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Extreme space weather events caused by super active regions during solar cycles 21–24

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Abstract Extreme space weather events including ≥X5.0 flares, ground level enhancement (GLE) events and super geomagnetic storms (Dst ≤ –250 nT) caused by super active regions (SARs) during solar cycles 21–24 were studied. The total number of ≥X5.0 solar flares was 62, among which 41 were X5.0-X9.9 flares and 21 were ≥X10.0 flares. We found that 83.9% of the ≥X5.0 flares were produced by SARs; 78.05% of the X5.0-X9.9 and 95.24% of the ≥X10.0 solar flares were produced by SARs; 46 GLEs were registered during solar cycles 21–24, and 25 GLEs were caused by SARs, indicating that 54.3% of the GLEs were caused by SARs; 24 super geomagnetic storms were recorded during solar cycles 21–24, and 12 of them were caused by SARs, namely 50% of the super geomagnetic storms were caused by SARs. We ascertained that only 29 SARs produced ≥X5.0 flares, 15 SARs generated GLEs and 10 SARs triggered super geomagnetic storms. Of the 51 SARs, only 33 SARs produced at least one extreme space weather event, while none of the other 18 SARs could trigger an extreme space weather event. There were only four SARs and each of them generated not only a ≥X5.0 flare, but also a GLE event and a super geomagnetic storm. Most of the extreme space weather events caused by the SARs appeared during solar cycles 22 and 23, especially for GLE events and super geomagnetic storms. The longitudinal distributions of source locations for the extreme space weather events caused by SARs were also studied.

Key words: Sun: sunspots — Sun: flares — Sun: particle emission — Sun: solar-terrestrial relations

1 INTRODUCTION

A major solar flare may lead to a sudden ionospheric disturbance, which may lead to sudden cosmic noise absorption induced by sudden electron density enhancement in the D region, short-wave fadeouts, sudden phase anomalies, sudden frequency disturbances, and a sudden increase in total electron content (TEC) (Mendillo et al. 1974). The duration of the effect of a solar flare on the ionosphere ranges from several minutes to tens of minutes. The duration of a geomagnetic storm is much longer than that of a solar flare. The article by Richardson et al. (2006) found that the largest geomagnetic storm caused by corotating interaction regions is weaker than a great geomagnetic storm (Dst ≤ –200 nT) based on the Burton equation (Burton et al. 1975), implying that a great geomagnetic storm can only be caused by associated coronal mass ejection (CME). Each solar cycle (SC) usually has about 3000 active regions (ARs). However, only a small fraction of the ARs can produce very strong eruptions. These ARs are defined as super active regions (SARs). Many articles have been devoted to the study of the concept of SAR (e.g. Bai 1987; Chen et al. 2011, and references therein). A flare that was accompanied by a hard X-ray with peak flux of ≥1000 counts s^{-1} is defined as a major flare. If an AR can produce five or more major flares, then the AR is considered an SAR (Bai 1987). It is evident that Bai (1987) only linked SARs with solar flares. The definition of SAR proposed by Wu & Zhang (1995) is decided by five parameters: the largest area of the AR, the flare index of the X class X-ray flares, the peak flux of 10.7 cm radio flux, the short-term total solar irradiance decrease and the peak flux of E>10 MeV protons. The concept of SAR proposed by Wu & Zhang (1995) linked SARs with both flare and solar proton events. However, the restrictive conditions for the five parameters were not mentioned. Five parameters

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that were considered to determine whether an AR is an SAR proposed by Tian et al. (2002) were: the largest area of the AR $\geq$1000 µh (millionths of solar hemisphere), the flare index $\geq$5.0, the peak flux of 10.7 cm radio flux $\geq$1000 s.f.u., and the flux of E >10 Mev$\geq$400 pfu (1 pfu=1 particle $cm^{-2}\,s^{-1}\,sr^{-1}$), and geomagnetic index Ap$\geq$50, respectively. If an AR can satisfy three of the five parameters, then the AR is an SAR. The concept of SAR proposed by Tian et al. (2002) linked SARs with SPEs and geomagnetic storms. Romano & Zuccarello (2007) defined flare index as

$$I(t) = 0.1 \times \sum B(t) + \sum C(t) + 10 \times \sum M(t) + 100 \times \sum X(t) \quad (1)$$

where $B(t)$, $C(t)$, $M(t)$ and $X(t)$ are the coefficients of the flare that occurred at time t and belong to the classes B, C, M and X, respectively.

