Proton flares and the topology of the magnetic field in the active regions of the Sun

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[1] Events in flare productive active regions (ARs) accompanied by proton flares are considered on the basis of the observations from the ground and spacecrafts during the recent decades. The principal features of the morphology, magnetic fields, and substance mass motions in the ARs and also their variations with time are analyzed. All the considered ARs had a common feature in the magnetic field structure: a rather extended configuration of the δ type existed in them. The observations in the high-altitude expedition of the Sternberg Institute and the data from publications have been used. *INDEX TERMS:* 7519 Solar Physics, Astrophysics, and Astronomy: Flares; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; 7514 Solar Physics, Astrophysics, and Astronomy: Energetic particles; *KEYWORDS:* Solar flares; Proton events; Energetic particles.

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1. Introduction

[2] Since charged particles most easily move along the field lines of the interplanetary magnetic field, the characteristics of a proton event depend strongly on the difference in heliographic longitudes of the flare itself and the base of the field line of the interplanetary magnetic field connecting the space station to the solar surface [*Shea and Smart*, 1990].

[3] However, it is widely known that solar proton events well correlate to strong bright H_α flares. Comparing the proton events registered from 1970 to 1980 (total 323 events) to H_α flares, *Su et al.* [2001] showed that not only strong H_α flares but also subflares SB and SN might be followed by proton events. Even H_α flares of the SF class may initiate small proton events, though the probability of their occurrence is less than 0.5%. The H_α flares of the 2B and 3B classes are the most productive for occurrence of proton events, in the case of two ribbon flares the occurrence of energetic particle (protons, in particular) being the most probable [*Jain*, 1986]. The probability of proton acceleration during the latter flares W_p is of the order of unity. The 2N and 3N flares are slightly less productive ($W_p \sim 10\%$). For the H_α flares of the importance 1N $W_p < 2\%$, whereas for the H_α flares of the 1B class $W_p \sim 33\%$. This means that both characteristics of H_α flares (area and brightness) play an important role.

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[4] The brighter a H_α flare and the larger its area, the more probable is an appearance of accelerated protons. For example, the probability of appearance of a proton event in a flare of the SB or 1N class is nearly the same. It is almost by a factor of 50 less than the probability of appearance of a proton event during a flare of the 3B class and by about a factor of 5 less than W_p for a H_α flare of the 3N class. Since the number of weak H_α flares is much higher than the number of strong flares and the probability of a proton event generation is directly proportional to the brightness and area of H_α flares, the observed maximum number of proton events corresponds to some intermediate class of H_α flares. The statistical analysis of the data for the 1970–1980 period showed [*Su et al.*, 2001] that the maximum number of proton events was related to H_α flares of the 1B class (~26% of all proton flares).

[5] Having considered the processes of particle acceleration in the current sheet in flares at the given parameters (magnetic field strength, temperature, velocity of plasma flowing into the current sheet), *Su et al.* [2001] proposed a possible explanation of the observed correlation of the number of proton events and the class of H_α flares.

[6] *Shea and Smart* [1990] analyzed the data on proton events (more than 200) registered during the 19th, 20th, and 21st solar activity cycles. There is no unambiguous relation between the number of proton events and sunspot number; that is, the increase of proton events does not correspond to the increase of sunspots, though one can state that less proton flares are observed in the solar activity minimum and more in the solar activity maximum. If one compares the

