R3	-	Yes	-
	Nov 5	X3.3	1890	R3	-	Yes	-
	Nov 8	X1.1	1890	R3	-	Yes	-
	Nov 10	X1.1	1890	R3	-	Yes	-
	Nov 19	X1.0	1893	R3	S1	Yes	-
2014	Jan 7	X1.2	1944	R3	S2	Yes	-
	Feb 25	X4.9	1990	R3	S1	Yes	G2
	Mar 29	X1.0	2017	R3	-	-	-
	Apr 25	X1.3	2035	R3	-	-	-
	Jun 10	X2.2	2087	R3	-	-	-
	Jun 10	X1.5	2087	R3	-	-	-
	Jun 11	X1.0	2087	R3	-	-	-
	Sep 10	X1.6	2158	R3	S2	Yes	G3
	Oct 19	X1.1	2192	R3	-	No	-
	Oct 22	X1.6	2192	R3	-	No	-
	Oct 24	X3.2	2192	R3	-	No	-
	Oct 25	X1.0	2192	R3	-	No	-
	Oct 26	X2.0	2192	R3	-	No	-
	Oct 27	X2.0	2192	R3	-	No	-
	Dec 20	X1.8	2242	R3	-	Yes	-
2015	May 5	X2.7	2339	R3	-	Yes	-
	Mar 11	X2.2	2297	R3	-	Yes	-

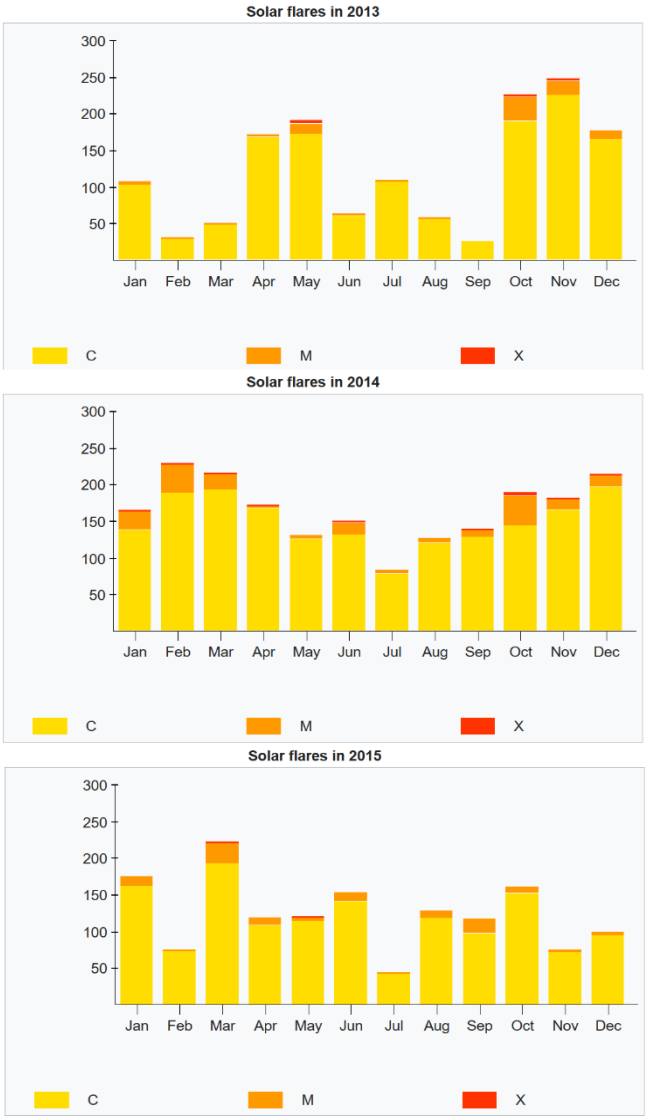


Figure 4: Solar Flare Events for the years 2013-2015

In June 2014, there were 3 X-class flares from the sun in a 2-days' time June 10 and June 11. Then again up to October the activity was moderately low. Only single X1.6 flare was erupted on September 10 from the sunspot region 2158. In October 2014, there were 6 X-class flares making it the most active month of the solar cycle 24. Four solar flares occurred within 5 days from sunspot AR 12192. On October 19 there was a major X1.1-class solar flare. On October 22 an M8.7-class flare was followed by an X1.6 event. The October 24 X3.1-class solar flare was strong enough to trigger a radio blackout[29]. In 2015, solar activity was moderately low marking the completion of the active phase and making way for the declining phase of the solar cycle 24[30]. Like the previous Table 1 and Table 2, in Table 3, the most powerful X-class solar flares and related events occurred during the active phase II of solar cycle 24 (2013-2015) has been shown. It is clear from the table that there were 12 X-class flares in 2013 and 15 X-class flares in 2014. 2014 was the most active year of the solar cycle 24. Only 2 X-class flares occurred in 2015 as shown in Table 3. Figure 4 shows the solar flare events occurred in the active phase II of solar cycle 24 (2013-2015). Here also the C-class flares are marked in yellow, M-class flares are marked in brown and the X-class flares are marked in red colour.