If $I(t)$ produced by an AR is greater than 500, then the AR is called an SAR by Romano & Zuccarello (2007). It is evident that SARs defined by Romano & Zuccarello (2007) are only linked with solar flares. Different researchers have different criteria for SARs, leading to different lists of SARs for the same period. Chen et al. (2011) select an adequate set of criterion parameters and reparameterize the SARs during SCs 21–23. The parameters used to define SARs in the article by Chen et al. (2011) are: (1) the largest area of the AR is greater than 1000 µh and (2) flare index is larger than 10. Note that 0.1 for an M1 class flare and 1.0 for an X1 class flare in the calculation of the flare index were proposed by Chen et al. (2011). (3) The peak value of 10.7 cm radio flux>1000 s.f.u., (4) the short term total solar irradiance decrease (ΔTSI) is lower than 0.1%. If an AR satisfies three of these four criteria, then the AR is an SAR. If the flare index of an AR is larger than 15, and any one of the other three other criteria are met, then the AR is also an SAR. The criteria proposed by Chen et al. (2011) to select SARs have three properties. First, the parameters selected to determine SAR are independent, each providing a complementary insight into SAR physics. Secondly, the parameters can be easy to access. Thirdly, the number of parameters used to select SARs is both simple and unique.

It has been found that 44% of all X class X-ray flares during SCs 21–23 were produced by 45 SARs (Chen et al. 2011). However, little attention has been paid to the relationship between SARs, super geomagnetic storms (SGSs, Dst $\leq$ –250 nT) and ground level enhancement (GLE) events. When an SAR erupts, it might only produce a flare, or it might produce both a flare and a CME, which may lead to a relativistic solar proton event and then cause a GLE event. If the CME and CME-driven shock finally reaches the Earth, it may trigger an SGS. In this context, SARs not only can produce very strong flares, but also are able to generate GLE events and super magnetic storms.

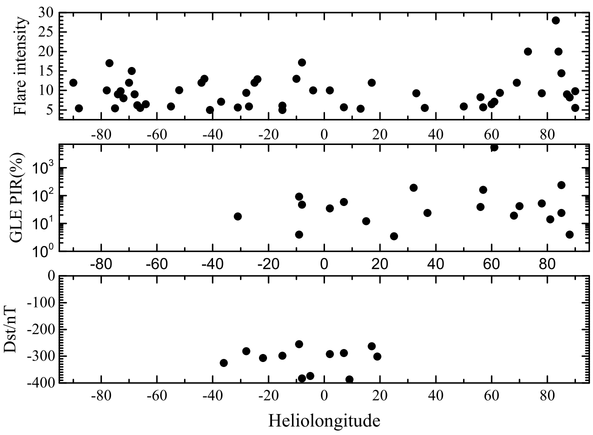

Fig. 1 The heliolongitudinal distribution of the source locations of extreme space weather events caused by SARs during SCs 21–24. From top to bottom, the figure displays the $\geq$X5.0 flares, PIR of the GLEs and SGSs, respectively.

There were 45 SARs during SCs 21–23, five SARs that appeared in SC 24 were identified by Chen & Wang (2016) and AR 12673 is also an SAR according to the criteria proposed by Chen et al. (2011). Hence, there were totally 51 SARs during SCs 21–24. Extreme space weather events are defined as solar flares with intensities $\geq$X5.0, SGSs (Dst $\leq$ –250 nT) and GLE events in this study. There is only one complete list of SARs during SCs 21–24 according to the criteria published in Chen et al. (2011). Now the question is how many extreme space weather events were caused by SARs during SCs 21–24. To answer such questions, the extreme space weather events caused by SARs during SCs 21–24 will be investigated based on the 51 SARs according to criteria proposed by Chen et al. (2011). This is the motivation for the present study. The data analysis is presented in Section 2, discussion is in Section 3 and the summary is in Section 4.

2 DATA ANALYSIS

2.1 Data Source

The flares with intensities $\geq$X5.0 during SCs 21–24 were obtained from the website *ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/xrs/*. The fluxes of E>10, 30, 50 and 100 MeV protons observed by GOES are available at the website *https://satdat.ngdc.noaa.gov/sem/goes/data/avg/*. The SGSs were acquired from the website at *http://wdc.kugi.kyoto-u.ac.jp/dstdir/*. GLEs can be directly referenced from the appendix in the article by Le & Liu (2020).