Table 1. Data on the ARs

AR	Date	Number of flares				Proton	Flare Class
		Optic	X Rays	Class X	Maximum X-Ray Class	Flux, pfu	X-Rays/Optic
McMath 11976	29 Jul to 11 Aug 1972	107		4	>X5	56,000	X5/3B
McMath 13043	28 Jun to 10 Jul 1974	234		5	X18	130	X18/2B
McMath 15314	21 May to 2 Jun 1978	91	20	1	X1	19	M5/2B
NOAA 3763	2–14 Jun 1982	201	93	2	X12	30	X12/3
NOAA 5395	6–19 Mar 1989	195	106	11	X15	3500	X4,5/3B
NOAA 5629	3–17 Aug 1989	43	43	5	X20	9200	X2.6/2B
NOAA 5698	16–29 Sep 1989	93	27	1	X9.8	4500	X9.8/
NOAA 5747	14–28 Oct 1989	108	48	5	X13	40,000	X13/4B
NOAA 5800	19 Nov to 2 Dec 1989	48	17	2	X2.6	7300	X2.6/3B
NOAA 6555	17–31 Mar 1991	123	59	6	X9.4	43,000	X9.4/1B
NOAA 6659	3–17 Jun 1991	87	67	6	X12	3000	X12/3B
NOAA 6703	26 Jun to 13 Jul 1991	32	15	1	X1.9	2300	X1.9/2B
NOAA 6891	23 Oct to 2 Nov 1991	125	74	5	X6.1	40	X6/3B
NOAA 7154	2–15 May 1992	43	11	–	M7.4	4600	M7/4B
NOAA 7205	18–26 Jun 1992	54	27	2	X3.9	390	X3/2B
NOAA 7321	24–31 Oct 1992	81	34	1	X1.7	2700	X1.7/2B
NOAA 7671	13–26 Feb 1994	10	5	–	M4	10,000	M4/3B
NOAA 9077	7–20 Jul 2000	106	30	3	X5.7	24,000	X5/3B
NOAA 9393	24 Mar to 4 Apr 2001	90	55	4	X20	1110	X20/

values averaged over three cycles, one can see that the maximum of the proton events distribution is observed a few years later than the maximum of sunspots. The cause of this phenomenon is not yet clear.

2. General Information on ARs

[7] The study of general characteristics of active regions generating proton flares is necessary for better understanding of the nature of proton flares. In this brief review, information on 19 active regions with increased flare activity observed on the Sun during the recent decades and accompanied by strong proton flares and geomagnetic effects (magnetic storms, aurora, and anomalous ionization in the Earth atmosphere) is considered. The delay of the proton fluxes near the Earth orbit relative to optical and X-ray photons is about 1–2 days depending on the heliographical longitude of the flare and the velocity of the ejected particles. The most energetic particles cover the distance to the Earth by 15–20 min. Proton events by their power may differ by 1.5 orders of magnitude and are often related to microwave bursts of II and IV types. In the analyzed events the maximum proton fluxes for the most powerful events were above 1000 pfu (up to 40,000 pfu where pfu is a proton flux unit: p cm^{-2} s^{-1} sr^{-1}). For the rest of the events the flux values exceeded at 1 AU 100 pfu.

[8] During one passage over the solar disk, 11 X class flares were registered in one of the most productive AR considered. For the sake of comparison we present the data by *Contarino et al.* [2002], who analyzed flare activity in 2259 sunspot groups during the 5-year period from 1996 to 2001. During this period, 559 energetic events (including flares of the M and X classes) were registered. This means that there is less than 0.4 event per one group. If only flares of the X class are taken into account, the productivity of one AR is even less.

[9] Table 1 shows the data on the ARs: the observation date, the number of optical and X-ray flares, their maximum class, the number of flares of the X class, the proton flux with $E > 10$ MeV, and the corresponding class of the flare. The information on proton events was taken from SGD (Catalogue of solar proton events 1987–1996, Moscow 1998, available at http://umbra.nascom.nasa.gov/SEP/), and particular publications.

[10] All the considered ARs have a common feature in the magnetic field (MF) structure: there existed rather extended configuration of the δ type. In 1966 it was still found that δ configurations either precede or accompany all proton events [*Warwick*, 1966]. The term δ configuration was introduced by *Künzel* [1960] and is used when the umbrae of opposite magnetic polarities are located in the common penumbra close to each other. Most often a small spot satellite emerges up in the same penumbra with the main spot, but δ configuration can exist in groups of spots with the magnetic structure of the β, $\beta\gamma$, and γ types. Observations have shown that the highest activity takes place when the areas of the penumbra and umbrae of opposite polarity involved in the δ configuration occupy considerable areas. It is known that the δ and γ configurations are the most flare active. Using the observations of 2789 AR during the 1989–1997 period, *Sammis et al.* [2000] showed that a relation between the power of X-ray flares and the structure of the

