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Evolution of a Long-lived Sunspot Group and Its Associated Solar-terrestrial Events *

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Abstract A long-lived sunspot group (AR 9604) on the south hemisphere that lasted five solar rotations and produced some strong bursts is analyzed. The focus is on its evolving features. Its whole life was successfully maintained by four Emerging Flux Regions (EFRs). Apart from the one that lasted only a short time and did not produce any bursts, the other three EFRs have the following common features: (1) A positive writhe of magnetic flux tubes and a twist of the field lines of the same sign, indicating kink instability. (2) A clockwise rotation and a high tilt because the writhe was right-handed. (3) A compact "island δ" structure of the sunspot group indicating concentrated kink instability. Since magnetic reconnection easily occurs at the kinked point of a very kink-unstable flux tube, these features should be the inducement of the strong bursts.

Key words: Sun — active region evolution

1 INTRODUCTION

The life-span of sunspot groups varies much: it can be as short as a few days or as long as several months. The evolution of sunspot groups, whether short- or long-lived, undergoes three phases: a growing phase, a mature phase and a decay phase. Most of sunspot groups are formed by one Emerging Flux Region (EFR), or two EFRs. A large and complex sunspot group can be formed by one large EFR or several EFRs, and last longer. As the flux tube crosses the photospheric surface, two flux concentrations of opposite polarity appear. So, the sunspot groups observed on the photosphere are substantially manifestation of the emergence of a flux tube formed by the toroidal magnetic field originated at the base of the convection zone. This way, the evolution of the active regions observed in the photosphere, chromosphere and corona can give some information on the flux tubes in the sub-photosphere and the convective zone. From this, we can presume the evolving characteristics of relevant flux tubes and analyze the relationship between such characteristics and solar bursts.

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Some authors have studied the evolution of long-lived active regions. For example, Tanaka (1991) examined the famous northern active region, McMath 1176 (N10°) of 1972. Zhang (1993) checked the evolution of longitudinal magnetic field in the long-lived active region NOAA6580 (N30°) of 1991. Lopez et al. (2000) analyzed and studied the evolution of a typical, simple active region NOAA 7912 (S10°) in 1995 that lasted five rotations.

The active region analyzed in this paper also lasted five rotations. They were successively numbered as NOAA 9604, NOAA 9632, NOAA 9672, NOAA 9704 and NOAA 9738. To distinguish the long-lived sunspot group from its various returns, we use the name AR 9604. In Section 2, the accompanying solar flares, Coronal Mass Ejection (CME) and their influence over the earth and near- earth space will be described. In Section 3, we will analyze the evolution of the active region. We will discuss the writhe, the twist and kink instability of this active region in Section 4. Section 5 will give our conclusions.

We collected 43 sets of sunspot images, magnetograms, Extreme UltraViolet (EUV) and soft X-ray images, one set for each day while the active region was on the visible disk. We tried to collecting the data that were taken in times as close as possible in order to facilitate analysis. The data are from Big Bear Solar Observatory (BBSO), the EUV Imaging Telescope (EIT) on Solar and Heliospheric Observatory (SOHO) and the Solar X-ray Telescope (SXT) on YOHKOH satellite. The vector magnetic field data are from the Huairou Solar Observing Station of NAOC. The CME images are from the Large Angle and Spectrometric Coronagraph –C2 (LASCO–C2) on SOHO. The Sudden Ionospheric Disturbance (SID) data are taken from SGD I (http://sgd.ngdc.noaa.gov) and Time & Frequency Bulletin from September to November, 2001 pressed by Shanxi Astronomical Observatory, Chinese Academy of Sciences. The data of solar flare, soft X-ray bursts, solar proton events and geomagnetic disturbances are obtained from http://vraben@sec.noaa.gov.