Table 1 Flares with Intensities ≥X5.0 Caused by SARs During Solar Cycles 21–24

No.	Date yyyy-mm-dd	Start hh:mm	Peak hh:mm	End hh:mm	Flare intensity	Location	AR	SAR?
1	1978–04–28	13:08	13:29	19:13	X5.0	N22E41	1092	Yes
2	1979–08–18	14:03	14:16	14:45	X6.0	N10E90	1943	No
3	1979–08–20	09:06	09:23	10:05	X5.0	N05E76	1943	No
4	1979–09–19	22:56	23:03	23:45	X5.0	N06E33	1994	No
5	1980–04–04	14:57	15:09	17:29	X5.0	N24W34	2363	No
6	1980–11–06	03:40	03:48	04:48	X9.0	S12E74	2779	Yes
7	1981–04–24	13:46	14:11	16:15	X5.9	N18W50	3049	Yes
8	1981–04–27	07:20	08:20	09:45	X5.5	N17W90	3049	Yes
9	1982–06–03	11:41	11:48	12:46	X8.0	S09E72	3763	Yes
10	1982–06–04	13:13	13:30	13:58	X5.9	S10E55	3763	Yes
11	1982–06–06	16:30	16:54	18:32	X12.0	S09E25	3763	Yes
12	1982–07–09	07:31	07:38	08:24	X9.8	N17E73	3804	Yes
13	1982–07–12	09:16	09:18	12:00	X7.1	N11E37	3804	Yes
14	1982–12–15	01:50	01:59	02:46	X12.9	S10E24	4026	Yes
15	1982–12–15	16:20	16:37	17:09	X5.0	S10E15	4026	Yes
16	1982–12–17	18:19	18:58	20:23	X10.1	S08W21	4025	No
17	1984–04–24	23:56	24:01	24:60	X13.0	S12E43	4474	Yes
18	1984–05–20	22:18	22:41	23:57	X10.1	S09E52	4492	Yes
19	1988–06–24	16:44	16:48	17:38	X5.6	S17W56	5047	No
20	1989–03–06	13:54	14:10	15:04	X15.0	N35E69	5395	Yes
21	1989–03–17	17:29	17:37	18:52	X6.5	N33W60	5395	Yes
22	1989–08–16	01:08	01:17	02:28	X20.0	S18W84	5629	Yes
23	1989–09–29	10:47	10:93	13:15	X9.8	S20W90	5698	Yes
24	1989–10–19	12:29	12:55	17:33	X13.0	S27E10	5747	Yes
25	1989–10–24	17:36	18:31	23:04	X5.7	S30W57	5747	Yes
26	1990–05–21	22:12	22:17	23:39	X5.5	N35W36	6063	Yes
27	1990–05–24	20:46	20:49	21:05	X9.3	N33W78	6063	Yes
28	1991–01–25	06:30	06:30	06:38	X10.0	S16E78	6471	Yes
29	1991–03–04	13:56	14:03	15:08	X7.1	unknown	unknown	unknown
30	1991–03–07	06:11	07:08	08:17	X5.5	S20E66	6538	Yes
31	1991–03–22	22:43	22:45	23:17	X9.4	S26E28	6555	Yes
32	1991–03–25	07:58	08:18	08:44	X5.3	S24W13	6555	Yes
33	1991–06–01	15:09	15:29	16:14	X12.0	N25E90	6659	Yes
34	1991–06–04	03:37	—	07:30	X12.0	N30E70	6659	Yes
35	1991–06–06	00:54	01:12	01:35	X12.0	N30E44	6659	Yes
36	1991–06–09	01:37	01:40	03:04	X10.0	N33E04	6659	Yes
37	1991–06–11	02:09	02:29	03:20	X12.0	N31W17	6659	Yes
38	1991–06–15	06:33	07:51	09:17	X12.0	N33W69	6659	Yes
39	1991–10–27	05:38	05:49	06:18	X6.1	S13E15	6891	Yes
40	1992–11–02	02:31	03:08	03:28	X9.0	S26W87	7321	Yes
41	1997–11–06	11:49	11:55	12:01	X9.4	S18W63	8100	Yes
42	2000–07–14	10:03	10:24	10:43	X5.7	N22W07	9077	Yes
43	2001–04–02	21:32	21:51	22:03	X20.0	N19W73	9393	Yes
44	2001–04–06	19:10	19:21	19:31	X5.6	S21E31	9415	Yes
45	2001–04–15	13:19	13:50	13:55	X14.4	S20W85	9415	Yes
46	2001–08–25	16:23	16:45	17:04	X5.3	S17E34	9591	No
47	2001–12–13	14:20	14:30	14:35	X6.2	N16E09	9733	No
48	2003–10–23	08:19	08:35	08:49	X5.4	S21E88	10486	Yes
49	2003–10–28	09:51	10:30	10:44	X17.2	S16E08	10486	Yes
50	2003–10–29	20:37	20:49	21:01	X10.0	S15W02	10486	Yes
51	2003–11–02	17:03	17:25	17:39	X8.3	S14W56	10486	Yes
52	2003–11–04	19:29	19:50	20:06	X28.0	S19W83	10486	Yes
53	2005–01–20	06:36	07:01	07:26	X7.1	N14W61	10720	Yes
54	2005–09–07	17:17	17:40	18:03	X17.0	S11E77	10808	Yes
55	2005–09–08	20:52	21:06	21:17	X5.4	S12E75	10808	Yes
56	2005–09–09	19:13	20:04	20:36	X6.2	S12E67	10808	Yes
57	2006–12–05	10:18	10:35	10:45	X9.0	S07E68	10930	Yes
58	2006–12–06	18:29	18:47	17:00	X6.5	S05E64	10930	Yes
59	2011–08–09	07:48	08:05	08:08	X6.9	N17W69	11263	No
60	2012–03–07	00:02	00:24	00:40	X5.9	N11E27	11429	Yes
61	2017–09–06	11:53	12:02	12:10	X9.3	S08W33	12673	Yes
62	2017–09–10	15:35	16:06	16:31	X8.2	S08W88	12673	Yes