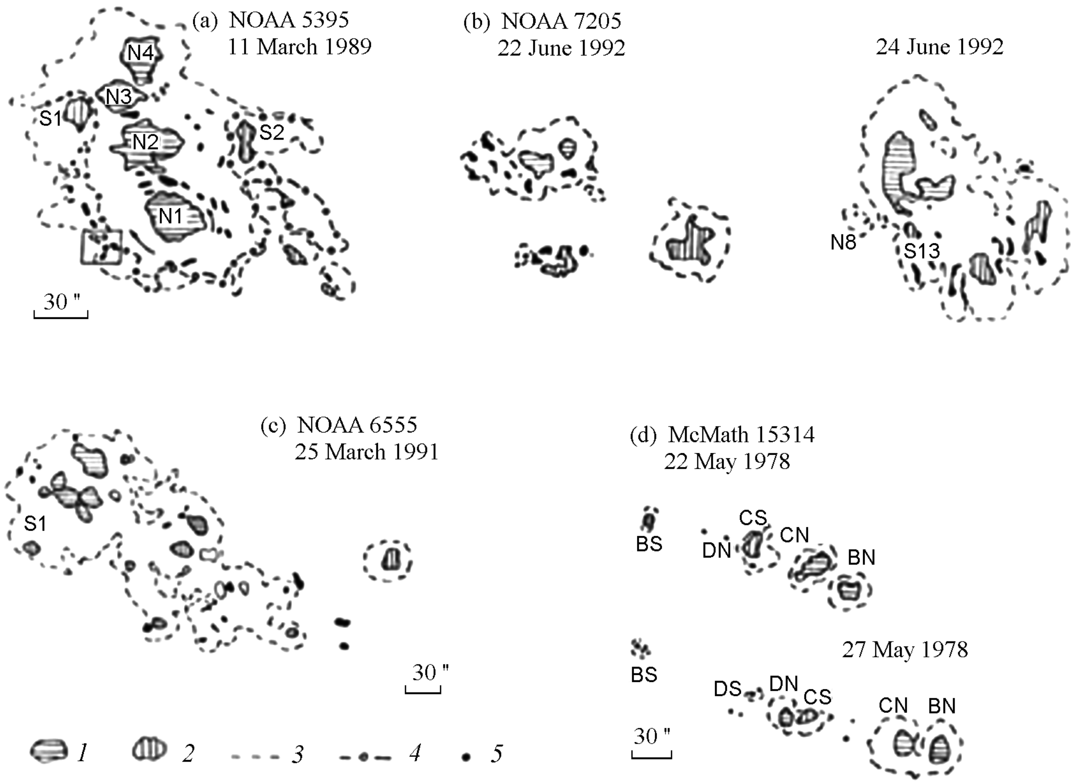

Figure 1. A schematic drawing of flare productive ARs: (a) AO NOAA 5395, 11 March 1989 (a large δ island formed as a result of long evolution of AR; according to Figure 1 in *Makarova et al.* [2001]); (b) AO NOAA 7205, 22 and 24 June 1992 (emerging large δ group; according to Figure 1 of *Van Driel-Gesztelyi et al.* [1997]); (c) AO NOAA 6555 (emergence of a small δ group near the old δ group; according to Figure 4b of *Fontenla et al.* [1995] and Figure 1 of *Choudhary et al.* [1998]); (d) AO McMath 15314, 22 and 27 May 1978 (formation of a δ group as a result of the collision of three usual bipoles; according to Figure 4 of *Gaizauskas et al.* [1994]); 1 and 2 are sunspots of the N and S polarity, respectively; 3 is the penumbra; 4 is the inversion line of the longitudinal magnetic field; and 5 are small pores and spots. The arrows show the direction of the motion in the AR. North is at the top, west is on the right.

magnetic field in the AR existed. Large ARs with the MF configuration of the $\beta\gamma\delta$ type are the most flare productive.

3. Evolution and Magnetic Configuration of ARs and Flares Within

[11] In this section the ARs evolution (processes leading to formation of the δ configurations, common features typical for ARs, and differences between ARs of different types) are analyzed. The results of the observations by ground-based instruments (in particular by cude-refractor Opton at High-Altitude Observatory of the Sternberg State Astronomical Institute (SSAI) with the H_α filter) and on board space stations obtained in the visible and far ultraviolet ranges of wavelengths and also in the X rays are used.