2.4 Decline Phase of Cycle 24 (2016-2019)

The declining phase of cycle 24 started in 2016 and it ended in 2019. In December, 2016 a sunspot group originally attributed to the new solar cycle 25 is observed[31]. The sunspot numbers continue to decline. During 2016, there were about 26 days with no sunspots. In March, 2017 reports indicate that there had been 24 days during which there were no sunspots[32]. In September 2017, On 6 September the largest X-class flare in a decade (X9.3) erupted from active region 2673[33]. Then, when this region was just crossing the west limb, on 10 September another X-class flare (X8.2) produced only the second ground-level particle event of the cycle. Sunspot region 2673 was one of the most active regions during the entire cycle, creating both of the largest flares in the cycle and 4 total X-class flares. No further M class flares would take place during the rest of Solar cycle 24. Like the previous tables, in Table 4, the most powerful X-class solar flares and related events occurred during the declining phase of solar cycle 24 (2016-2017) has been shown. It is clear from the table that there were 4 X-class flares in this period. Figure 5 shows the solar flare events occurred during the 1st two years of declining phase of solar cycle 24 (2016-2017). Here also the C-class flares are marked in yellow, M-class flares are marked in brown. There were no X-class flares.

Table 3: The strongest flares of Solar Cycle 24 for the years 2013-2015 (X-class) and related events

Year	*Date*	*Class*	*Sunspot region*	*Radio B.*	*SR Storm*	*CME*	*GM Storm*
2016	Apr 18	M6.7	2529	R2	-	Yes	-
	Jul 23	M7.6	2567	R2	-	Yes	-
	Jul 23	M5.5	2567	R2	-	Yes	-
2017	Apr 2	M5.3	2644	R2	-	No	-
	Apr 2	M5.7	2644	R2	-	No	-
	Sep 4	M5.5	2673	R2	-	?	-
	Sep 6	X9.33	2673	R3	S1	Yes	-
	Sep 6	X2.2	2673	R3	-	?	-
	Sep 7	X1.3	2673	R3	S2	No	G4
	Sep 7	M7.3	2673	R2	-	?	-
	Sep 8	M8.1	2673	R2	-	?	-
	Sep 10	X8.2	2673	R3	S3	Yes	-
2018	-	-	-	-	-	-	-
2019	-	-	-	-	-	-	-

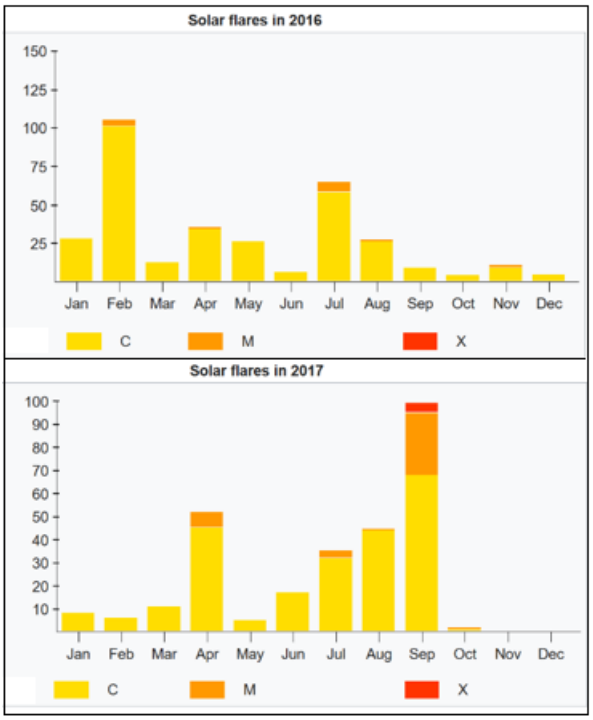
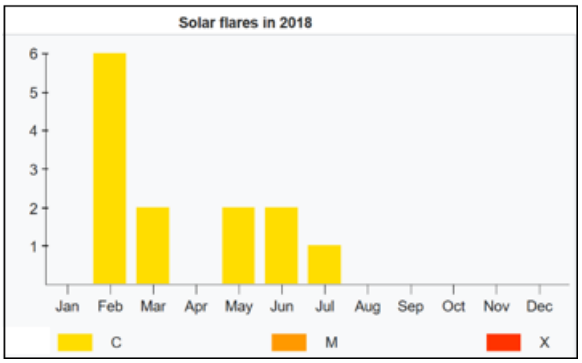