2 BURSTS AND SOLAR-TERRESTRIAL EFFECTS

The strong bursts produced by the long-lived sunspot group, AR 9604, all occurred during three returns (known as NOAA 9632, NOAA 9672 and NOAA 9704), including three X-class flares, 10 M-class flares and 12 CMEs, five of which were fast halo CMEs with $v > 1000\,\mathrm{km\ s^{-1}}$. The resuolting geophysical effects included four solar proton events, 10 SID with I$>$ 2 and four geomagnetic disturbances (Table 1). Of the six strong solar proton events with peak flux $> 10\,000$ pfu (in units of particle $\mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$) occurred so far in solar cycle 23, two belonged to AR 9604. The CMEs and relevant flares, the active region corresponding to the bursts and their associated events, are given in Table 1.

Table 1 shows the following features: (1) The fast CMEs roughly corresponded with strong flares. (2) The solar proton events and geomagnetic disturbances were led by fast halo CMEs with $V > 1000\,\mathrm{km\ s^{-1}}$. (3) Their intensities were not related to any positive or negative values of the acceleration.

3 EVOLUTIONS OF SUNSPOT GROUP AND MAGNETIC FIELD

The long-lived sunspot group AR 9604 is remarkable for its emergence with a large tilt angle, its concentration and its continuous rotation. First, we must define the tilt angle of the magnetic polarity axis of an active region and describe the method of its calculation.

3.1 Tile Angle of the Magnetic Polarity Axis

The tilt angle of the magnetic polarity axis in an active region is defined as the angle between the line joining the opposite polarities and the solar equator (Tian et al. 1999). Accordingly, the angle between the line joining a pair of the spots with opposite polarities and the solar equator is taken as the tilt angle of the magnetic polarity axis of the corresponding Emerging Flux Region (EFR). Our task here is to analyze the development and evolution of sunspot group or magnetic field in the line of sight. Now, it is well known that the least magnetic intensity of spots observable is 400 G (Zirin 1988), so we set the minimum critical value of magnetic intensity at 400 G in order to be sure that the tilt angle is not affected by weak magnetic fields and that we can bring out the essential character of the rotation. The position of each main spot (main magnetic flux) is approximately indicated by the magnetic flux weighted center of each magnetic polarity in the line of sight (Tian et al. 2001) according to the following formula:

$$\begin{aligned} x_c &= \frac{\sum x(j,i)\, B_{||}(j,i) ds}{\sum B_{||}(j,i) ds}\,, \\ y_c &= \frac{\sum y(j,i)\, B_{||}(j,i) ds}{\sum B_{||}(j,i) ds}\,, \end{aligned} \qquad (1)$$

where, $ds = dxdy$ is the area of each pixel.

In Fig. 1, the origin of the polar coordinates, "P", corresponds to the weighted center of the *preceding* polarity defined by the Hale-Nicholson law whether the sunspot group is on the southern or northern hemisphere and azimuth is reckoned from the easterly direction. The radius vector (from P) to the weighted center of the *following* polarity defined by the Hale-Nicholson law then defines the magnetic polarity axis of the active region or EFR, and its azimuth (ϕ) of the magnetic polarity axis is the Tilt Angle of Magnetic Polarity Axis (TAMPA) of the active region or EFR.

The azimuth ϕ from East via South to West is positive (that is to say, the magnetic polarity axis rotates clockwise), and negative from East via South to West. Consequently, a northern active region obeying the Hale-Nicholson and Joy laws has $0 \leq \phi \leq 45°$ (or $-360° \leq \phi \leq -315°$), and a southern active region, has $0° \geq \phi \geq -45°$ (or $315° \leq \phi \leq 360°$). An active region obeying the Hale law is called a "Hale region", otherwise, a "non-Hale region".