[12] Among the considered ARs one can find compact ARs which are δ spots with a vast penumbra or δ islands with dimensions of tens thousands of kilometers (AR McMath 11976, NOAA 5395, NOAA 5629, NOAA 5747, NOAA 6659, NOAA 7070) or extended ARs with a complicated structure of the magnetic field of the $\beta\gamma\delta$ configuration (AR NOAA 9077, NOAA 9393).

[13] Study of the evolution of different ARs shows that δ configurations can be formed as a result of different processes. This problem was considered in detail by *Zirin and Liggett* [1987] and *Tang* [1983]. Figure 1 shows schematic images of ARs of different magnetic configurations. The spot polarities, penumbra boundary, and the inversion line of the longitudinal magnetic field are shown. Arrows show the direction of sunspot motion. Examples are presented of the cases, when the AR was formed as a large δ configuration in the process of durable evolution (AO 5395, 11 March 1989), when an emergence of a large δ group was observed (AO 7205, June 1992), when a rapid emergence of a new δ group near the old set of sunspots was observed (AO 6555, March 1991), and when δ configuration was formed as a result of the collision of two ordinary bipolar sunspot groups

and mergence of the following spot of one group with the leading spot of the other group.

[14] On 11 March 1989, AR 5395 was located near the central meridian and presented a large monolithic formation of the N polarity surrounded from three sides by the south polarity field (Figure 1a). This AR was observed on the Sun during several rotations. Just in March it was formed as a large δ configuration and demonstrated unusually high flare and geophysical activity. On 11 March its length was about $100''$. Similarly, the AR 6659 presented a large monolithic island of the S polarity. Such large δ islands are the most flare productive. This fact can be seen in Table 1. The numbers of the ARs presenting large δ configurations are underline.

[15] The flare of the X15 importance was the most powerful X-ray flare in AR 5395. The most powerful proton event coincided with the 3B/X4.5 flare. In the scope of the data available for 19 active regions, there seems to be no correlation between the power of proton events and AR productivity in the X-ray range. For example, AR 5747 gave a powerful proton flare (40,000 pfu) as compared to the flare in AR 5395 (3500 pfu), but only 5 flares of the X class occurred in AR 5747, whereas 11 flares of the X class occurred in AR 5395. Table 1 shows that the proton flux can be associated to X-ray flares of both X and M classes.

[16] Sometimes emergence of a united compact system of δ island is observed. Generation of isolated δ groups probably is related to a formation of complicated magnetic tubes in the base of the convective zone. For example, the AR 7205 was born on the solar disk on 18 June 1992 at the western edge of a coronal hole and first 3 days consisted of ragged small spots. On 22 June the AR looked as a bipolar group with two leading spots of the S polarity and one following spot of the N polarity (Figure 1b). The leading and tail spots moved in the opposite directions from each other and were connected by a system of arch loops. However, already on 23 June one of the leading spots and the following spot united into a δ spot [*Van Driel-Gesztelyi et al.*, 1997]. A new bipole N8S13 which emerged on 23 June to 25 June fused to the main δ spot (Figure 1b), and its leading part continued to grow until 26 June when the AR reached the west limb. The AR was the most flare productive on 25 and 26 June. It remained active also after the disappearance behind the limb.

[17] Satellite sunspots of the opposite polarity often emerge near a group of spots which have existed earlier. For example, the spot group observed in March 1991 as the AR 6555 existed for three more rotations. During the previous passage over the solar disc (the AR 6509) it presented a complicated system with a large spot of the N polarity. In March 1991 a rapid emergence of a new δ group was observed near the old complex in the vicinity of the S1 spot (Figure 1c). During the next rotation (April 1991) only the area with short-lived and scattered pores of the N polarity was observed on the place of this AR [*Kalman*, 1997]. This AR was very active: a proton flare with the flux of 43,000 pfu occurred in it.