Figure 5: Solar Flare Events for the years 2016-2017

In January 2018, a small active region, NOAA 12694, appeared at the surprisingly high latitude of S32, near the disk center. In March 2018, NOAA reported that the number of sunspots was the lowest since 2009, and that recent activity matched that of the low activity in 2007 and 2008. As this is a proof of the solar minimum, Solar Cycle 24 has become a short (10 year) and weak cycle. Sunspots were observed on only 5 days that month. In May 2019, a C6.8 flare took place, the strongest solar flare to take place since October 2017[34]. In July 2019, NASA's Solar Dynamics Observatory recorded a sunspot from Solar Cycle 25. This sunspot is significant compared to previous sunspots from Solar Cycle 25 due to the fact that it lasted long enough to get a designation[35]. In October 2019, the sun reached its absolute solar minimum, marking the end of Solar cycle 24 and the beginning of Solar cycle 25. Like the previous figure, Figure 6 also shows the solar flare events during the last two years of declining phase of solar cycle 24 (2018-2019). Here also the C-class flares are marked in yellow, M-class flares are marked in brown. There were no X-class flares.



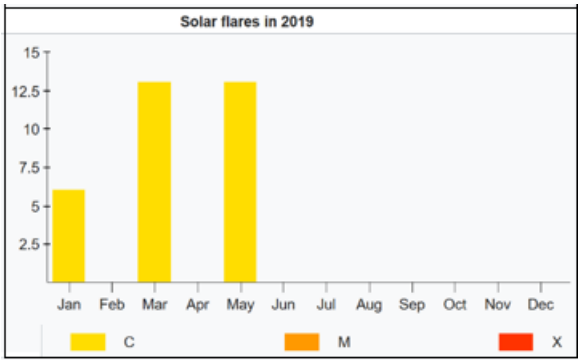


Figure 6: Solar Flare Events for the years 2018-2019

3. Conclusions

Prior to the minimum between the end of Solar Cycle 23 and the beginning of Solar Cycle 24, two theories predicted how strong Solar Cycle 24 would be. One camp postulated that the Sun retained a long memory (Solar Cycle 24 would be active) while the other asserted that it had a short memory (quiet). Prior to 2006, the difference was substantial with a minority of researchers predicting "the smallest solar cycle in 100 years." Another group of researchers, including one at NASA, predicted that it "looks like it's going to be one of the most intense cycles since record-keeping began almost 400 years ago." The delayed onset of high latitude spots indicating the start of Solar Cycle 24 led the "active cycle" researchers to revise their predictions downward and the consensus by 2007 was split 5-4 in favour of a smaller cycle. By 2012, consensus was a small cycle, as solar cycles are much more predictable 3 years after minima. NASA funded and used Ken Schatten's physics-based models, which utilized a solar Dynamo model, to accurately predict the low. This method used the correlation between solar magnetic field strength at solar minimum to sunspot number at solar maximum to accurately predict the peak solar flux of each of the last three solar cycles. Schatten's predictions become accurate as early as solar minima, 5–6 years before solar max. In early 2013, after several months of calm, it was obvious that the active 2011 was not a prelude to a widely predicted late 2012-early 2013 peak in solar flares, sunspots and other activity. This unexpected stage prompted some scientists to propose a "double-peaked" solar maximum, which then occurred. The first peak reached 99 in 2011 and the second peak came in early 2014 at 101.

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Author Profile

Dr. Debojyoti Halder completed his Ph. D. in 2016 from the University of Kalyani in the applied field of science and technology. He has designed and constructed Radio Astronomical Instruments which includes wind-proof Log Periodic Dipole Array for investigating the dynamic behavior of the Sun as well as long distance Radio Signals propagating through the Ionosphere and has already published more than 20 research papers in reputed International Journals and Proceedings. His field of interest includes Radio Astronomy and Communication Applications.