DELTA-SUNSPOTS AND X-CLASS FLARES

SHI ZHONGXIAN and WANG JINGXIU
Beijing Astronomical Observatory, Chinese Academy of Sciences, Beijing 100080, China

(Received 25 May, 1993; in revised form 26 July, 1993)

Abstract. All δ-sunspots from September 1986 to December 1992 in solar cycle 22 are used to investigate the characteristics of δ-sunspots and the relationship between δ-sunspots and X-class X-ray flares. The main results of this statistical study are as follows.

(1) The earlier discoveries on the formation and disintegration patterns of δ-sunspots (Tang, 1983; Zirin and Liggett, 1987; Zirin, 1988) are confirmed. In a general sense, all δ-sunspots form from the penetration of two different dipoles. Delta-sunspots could be disintegrated by *in situ* flux cancellation. In addition, some δ-sunspots become separated by the sliding apart of opposite polarities.

(2) A prominent characteristic of δ-sunspots is the imbalanced flux between the two polarities. A sample of 58 δ-sunspots observed by the Solar Magnetic Field Telescope at Huairou, in which there are one or more X-class flares, maintains an average flux ratio of 6.6 between the majority and minority polarities. Unlike the early results of Tang (1983), two-third of them show a dominant flux from the preceding spots.

(3) The number of δ-sunspots seems to be an index of solar activity. More than 95% of X-class X-ray flares take place in active regions of δ-sunspots; while 23% of δ-sunspots are generators of X-class X-ray flares. The productivity of X-class flares is closely correlated to the lifetime of δ-sunspots in this manner: $P_{xxf} = -0.12 + 0.02T_\delta^2$.

1. Introduction

Delta-sunspots are sunspots with opposite polarity umbrae in a common penumbra. It has long been recognized that δ-sunspots are highly flare-productive (Künzel, 1960), and a necessary condition for a proton flare is the appearance of δ-sunspots in an active region (Warwick, 1966). In practical solar prediction, δ-sunspots have been considered as one of the primary phenomena preceding great flares (Zirin and Marquette, 1991). A recent statistical study (Xu *et al.*, 1991) further shows that γ-ray bursts are closely correlated to δ configurations of magnetic fields. Hence, the study of δ-sunspots is extremely important in understanding flare physics.

Previously, Tang (1983) and Zirin and Liggett (1987) discovered that most δ-sunspots form from collisions of spots of opposite polarity from different dipoles, or in other words by unions of non-paired spots. Zirin has concluded that once the spots lock together, they never separate. However, examples of δ-sunspot distintegration by *in situ* flux cancellation have been presented by a few authors (Zirin and Wang, 1990; Wang *et al.*, 1991). It should be emphasized that the term of flux cancellation used in this paper is only a descriptive term. By this term it is meant that mutual flux disappearance is observed in encountering magnetic features of opposite polarity from the time sequence of line-of-sight magnetograms. Slow magnetic reconnection in the lower atmosphere and flux submergence seem to be the most likely physical processes involved in the observed flux cancellation (Wang and Shi, 1993). Strong magnetic shear was identified on the magnetic

Solar Physics **149:** 105–118, 1994.

neutral line (polarity inversion line) of δ-sunspots (Zirin, 1988, 1993). These facts imply physically that the δ-sunspots might well reflect the interaction of two sets of magnetic loops, which are topologically independent and of very high field strength, including magnetic shear generation as well as reconnection.

In this paper, δ-sunspots in solar cycle 22 are used as a sample to further examine the previous discoveries, and to investigate the statistical properties of δ-sunspots, particularly in terms of flux distributions and productivity of great flares. The data base for this study includes vector magnetograms obtained at Huairou Solar Observing Station, sunspot photographs of the Shahe Station of Beijing Astronomical Observatory, and X-ray flare lists of *Solar Geophysical Data*. To reduce the selection effects of this statistical study, Mt. Wilson Sunspot Drawings (Hale and Nicholson, 1938) from 1917 to 1924 of solar cycle 15 were taken to check the results from this solar cycle.

By definition, in the common δ-sunspot penumbra there are, in fact, two or more sunspots of opposite polarities. However, these sunspots are locked together and appear as a union. For clearness and simplicity in wording, this union of sunspots is referred to as a δ-sunspot. The opposite polarity sunspots locked together as a δ-sunspot are called components sunspots.