2.2 ≥ X5.0 Solar Flares Caused by SARs

According to the source locations of the ARs that produced ≥X5.0 flares and the list of 51 SARs, ≥X5.0 flares and the corresponding ARs are listed in Table 1. In the table, the number of ≥X5.0 flares is in column (1), the date of the flare in column (2), the start, peak and end times of the flare in columns (3), (4) and (5), respectively, the flare intensity in column (6), the source location of the flare in column (7), the NOAA number of the AR in column (8) and whether the AR is an SAR in column (9). There

Table 2 The GLE Events Caused by SARs During Solar Cycles 21–24

GLE No.	Date yyyy-mm-dd	Location	Flare	AR	SAR?
27	1976–04–30	S08W46	2B/X2.0	700	No
28	1977–09–19	N08W57	3B/X2.0	889	No
29	1977–09–24	N10W120	—	889	No
30	1977–11–22	N24W40	2B/X1.0	939	No
31	1978–05–07	N23W72	2B/X2.0	1095	No
32	1978–09–23	N35W50	3B/X1.0	1294	No
34	1981–04–10	N07W36	2B/X2.3	3025	No
35	1981–05–10	N03W75	2B/M1.3	3079	No
36	1981–10–12	S18E31	2B/X3.1	3390	Yes
37	1982–11–26	S12W87	2B/X4.5	3994	No
38	1982–12–07	S19W86	1B/X2.8	4007	No
39	1984–02–16	S-W130	—	4408	No
40	1989–07–25	N26W85	1B/X2.5	5603	No
41	1989–08–16	S15W85	2N/X20	5629	Yes
42	1989–09–29	S24W105	1B/X9.8	5698	Yes
43	1989–10–19	S25E09	3B/X13	5747	Yes
44	1989–10–22	S27W32	1N/X2.9	5747	Yes
45	1989–10–24	S29W57	2N/X5.7	5747	Yes
46	1989–11–15	N11W28	2B/X3.2	5786	No
47	1990–05–21	N34W37	2B/X5.5	6063	Yes
48	1990–05–24	N36W78	1B/X9.3	6063	Yes
49	1990–05–26	N35W103	–/X1.4	6063	Yes
50	1990–05–28	N35W120	C9.7	6063	Yes
51	1991–06–11	N32W15	2B/X12	6659	Yes
52	1991–06–15	N36W70	2B/X12	6659	Yes
53	1992–06–25	N09W69	2B/X3.9	7205	No
54	1992–11–02	S25W100	–/X9.0	7321	Yes
55	1997–11–06	S18W68	2B/X9.4	8100	Yes
56	1998–05–02	S15W15	3B/X1.1	8210	No
57	1998–05–06	S11W65	1N/X2.7	8210	No
58	1998–08–24	N18E09	3B/M7.1	8307	Yes
59	2000–07–14	N22W07	3B/X5.7	9077	Yes
60	2001–04–15	S20W85	2B/X14	9415	Yes
61	2001–04–18	S20W115	–/C2.2	9415	Yes
62	2001–11–04	N06W18	3B/X1.0	9684	No
63	2001–12–26	N08W54	1B/M7.1	9742	No
64	2002–08–24	S02W81	1F/X3.1	10069	Yes
65	2003–10–28	S16E08	4B/X17.0	10486	Yes
66	2003–10–29	S15W02	2B/X10.0	10486	Yes
67	2003–11–02	S14W56	2B/X8.3	10486	Yes
68	2005–01–17	N15W25	3B/X3.8	10720	Yes
69	2005–01–20	N14W61	2B/X7.1	10720	Yes
70	2006–12–13	S06W23	4B/X3.4	10730	Yes
71	2012–05–17	N11W76	1F/M5.1	11476	No
72	2017–09–10	S08W88	–/X8.2	12673	Yes