[18] Formation of a δ configuration can happen as a result of a collision of two usual bipolar sunspot groups and mergence of a following spot of one group to the leading spot of the other group. This results in a formation of a δ spot with the polarity reversed as compared to the polarity corresponding to the Hale-Nicolson law. Such process could be observed in the AR McMath 15314 which presented a huge complex consisting of five bipoles A, B, C, D, and E (Figure 1d). The region B appeared near the eastern limb as a large spot of the leading polarity. The C and D regions emerged close to each other with the difference of a few days within the B region. Figure 1d shows the AR on 27 May when the distance between CS and DN became minimum.

[19] As a result of the continued emergence of magnetic fluxes, there occurred a fusion of two spots of the leading polarity (BN-CN) and also mergence of the leading and the following spots of the inner groups (DN-CS) in one penumbra with formation of a δ spot [*Gaizauskas et al.*, 1994]. Uniting into one spot with the common penumbra of two spots of the opposite polarity belonging to two different dipoles, apparently, has been prepared by a reconnection of magnetic field lines under the photosphere or during the emergence of the new magnetic flux. During 5 days, insignificant flares were observed, and only on 28 May the 1B/X1 flare occurred when the umbra in the δ spot began to decay accompanied by rapid motions at the photosphere level [*Gaizauskas et al.*, 1994].

4. General Characteristics of ARs and the Relation to Proton Events

[20] *Zhou and Zheng* [1998] analyzed 11 ARs observed during the 5-year period from March 1989 to February 1994 characterized by powerful proton events. *Zhou and Zheng* [1998] emphasized that almost all AR had a spot morphology of the δ type, when several umbrae of the opposite magnetic polarity were submerged into the joint semi-shadow. For the majority of ARs the total area of the spots was more than 1000 μh (millionth of the hemisphere), the ARs covered more than 10 degrees in heliographic coordinates on the solar disc, and their magnetic configuration was of the $\beta\gamma\delta$ type. Usually such AR are characterized by an unbalance of the magnetic flux. The flux of the leading polarity may be up to 80 and more percents (AO NOAA 5395, 5629, 6555, 6659). Therefore the magnetic field lines connected to the most part of the AR area are closing outside the boundaries of AR sometimes at large distances in other active complexes or at elements of the enhanced chromospheric net.

[21] In all AR a strong magnetic field (2500–3000 G) as comparable to MF within the umbra is observed [*Makarova et al.*, 2001]. Parallel to the MF neutral line, there exists a narrow corridor with high (0.3–0.5 G km^{-1}) gradients of the strength of the longitudinal magnetic field [*Sakurai et al.*, 1992] and strong (up to 4000 G) transverse magnetic fields detected in polarization observations of spectral lines [*Tanaka*, 1991; *Zirin and Wang*, 1993]. The spot motions with high velocities of dozens of m s^{-1} up to a few hundred m s^{-1} and motions in the penumbra along the neutral line of MF were observed [*Tang and Wang*, 1993; *Wang et al.*, 1991; *Zhang et al.*, 1994].

[22] In the AR McMath 13043 which presents a large spot having formed as a result of a fusion of two multipoles, a velocity up to 800 m s^{-1} was observed. *Liu and Zhang* [2001] analyzed the relation between the large-scale motions of sunspots and the strong flare on 14 July 2000 (3B/X5.7) in AR 9077. They found that a specific configuration of MF and rapid fragmentation led to a well-pronounced shear structure. The spot motion induced activation of part of the filament. The emergence magnetic flux initiated the flare on 14 July at the stage of the beginning of AR destruction.

[23] The magnetic field in the considered AR has a pronounced shear character in the penumbra. This fact is seen in the images obtained with a high spatial resolution in the H_α and HeI D_3 lines and is confirmed by the measurements of the transverse magnetic field. One can see that the filaments are parallel or almost parallel to the neutral line of MF. For example, in the AR 5395 on 11 March the mean shear angle along the eastern boundary of the inversion line of MF was 61° [*Chen et al.*, 1994]. In the penumbra the magnetic field lines are often twisted into a helix [*Zhang*, 1995b; *Zhang et al.*, 1994]. Though the shear character of MF in the flare productive AR is well known; however, still it is not clear why the changes occurring in the topology of MF during a flare are ambiguous. Observations show that as a result of a flare the degree of the shear may decrease, stay unchanged, or increase [*Spirock et al.*, 2002; *Zhang*, 1995a]. Constancy or intensification of the magnetic shear after a flare probably is explained by the fact that the flares were induced by interaction of new emerging fluxes into the already existing magnetic field and the flares did not result in a sufficient relaxation of MF.