2. Formation and Disintegration

The formation patterns of δ-sunspots revealed by Tang (1983) and Zirin and Liggett (1987) are fully confirmed by the sample used for this study. For all δ-sunspots whose formation process can be followed, one always finds that two component sunspots in a δ-spot come from different dipoles. At least from the beginning of the δ-sunspot formation, they maintain their own topological connectivity. Many examples show that individual dipoles tend to expand independently, with different orientation and separation speed. For some favorable distributions, a leading polarity from one dipole pushes into the following polarity of another dipole, or *vice versa*. The interpenetration, or in other words, the collision-merging of opposite polarities eventually results in the formation of δ-sunspots. However, unlike the conclusions of Zirin and Liggett (1987), further proper motions of those individual dipoles, sometimes, could even separate a δ-sunspot into two unlocked pieces.

In Figure 1, an example of a δ-sunspot separation is shown by a time sequence of sunspot photographs in conjunction with Huairou line-of-sight magnetograms from November 11 to 15, 1988 for AR 5227. In the line-of-sight magnetograms, solid (dashed) isogauss contours represent the field of positive (negative) polarity. The isogauss levels are ± 40, 80, 160, 320, 640, 960, 1280, 1600, ... G. The first dipole appeared on November 8, and the second one emerged three days later. Their preceding and following sunspots are denoted as P1, F1 and P2, F2, respectively, in the first frame of the figure, on November 12. The second dipole (P2, F2) is still in a fast emerging phase at that time, so that its proper motion is vigorous. By the collision of F2 from the second dipole and P1 from the first dipole, δ-sunspot