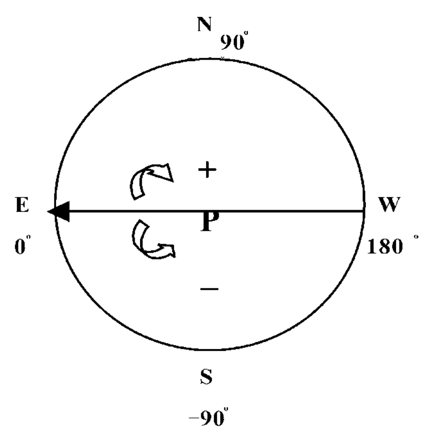

Fig. 1 Orientation of TAMPA.

Table 1 CMEs and Relevant Flares in AR 9604 and Their Associated Events on Earth

Reg.	Flare		CME				Proton	Geomag.	SID
NOAA	Start day /time (UT)	Class	Ang. Width (°)	Linear Fit Speed (km s^{-1})	20 $R_\odot$ Speed (km s^{-1})	Accel. (km s^{-2})	Peak Flux (PFU)	Disturb.	(Imp.)
9632	09.23/1418	C6.5/SF	165			–4.0			2
	09.24/0932	X2.6/2B	360	2402	2500	+54.1	12900	$K=6$ –102nT	3
9672	10.18/1907	C8.5/SF	162	634	624	–2.0			
	10.22/1427	M6.7/2N	360	1336	1317	–8.0	24.2	$K=5$	2^+
	10.22/1744	X1.2/2B	106	618	572	–7.6		–165nT	2^+
	10.25/1442	X1.3/2B	360	1092	1087	–1.5		$K=6$ –157nT	3
	10.29/0152	M1.3	29	318	1085	+47.4			
	10.29/0807	M1.0/1F	105	617	429	–12.4			
9704	11.17/0449	M2.8/1N	360	1379	1350	–22.5	34		3^-
	11.21/1207	C4.7/SF	360	518	507	–1.2			2
	11.22/2232	M9.9/2N	360	1437	1409	–12.9	18900	$K=9$ –221nT	
	11.25/0100	C4.5/SF	9	580	0	–25.9			

According to the Hale-Nicholson law, in Cycle 23, the preceding sunspot of a sunspot group on the southern (northern) hemisphere has negative (positive) polarity. Now, AR 9604, appeared on the south hemisphere during the peak years of cycle 23, so the origin of the polar coordinates "P" in Fig. 1 represents negative (**S**) polarity. Although our main purpose is to analyze the evolution of the sunspot group, in order to cut down as much as possible errors due to projection effects, we limited our calculation of TAMPA to 41° on either side of the central meridian.

It is well known that the morphology of a spot group is influenced by the solar differential rotation, and the influence is especially strong when the line joining the opposite polarities is perpendicular to the solar equator. Fortunately, AR9604 presented a compact "island δ" structure most of the time and the angular distance in the north-south direction between the main spots of opposite polarities never exceeded 6° and the angular distance between the weighted centers of the two polarities was always less than 3.5°. Therefore, the influence of differential rotation was very small, and accordingly, we neglected it when estimating the rotation of the spot group or magnetic flux tube.

3.2 Returns and Evolving Features of the Active Region

A pore appeared on the Southwestern part of the solar disk on 2001 September 2. Its heliographic coordinate was S21° W47° (L269°). It formed a sunspot group with two well-separated spots, that one with the positive polarity (N) was located almost exactly northward of the one with the negative polarity (S) on Sept. 3 (the relevant EFR is marked EFR (S, N) in Fig. 2a). Its magnetic polarity axis was thus perpendicular to the equator (a perpendicular magnetic configuration). This small sunspot group was numbered as NOAA 9604. Obviously, it was a non-Hale region. It followed the solar rotation to the back of the sun on Sept. 5.