were 62 flares with intensities ≥X5.0 during SCs 21–24, as affirmed in Table 1. Of the 62 ≥X5.0 flares, nine of them were not caused by SARs. The source location for one flare that occurred on 1991 March 4 is unknown; 51 flares with intensities ≥X5.0 were caused by SARs, indicating that 83.9% of the flares with intensities ≥X5.0 were caused by SARs. If we divide ≥X5.0 flares into two subgroups, the numbers of X5.0-X9.9 and ≥X10.0 flares are 41 and 21, respectively. We can thus affirm that 78.05% of the X5.0-X9.9 and 95.24% of the ≥X10.0 flares were produced by SARs.

2.3 GLE Events Caused by SARs

The GLE events and their corresponding ARs are listed in Table 2. In the table, the number of the GLE event is in column (1), the date in column (2), the source location of the GLE event in column (3), the flare associated with the GLE event in column (4), the NOAA number of the AR in column (5) and whether the AR is an SAR in column (6). We can see from Table 2 that there were 46 GLEs during SCs 21–24. Of the 46 GLEs, 25 GLEs were caused by SARs, namely 54.3% of the GLE events during SCs 21–24 were caused by SARs.

2.4 Super Geomagnetic Storms Caused by SARs

The ARs that produced SGSs during different SCs have been investigated by many researchers (e.g. Cliver & Crooker 1993; Zhang et al. 2007). Meng et al. (2019) collected various information on the ARs that produced CMEs responsible for the SGSs during SCs 19–24. According to the ARs related to the SGSs during SCs 21–24, each SGS and the corresponding AR during SCs 21–24 are listed in Table 3. In Table 3, column (1) is the number of the SGS, column (2) is the date, column (3)

Table 3 SGSs and Related ARs During Solar Cycles 21–24

No.	Date yyyy-mm-dd	Dst nT	Location	AR	SAR?
1	1981–04–13	–311	N07W36	3025	No
2	1982–07–14	–325	N11E36	3804	Yes
3	1982–09–06	–289	N12E35	3886	No
4	1986–02–09	–307	S11W21	4711	No
5	1986–02–09	–307	N32E22	5395	Yes
6	1989–03–14	–589	N23W24	5687	No
7	1989–09–19	–255	S25E09	5747	Yes
8	1989–10–21	–268	N11W28	5786	No
9	1989–11–17	–266	N24E28	6007	No
10	1990–04–10	–281	S26E28	6555	Yes
11	1991–03–25	–298	S13E15	6891	Yes
12	1991–10–29	–254	S14W20	6909	No
13	1991–11–09	–354	S26E07	7154	No
14	1992–05–10	–288	N15W66	8933	No
15	2000–04–07	–288	N22W07	9077	Yes
16	2000–07–16	–301	N20W19	9393	Yes
17	2001–03–31	–387	S23W09	9415	Yes
18	2001–04–11	–271	N06W18	9684	No
19	2001–11–06	–292	S15W02	10486	Yes
20	2003–10–30	–383	S16E08	10486	Yes
21	2003–10–30	–353	S01E16	10501	No
22	2003–11–20	–422	N09E05	10501	No
23	2004–11–08	–374	N09W17	10696	Yes
24	2004–11–10	–263	N09W17	10696	Yes