[24] *Zhou and Zheng* [1998] analyzed the ARs rotation during their motion over the solar disk. To study the rotation of a group of sunspots in an AR a characteristic line is chosen. For example, in the AR 5395 the line was chosen connecting the centers of the two largest sunspots. Every day the angle between this line and the east-west direction was measured. The projection effect was taken into account. It was found that at the moments when the rotation velocity (calculated in the degrees per day) reaches its maximum value a strong proton flare can occur. Then the rotation velocity begins to decrease and the group starts rotating into the opposite direction. One can suggest that when the turning angle reaches some critical value, the twisting of the magnetic field lines increases, a reconnection occurs, and the magnetic energy is released in the form of a proton flare. The forces of elasticity and magnetic line tension make the group to rotate in the opposite direction after the flare has occurred.

[25] There are observational data indicating that the character of disturbance propagation in the interplanetary space depends on the solar activity cycle. For example, the observations on board the Ulysses spacecraft showed that strong disturbances during the maximum of solar activity in June 1991 were apparently related to six flares of the (1F–4B)/(X10–X12) classes in the AR NOAA 6659 (a heliographic latitude of the AR was N34). One of the flares occurred behind the limb. The character of propagation of these interplanetary disturbances was in a highest degree anisotropic. The majority of the disturbances were observed in the northern hemisphere of the interplanetary space. Therefore one can conclude that the source of the interplanetary disturbance was located within or around the active region where a series of powerful flares occurred. Observations during the rising branch of the solar activity cycle in November 1997 demonstrated a different character of interplanetary disturbances: they were approximately symmetric in the southern and northern hemispheres relative the heliospheric current sheet, though a flare of the X9 class was also observed [*Watanabe et al.*, 2000].

[26] The entire set of the observational data currently can not be explained by any model of a solar flare. *Shea and Smart* [1990] indicated that the idea that energetic particles are always related to strong solar flares contradicts to observations. Cases are known when proton flux was related to the disappearance of a filament without an accompanying flare [*Kahler et al.*, 1986]. Though AR are large δ islands and most often are a source of energetic protons, this can not be considered as a regularity. For example, no flare accompanied by proton fluxes was detected within the AR 7070, which was a large δ configuration. On the other hand, studies of the line intensities in the 1200–1800 Å range during the impulsive phase of the 3B/X3 flare on 27 February 1992 (NOAA 7070) showed an increase of the solar emission in the C IV and Si IV lines by a factor of 12–13. This corresponds to the increase of the intensity of the flaring plasma by a factor of 15,000. The increase of the emission of the Ly_α line (by ∼6%) agrees with the current model of the flares at the decaying phase. However, the cause of such increase in the intensity of the C IV and Si IV lines is not yet clear, though there is an agreement with the observations conducted for stars [*Brekke et al.*, 1996].

5. Summary

[27] Thus we considered events in the most flare-productive AR accompanied by powerful proton events.

[28] 1. All the ARs are characterized by the magnetic configuration of the δ type.

[29] 2. Some general characteristics of AR are presented such as magnetic twist, unbalanced magnetic flux, strong penumbra magnetic field, spot motions with high velocities, and new magnetic field emerging into penumbra.

[30] 3. No relation between the power of proton events and intensity of X-ray flares is found, this fact in some way agreeing to the results of *Uddin et al.* [1990], who concluded that proton fluxes and the emission in the extreme X rays weakly correlate to each other. *Uddin et al.* [1990] analyzed the data on proton events with energies $E > 10$ MeV which occurred within the period 1976–1986.

[31] 4. There is a series of observational data (intensification of emissions of some lines in the transition region during the impulsive phase of a flare and dependence of the character of interplanetary disturbances propagation on solar activity cycle) which do not fit the current models of solar flares.

[32] 5. Apparently, a complex approach to the consideration of all these events is needed. Comparison of other

characteristics of proton fluxes (but not the fluxes with energy $E > 10$ MeV) and X-ray emission from solar flares can give a different answer to the question on correlation between proton and X-ray flares.

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