A sunspot group was observed on the south-east limb of the solar disk on 2001 September 21. Its location was S18° E76° (L268°). It was the first observed return of NOAA 9604 and was numbered NOAA 9632. The main pair of spots with opposite polarities was made up of

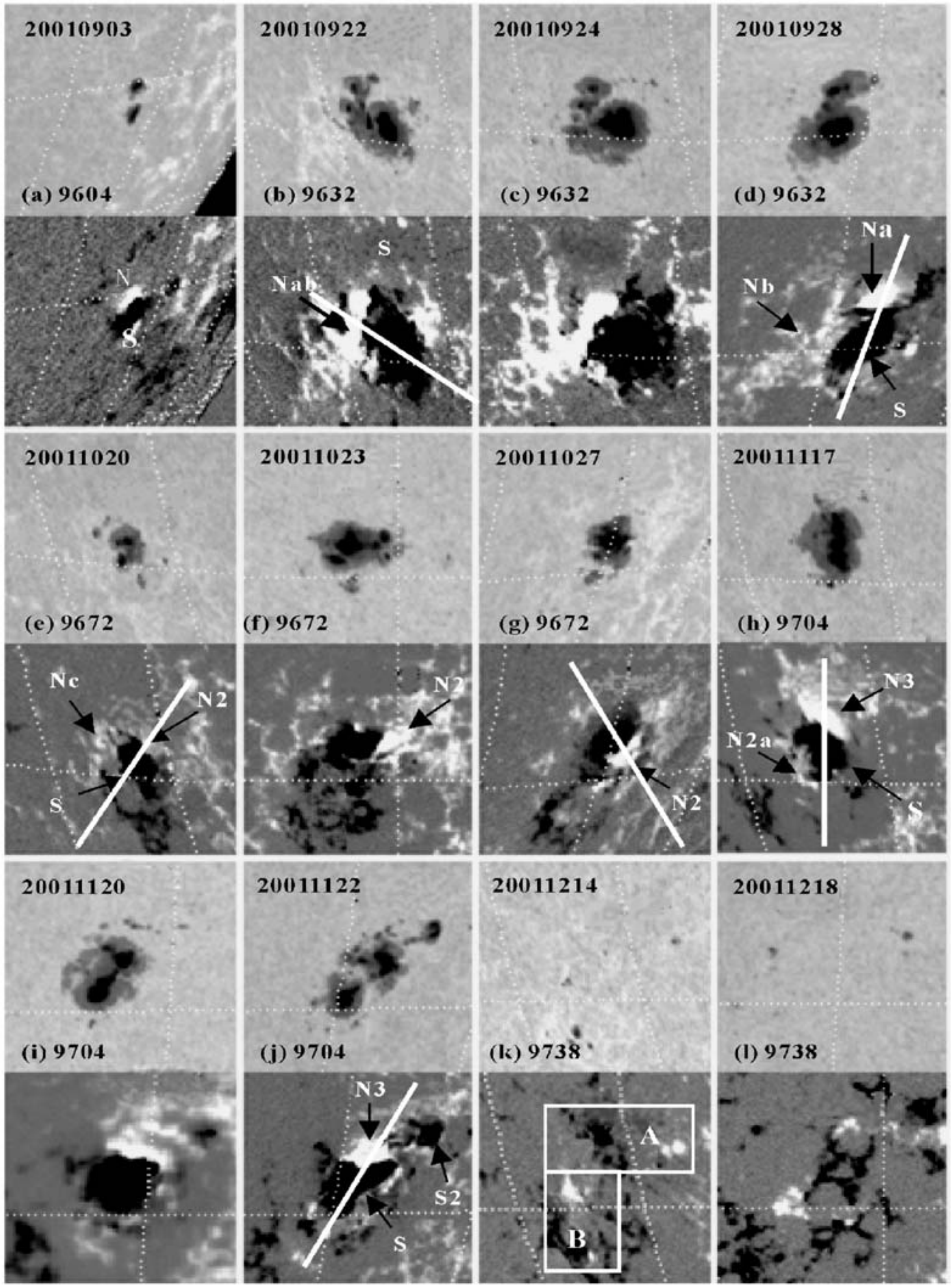

Fig. 2 Evolution of the long-lived spot group AR 9604. The top of each pair of images is the sunspot photo and the bottom, is the longitudinal magnetogram. White for positive (N) polarity, black for negative (S) polarity, the white line indicates roughly the magnetic polarity axis of the EFR.