Table 4 Extreme Space Weather Events Caused by SARs During Different Solar Cycles

SC	SARs and ≥X5.0 flares				SARs and GLE events				SARs and Dst≤–250 nT storms			
	N_{SAR1}	N_{SAR2}	N_{SAR}	$N_{\geq X5}$	N_{SAR1}	N_{SAR2}	N_{SAR}	N_{GLE}	N_{SAR1}	N_{SAR2}	N_{SAR}	N_{SGS}
21	8	9	17	13	1	16	17	1	1	16	17	1
22	11	5	16	21	6	10	16	12	4	12	16	4
23	8	4	12	15	7	5	12	11	5	7	12	7
24	2	4	6	3	1	5	6	1	0	6	6	0
total	29	22	51	51	15	36	51	25	10	41	51	12

Table 5 SARS Producing All Three Types of Extreme Space Weather Events

SAR	≥X5.0 flare	No. of GLE	No. of SGS
5747	X13+X5.7	3	1
9077	X5.7	1	1
9415	X5.6+X14.4	2	1
10486	X5.4+X17.2+X10 +X8.3+X28	3	2

is the SGS intensity, the source location of the AR is in column (4), the NOAA number of the AR in column (5) and whether the AR is an SAR in column (6). We can see from Table 3 that there are 24 SGSs during SCs 21–24. Of the 24 SGSs, 12 of them were caused by SARs, namely 50% of the SGSs were caused by SARs.

2.5 Extreme Space Weather Events Caused by SARs During Different Solar Cycles

We use N_{SAR1} and N_{SAR2} to indicate the numbers of SARs that can produce and cannot produce extreme space weather events during an SC, respectively. N_{SAR} indicates the total number of SARs during an SC. The extreme space weather events caused by SARs during different SCs were analyzed and the derived results are listed in Table 4. We can see from Table 4 that only 29 SARs could generate ≥X5.0 flares. The numbers of SARs that can produce ≥X5.0 flares in SCs 21, 22, 23 and 24 are 8, 11, 8 and 2, respectively, and the numbers of ≥X5.0 flares caused by SARs in SCs 21–24 are 13, 21, 15 and 3, respectively. The numbers of SARs that could produce GLE events in SCs 21, 22, 23 and 24 are 1, 6, 7 and 1, respectively, and the numbers of GLE events caused by SARs in SCs 21–24 are 1, 12, 11 and 1, respectively. Only 10 SARs produced SGSs. The numbers of SARs that triggered SGSs in SCs 21, 22, 23 and 24 are 1, 4, 5 and 0, respectively, and the numbers of SGSs caused by SARs in SCs 21–24 are 1, 4, 7 and 0, respectively. The results indicate that the contribution to the extreme space weather events made by SARs in solar cycle 24 is the smallest. Most extreme space weather events caused by SARs, especially for GLE events and SGSs, appeared in SCs 22 and 23.

2.6 The Properties of the Source Locations of the Extreme Space Weather Events Caused by SARs

The longitudinal distribution of source locations for extreme space weather events caused by SARs is plotted in Figure 1. As displayed in the top panel of Figure 1, the longitudinal scope for the flares with intensities ≥X5.0 caused by SARs ranged from E90 to W90. The

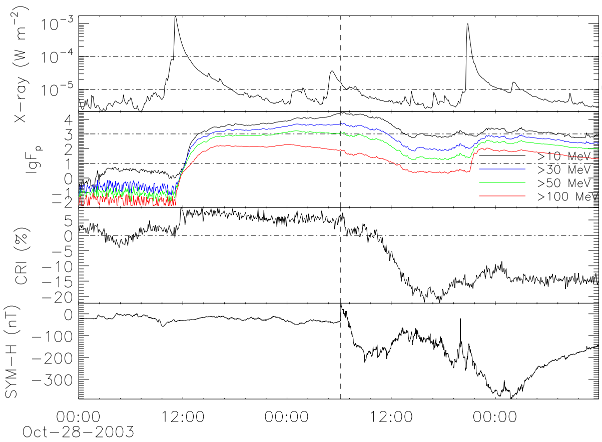

Fig. 2 The solar activities and their geoeffectiveness caused by SAR 10486 during 2003 October 28–30. From top to bottom, it shows solar flares, the fluxes of $E>10$, 30, 50 and 100 MeV protons observed by GOES 10, the counting rate of cosmic rays observed by the Oulu neutron monitor and the SYM-H index, respectively. The dashed line signifies the moment of the SSC.