S and Nab (see Fig. 2b). Only the low latitude tail of Nab spread, its position relative to S remaining unchanged. The high latitude front sequentially rotated clockwise. Therefore, the main flux of positive polarity (Nab) was stretched and eventually torn into two (Na and Nb) on September 27 (Fig. 2d). NOAA 9632 was a tight "island δ" spot group. The significant features in its evolution are the continuous clockwise rotation of the main spots (Figs. 2b, c and d), the perpendicular magnetic configuration and an obvious shear of the transverse field. It went behind the west limb on October 2. Generally, NOAA 9632 was all the time a non-Hale region.

The second return of NOAA 9604 was NOAA 9672 which came into view on October 16. Its location on October 19 was S20° E53° (L269°). The main pair of opposite spots are labelled S and N2 (Fig. 2e) and formed again a tight "island δ" spot group. N2 rotated clockwise around S. The area of the "island δ" spot evidently increased (Figs. 2e and 2f). The magnetic configuration of the active region was one of reversed polarities. A secondary pair of spots of opposite polarity consisted of S and Nc (Fig. 2e), this pair obviously dissolved and then died out on October 24. Shear was displayed in the transverse field of the active region. NOAA 9672 went past the west limb on October 30.

The next return appeared on the east limb on November 14 as NOAA 9704. Its location on November 15 was S18° E56° (L269°). Its main magnetic fluxes of opposite polarity are labelled S and N3 (Fig. 2h). S and N3 formed again a tight "island δ" structure, which was again a perpendicular magnetic configuration. N3 rotated clockwise around S (Figs. 2h, 2i and 2j). A secondary pair of spots with opposite polarity consisted of S and N2a (Fig. 2h). In addition, another negative polarity (S2) emerged on November 19, a spot was distinguished on November 20, its area reached a maximum on November 22, then, it quickly decayed. The relevant EFR is labelled (S2, N3)); it did not produce any flare. NOAA9704 ran into the back of the sun on November 27.

The fourth return of NOAA 9604 is numbered NOAA 9738 which started with a small spot coming into view on December 12. Two small separated spots without penumbra were observed on December 13, located at S19° E53° (L264°). Some new small spots appeared after December 14. No sunspot groups are seen around NOAA 9738 on the synthetic photosphere map. The magnetograms show that the area of the spots was the area where negative polarity flux dominated and where fluxes of opposite polarities were mixed together. The preceding and the following spot groups were each a small bipolar region (marked A and B in Fig. 2k). The bipolar region B was a perpendicular magnetic configuration while the biploar region A had its magnetic axis parallel to the equator and its polarities reversed. We found the whole region continued to rotate clockwise (see Figs. 2k and 2l). So, it is again an active region that violated the Hale-Nicholson and the Joy laws. It disappeared behind the visible disk at S17° W51° on December 22, Here, we should point out that, for all five rotations, the main negative polarity flux was labelled by the same letter S, because it always appeared at the same location.

Table 2 shows the location of five sunspot groups at various times, and rough estimates of their TAMPA and rotating velocity. From the results, we can conclude that the five active regions did not represent the manifestation of one buoyant flux tube. We can identify EFR (S,Nab), EFR (S, Na), EFR (S, Nb) and EFR (S, Nc) as returns of EFR (S, N), and EFR (S, N2a) as a return of EFR (S, N2). EFR (S2, N3) was very weak and decayed soon after it emerged. So, this long-lived region was successively maintained by four EFRs. And of these the three main ones are EFR (S, N), EFR (S, N2) and EFR (S, N3).