longitudinal area of the source locations of GLE events caused by SARs ranged from E31 to W120 according to Table 2, and the heliolongitude of the strongest GLE events is located around W60, which is shown in the second panel of Figure 1. It can be noted that the abscissa scope in the second panel only ranged from E90 to W90 which is consistent with the upper and lower panels. The peak increase rate (PIR) for each GLE event that occurred during SCs 21–23 is obtained from Belov et al. (2010), while the PIR for the GLE that occurred on 2017 September 10 is referenced from Zhao et al. (2018). The longitudinal span of the source locations of the SGSs caused by SARs ranged from E36 to W19, as depicted in the lowest panel of Figure 1, indicating that only the CMEs produced by the corresponding SARs with source locations around the solar disk center can produce SGSs.

3 DISCUSSION

Among the 51 SARs, 18 of them did not produce a ≥X5.0 flare, nor did they produce a GLE event or an SGS. For the remaining 33 SARs, each of them produced at least an extreme space weather event. In this context, 64.7% (or 33/51) of the SARs generated extreme space weather events. Ten SARs triggered both a ≥X5.0 flare and a GLE, but they did not produce an SGS. Only four SARs not only initiated at least a ≥X5.0 flare, but also produced at least a GLE event and an SGS. Here, we showcase an example in Figure 2. As depicted in Figure 2, the SAR 10486 with source location at S16E08 generated an X17.2 flare and a CME with projected speed 2459 km s^{-1} on 2003 October 28. The flux of $E>10$ MeV protons increased quickly after the flare and the CME, and reached its peak flux of 29 500 pfu at 06:10 UT, 2003 October 29, which is consistent with the moment of sudden storm commencement (SSC), indicating that the flux of $E>10$ MeV protons reached its peak flux at the moment when the CME-driven shock reached the magnetosphere. As demonstrated in the second panel of Figure 2, the cosmic ray intensity (CRI) obviously increased, namely that a GLE event was observed. When the CME-driven shock and the CME itself reached the magnetosphere, it triggered an SGS (Dst_{min}=–353 nT, $SYM\text{-}H_{min}$=–391 nT). The SGS was mainly caused by an interplanetary CME (ICME) (Zhang et al. 2008). SAR 10486 initiated X5.4+X17.2+X10 +X8.3+X28 flares, three GLE events and two SGSs; four SARs, which produced not only a ≥X5.0 flare, but also a GLE event and an SGS, are listed in Table 5.

Different lists of SARs given by different researchers will lead to different extreme space weather events caused by the corresponding SARs. Which one is better? To answer this question, we made a comparison between the SARs reported by Tian et al. (2002) with those published by Chen et al. (2011) in solar cycle 22. There were 14 SARs during solar cycle 22 given by Tian et al. (2002), while 16 SARs in solar cycle 22 given by Chen et al. (2011). Nine SARs occurred in both lists of the SARs, so we only compare the different SARs in the two lists. The comparison is displayed in Table 6. We can see from Table 6 that the solar flare activities of the SARs proposed by Chen et al. (2011) shown in Table 6 were much stronger than those proposed by Tian et al. (2002). The comparison between the different SARs during solar cycle 22 by Tian et al. (2002) and by Chen et al. (2011) implies that the concept of SAR proposed by Chen et al. (2011) puts more emphasis on flare activity than that proposed by Tian et al. (2002), while the concept of SAR put forward by Tian et al. (2002) paid more attention to the geoeffectiveness of SARs than that purported by Chen et al. (2011). The comparison tells us that both criteria proposed by Tian et al. (2002) and by Chen et al. (2011) should be improved. Anyway, there was only a complete list of the SARs for SCs 21–24 according to the criteria published by Chen et al. (2011). This is the reason why we study the extreme space weather events during SCs 21–24 caused by SARs only based on the 51 SARs according to the criteria proposed by Chen et al. (2011). The criteria for SAR will be more reasonable after more study and descriptions of the extreme space weather events caused by SARs will be revised.