Table 2 Rough Estimates of the TAMPA and Rotating Velocity of the EFRs of AR 9604 on Various Dates

NOAA	Date	Location	EFR	TAMPA	Rotating velocity
9604	010903	S21 W61	EFR (S, N)	≈ +117°*	13.2°/day
9632	010923	S18 E32	EFR (S, Nab)	+35°(395°)	
9632	010923	S18 E32	EFR(S,Na)	+43° (407°)	13.0°/day
9632	010928	S20 W33	EFR(S,Na)	+108° (468°)	
9632	010928	S20 W33	EFR(S,Na)	+108° (468°)	13.2°/day
9672	011020	S20 E40	EFR(S,Nc)	+38° (+758°)	
9604	010902	S21 W46	EFR(S,N)	≈ +117° *	11.3°/day
9632	010923	S18 E32	EFR(S,Nb)	–5°	
9632	010928	S20 W33	EFR(S,Nb)	–6°	
9672	011021	S18 E26	EFR(S, N2)	+175°	6.0°/day
9672	011024	S18 E00	EFR(S, N2)	+193° (–167°)	
9672	011024	S18 E00	EFR(S,N2)	+193° (–167°)	5.5°/day
9672	011026	S18 W41	EFR(S, N2)	+204° (–156°)	
9672	011026	S18 W41	EFR(S, N2)	+204° (–156°)	5.3°/day
9704	011117	S18 E41	EFR (S, N2a)	+320° (–40°)	
9704	011116	S18 E41	EFR (S, N3)	+90°	5.0°/day
9704	011119	S16 E02	EFR (S, N3)	+105°	
9704	011119	S16 E02	EFR (S, N3)	+105°	3.3°/day
9704	011122	S18 W38	EFR (S, N3)	+115°	
9704	011122	S18 W38	EFR (S2, N3)		
9738	011215	A		+145°	
9738	011215	B		+90°	

"*" where evidence is insufficient.

In conclusion, the long-lived active region, AR 9604, lasted 111 days from its birth on 2001 September 2 to its end on 2001 December 22. It rotated clockwise all the time. Its main morphology was a tight "island δ" structure and a transverse magnetic field that displayed shear during its mature phase. It was a non-Hale region with a perpendicular magnetic configuration at the beginning and was a non-Hale active region with mixed magnetic polarities before the end.

4 DISCUSSION

When a buoyant Ω-flux tube rises up to the solar surface, it is seen as an EFR. The evolution of the magnetic field of the photosphere resulted from the emergence of a distorted flux tube is determined by the writhe of the tube and the twist of the field lines. Most active regions are formed by magnetic flux tubes with an obvious writhe and twist (Lopez et al. 2000), therefore the writhe and the twist are two significant parameters for the long-term evolution and activity of the active region. TAMPA (ϕ) and the force free factor ($\alpha_{\rm best}$) are quantitative measures of the writhe and the twist. We now discuss the writhe and the twist of AR 9604.

4.1 Writhe

We know that the relative position of the two legs of a distorted magnetic flux tube can change as the flux tube rises. Thus, the photospheric sections of the two legs (i.e., the observed positive and negative magnetic fields on the photosphere) will show different tilt angles in time. A clockwise/counter-clockwise tilt from the east-west direction would correspond to a right-handed/left-handed writhe of the Ω-flux tube (Fan et al. 1999). So, we can speculate on the writhe direction of the flux tube. From the stipulation on the sign of TAMPA in Sect. 3.1, a positive/negative TAMPA of the EFR corresponds to a clockwise/ counterclockwise rotation (the right-handed/left-handed writhe). The analysis in Sect. 3.2 and the results of Table 2 indicate that EFR (S, N), EFR (S, N2) and EFR (S, N3) rotated clockwise and their TAMPAs were positive. So, all the three were formed by the rising of a buoyant flux tube with a right-handed writhe (we are unable to analyse the evolution of EFR (S2, N3) because it did not last long enough). Analyses have shown that most of active regions in the southern/northern hemisphere have a negative/positive TAMPA (Tian et al. 2001). So, active regions with a right/left -handed writhe in the northern/southern hemisphere, obey the Hale-Nicholson and Joy's laws. However, AR 9604 was in the southern hemisphere and had the right-handed writhe (positive tilt), so it disobeyed the Hale-Nicholson Law and Joys Law and was a non-Hale region.