4 SUMMARY

The following lists the major points concluded from this study:

(i) There were 62 ≥X5.0 flares and 51 SARs during SCs 21–24. Of the 62 ≥X5.0 flares, 51 of them were produced by SARs, namely 83.9% of the ≥X5.0 flares were produced by SARs. Of the 51 ≥X5.0 flares, the

Table 6 Comparison of Different SARs During Solar Cycle 22

SAR	Date on the disk	LA (μh)	FI	X-class flares	10.7 cm peak flux (s.f.u.)	SPEI[1] (pfu)	Ap	Authors
5800	891119-1202	590	3.6	X1.0+X2.6	2100	7300	110	Tian et al. (2002)
6022	900414-0427	1070	1.4	X1.4	11000	12	125	Tian et al. (2002)
6703	910628-0713	280	1.9	X1.9	1778	2300	135	Tian et al. (2002)
7154	920504-0515	500	2.1	(M7.4)<X1.0	3100	4600	180	Tian et al. (2002)
7671	940213-0226	450	1.7	(M4.0)<X1.0	190	10000	95	Tian et al. (2002)
5312	890106-0120	1800	20.64	2(X1.1+X1.4)+X2.3+X2.1	1400	NG[2]	NG	Chen et al. (2011)
5533	890609	920	11.37	X4.1+X3.0	1100	NG	NG	Chen et al. (2011)
5669	890829-0912	3080	13.32	X1.2+X1.1+X1.3	4800	NG	NG	Chen et al. (2011)
5852	891225-1231	1500	6.42	X2.8	1600	NG	NG	Chen et al. (2011)
6471	910125-0208	2210	15.27	X10+X1.9	3500	NG	NG	Chen et al. (2011)
6538	910305-0317	910	17.08	X1.5+X2+X5.5+X2.5+X1.7	3500	NG	NG	Chen et al. (2011)
6545	910311-0322	830	16.93	X1.7+X1.3+X3.9+X1.8+X1.8+X1.0	3600	NG	NG	Chen et al. (2011)

numbers of X5.0-X9.9 and ≥X10.0 flares are 41 and 21, respectively, and 78.05% of the X5.0-X9.9 and 95.24% of the ≥X10.0 solar flares were produced by SARs. The number of ≥X5.0 flares produced by the SARs in SCs 21, 22, 23 and 24 were 13, 21, 15 and 3, respectively. Only 29 SARs could generate ≥X5.0 flares, indicating that only 56.9% of the SARs could trigger ≥X5.0 flares. The longitudinal area of the source locations of the flares with intensities ≥X5.0 caused by SARs ranged from E90 to W90.

(ii) Forty-six GLEs were registered during SCs 21–24. Of the 46 GLE events, 25 GLE events were caused by SARs, namely 54.3% of the GLEs were caused by SARs. The numbers of GLE events caused by the SARs in SCs 21, 22, 23 and 24 were 1, 12, 11 and 1, respectively, indicating that most of the GLE events caused by the SARs came from SCs 22 and 23. Only 15 SARs could produce GLE events, namely only 29.4% of the SARs generated GLE events. The longitudinal scope of the source locations of GLE events caused by SARs ranged from E31 to W120. The longitude of the source location for the strongest GLE event is located around W60.

(iii) There were 24 SGSs during SCs 21–24; 12 SGSs were caused by SARs, namely 50% of the SGSs were caused by SARs. The numbers of SGSs caused by SARs in SCs 21, 22, 23 and 24 were 1, 4, 7 and 0, respectively. Only 10 SARs could produce SGSs, indicating that only 19.6% of the SARs could generate SGSs. The longitudinal span of the source locations of SGSs caused by SARs ranged from E36 to W19.

(iv) Of the 51 SARs, only 33 SARs produced at least one extreme space weather event, while none of the other 18 SARs produced an extreme space weather event. There were only four SARs and each of them could produce not only a ≥X5.0 flare, but also a GLE event and an SGS. Most of the extreme space weather events caused by the SARs appeared during SCs 22 and 23, especially for the GLE events and SGSs. Solar Cycle 24 is a very weak cycle, the number of the SARs is small and the number of extreme space weather events caused by the SARs is also small, in particular, there was no SGS in solar cycle 24.

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