Figure 3 gives the Extreme UltraViolet (EUV, 28.4 nm) image on September 23, the SOHO C2/EIT patched image on September 24 and the YOHKOH soft X-ray images of October 25 November 20. These images refer to NOAA 9632, NOAA 9672 and NOAA 9704. A clockwise writhe of the magnetic loops is clearly displayed. These observations are consistent with our analysis above.

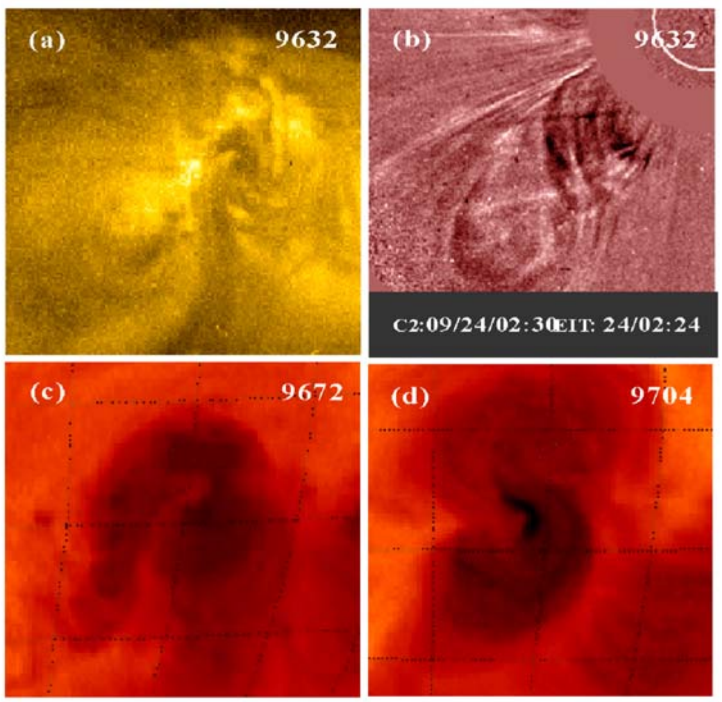

Fig. 3 Images of AR 9604 observed by SOHO and YOHKOH satellites. (a) EUV image (28.4 nm) of NOAA9632 observed by SOHO on 2001 Sept 23. (b) SOHO C2/EIT patched image of on NOAA9632 on 2001 Sept 24. (c) YOHKOH Soft X-ray image of EFR (S, N2) on 2001 Oct 25. (d) YOHKOH soft X-ray image of EFR (S, N3) on 2001 Nov 20.

4.2 Twist

Studies on the twist of the field lines in magnetic flux tubes in the active regions include studies of the morphology of filaments (Martin 1994) and coronal loops (Rust & Kumer 1996), computation of the force-free parameter $\alpha_{\rm best}$ (Pevtsov 1995) and of the mean current helicity (Abramenko et al. 1996; Bao & Zhang 1998). These parameters carry information on the twist of magnetic field lines in the flux tube rising more or less to the photosphere. Because positive/negative values of the force-free parameter $\alpha_{\rm best}$ and mean current helicity correspond to the direction and degrees of the twist of the field lines, they are paid close attention.

Positive/negative helicity predominate in the southern/northern hemisphere, and positive/negative values of force-free parameter $\alpha_{\rm best}$ correspond to right/left handed twist; this is known as the rule of helicity sign (Tian et al. 2002). We know from the set of spot maps and magnetograms that the main negative and positive magnetic fluxes of NOAA 9632 are S and Nab on September 26, those of NOAA 9672 are S and N2 on October 23 and those of NOAA 9704 are S and N3 when they passed helio-centric longitude at these dates. We calculated the force-free parameter $\alpha_{\rm best}$ of EFR (S, N3) in NOAA 9632, EFR (S, N4) in NOAA 9672 and EFR (S, N5) in NOAA 9704. They are $+0.042 \pm 0.004\,\mathrm{M\ m^{-1}}$ $+0.045 \pm 0.005\,\mathrm{M\ m^{-1}}$ and $+0.046 \pm 0.001\,\mathrm{M\ m^{-1}}$, respectively. These results indicate that the twist was right-handed in these regions, obeying the rule of helicity sign.

4.3 Kink Instability

The writhe of the magnetic flux tube in space and the twist of the field lines are manifestations of instability in an active region. Theoretically, for a kinked flux tube, the direction of the writhe of the tube axis should be the same as that of the twist within the flux tube (Fan et al. 1999). The three main EFRs of AR 9604 had a right-handed writhe and a right-handed twist. In addition, large tilt angle, rotation and tight "island δ" structure are their common features. Therefore, we think that the magnetic flux tubes forming AR 9604 are ones with concentrated kink instability. Linton et al. theoretically explored the relationship between the emergence of magnetic flux tubes with kink instability and the formation of δ spot. They pointed out that a δ spot formed by the flux tubes with kink instability is closely related to flare activity, especially a tight δ spot formed by flux tubes with concentrated kink instability that had a large tilt angle (Linton et al. 1998, 1999). The evolving features of the first, second and third returns of AR 9604 confirmed their conclusion. So, we think that concentrated kink instability should be the origin of the strong bursts that occurred in NOAA 9632, NOAA 9672 and NOAA 9704.

5 CONCLUSIONS

The main morphology of AR 9604 was a tight "island δ" structure throughout its lifetime. The maximum area of the group was 790μh. It was a medium size spot group. It emerged with a high tilt and died with mixed magnetic polarities. Throughout its lifetime it disobeyed the Hale-Nicholson and Joy's laws and violated Zirin's rule on the growth, evolution and death of active regions (Zirin 1988).

The life span of the three main EFRs got shorter and shorter, their rotating angle decreased one by one and their rotating velocity slowed down one by one. Are these features of AR9604 common to all active regions consisting of several EFRs ? EFR (S, N) and EFR (S, N2) rotated with roughly the same velocity but EFR (S, N3) slowed down. Does the slowing-down of EFR indicate the decaying of the region? We plan to do further statistical analysis with more data in future.

The flux tubes that formed these regions had obviously a right-handed writhe. Therefore, they emerged with a high tilt and displayed clockwise rotation and their transverse field was sheared during the mature phase. The same sign of their writhe and twist indicated that kink instability existed in the flux tube. The compact "island δ" structure of the sunspot group revealed that the kink instability was a concentrated one. It is widely believed that magnetic reconnection is the fundamental process that drives solar activity and space weather and it is likely to be the main mechanism by which solar magnetic field releases energy. Moreover, theoretical study holds that magnetic reconnection easily occurs at the kink point of a very kink-unstable flux tube (Linton et al. 1999). So, these should be the cause of strong bursts in such regions.

The results given by Tables 1 and 2 are: (1) The intensity and amount of flares and CMEs in AR 9604 did not scale with the rotating velocity of the EFRs. (2) Fast CMEs roughly corresponded with strong flares. (3) The solar proton events and geomagnetic disturbances were all led by fast halo CMEs with $V > 1000\,\mathrm{km\ s^{-1}}$. Their intensity, however, was not related to any positive or negative values of the acceleration.

A medium size active region had six fast halo CMEs. Does it imply that the kink instability of the flux tube is conducive to CMEs? To answer this question more statistical analysis on more samples are needed. If it is true, it will be very helpful for the predictions of halo CMEs and their associated geophysical effects.

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