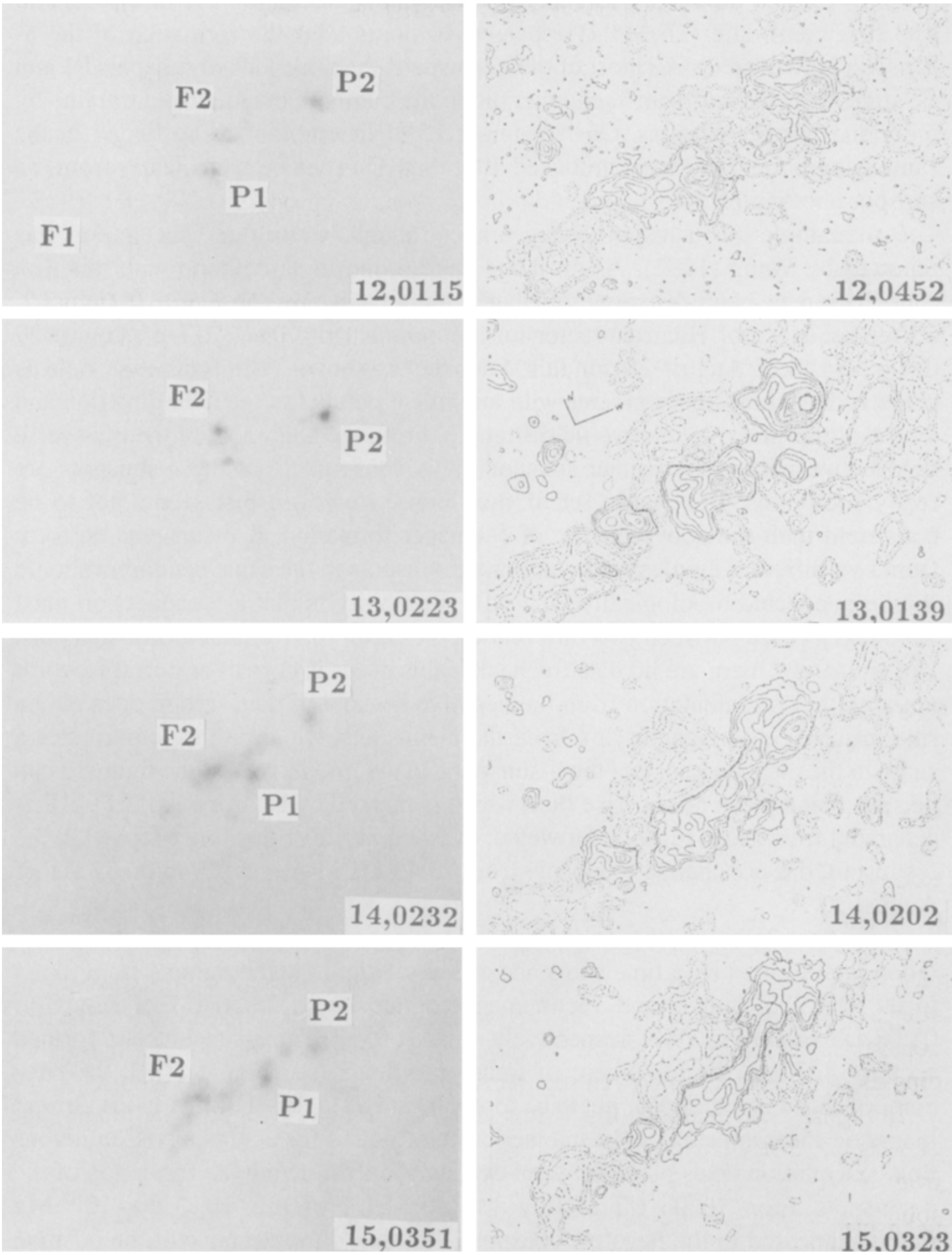


Fig. 1. Time sequence of sunspot photographs (*left*) and corresponding line-of-sight magnetograms from November 12 to 15 for AR 5227. In the line-of-sight magnetograms, solid (dashed) isogauss contours represent the field of positive (negative) polarity. The isogauss levels are ±40, 80, 160, 320, 640, 960, 1280, 1600 G. Two dipoles are marked as (P1, F1) and (P2, F2). A δ-sunspot (P1, F2) formed by interpenetration of these two dipoles. Further proper motions of the two dipoles separated the δ-sunspot into two unlocked sunspots.

(P1, F2) formed on November 13. After that, 37 flares took place in this region. The first great flare (1B/M3.2) appeared 20 hours after the formation of the δ-sunspot. However, unlike most of the δ-sunspots, the once-locked sunspots P1 and F2 slide apart farther from each other along the common magnetic neutral line by individual proper motions. On November 15, their umbrae are no longer in the same penumbra. They were unlocked after that. This can be seen clearly from the sunspot photograph.

An example of δ-sunspot disappearance though *in situ* flux cancellation was reported by Wang (1992). As no flares were found in association with this flux cancellation, he naturally suggested that a submergence was observed. In Figure 2, a time sequence of Huairou vector magnetograms from 03:03 UT of August 29 to 06:32 UT of August 30 for this δ-sunspot is shown. The transverse field is presented by short line segments with alignment parallel to the field direction and length proportional to relative field strength. From the alignment of the transverse field between two component sunspots, it is confirmed that the δ-sunspots are really footpoints of a single set of flux loops. However, this seems not to be consistent with the above picture of δ-sunspot formation. If δ-sunspots do form from two different dipoles, two component sunspots in the same penumbra should not be connected topologically. The only possibility is that a reconnection must have taken place between two different dipoles after the formation of δ-sunspots. Unfortunately, there are no data to check if this guess is correct or not. It is worth noticing that fragmentation from the negative sunspot of the δ-group does play a role in removing magnetic flux from the δ-sunspots, which in turn contributes a share to the disappearance of the δ-sunspots. In the middle row of the figure, it can be seen that a piece of negative flux, which is marked by an arrow at 02:11 UT, is separated from the δ-sunspot. However, the total negative flux, once locked in the δ-sunspot, did not change obviously from 23:43 UT of August 29 to 06:32 UT of August 30.

In Figures 3(a) and 3(b), an example of δ-sunspot disintegration by flux cancellation is presented by a time sequence of line-of-sight magnetograms from 02:03 to 09:50 UT of July 8 and vector magnetograms from 23:56 UT of July 8 to 08:03 UT of July 9, 1989, respectively, for AR 5572. The δ-sunspots are formed on July 8. From the alignment of transverse fields (see Figure 3(b)), the two-component sunspots appear not to be footpoints of a single set of flux loops. Strong magnetic shear appears on the magnetic neutral ine of the δ-sunspots. Continuous flux cancellation takes place between two sunspots following the formation of the δ-sunspots. From 02:03 UT of July 8 to 00:04 UT of July 10, 3.1×10^{20} Mx flux disappeared in the negative sunspots. The flux disappearance of the positive sunspot is also obvious. Assume that the flux disappearance is of equal amount in both polarities, then an average rate of flux disappearance of 1.5×10^{19} Mx hr^{-1} would be obtained. On July 9, there are no longer any δ-sunspots in this active region. A large flare (3B/M5.1) took place in the close vicinity of the δ-sunspot after many hours of flux cancellation.

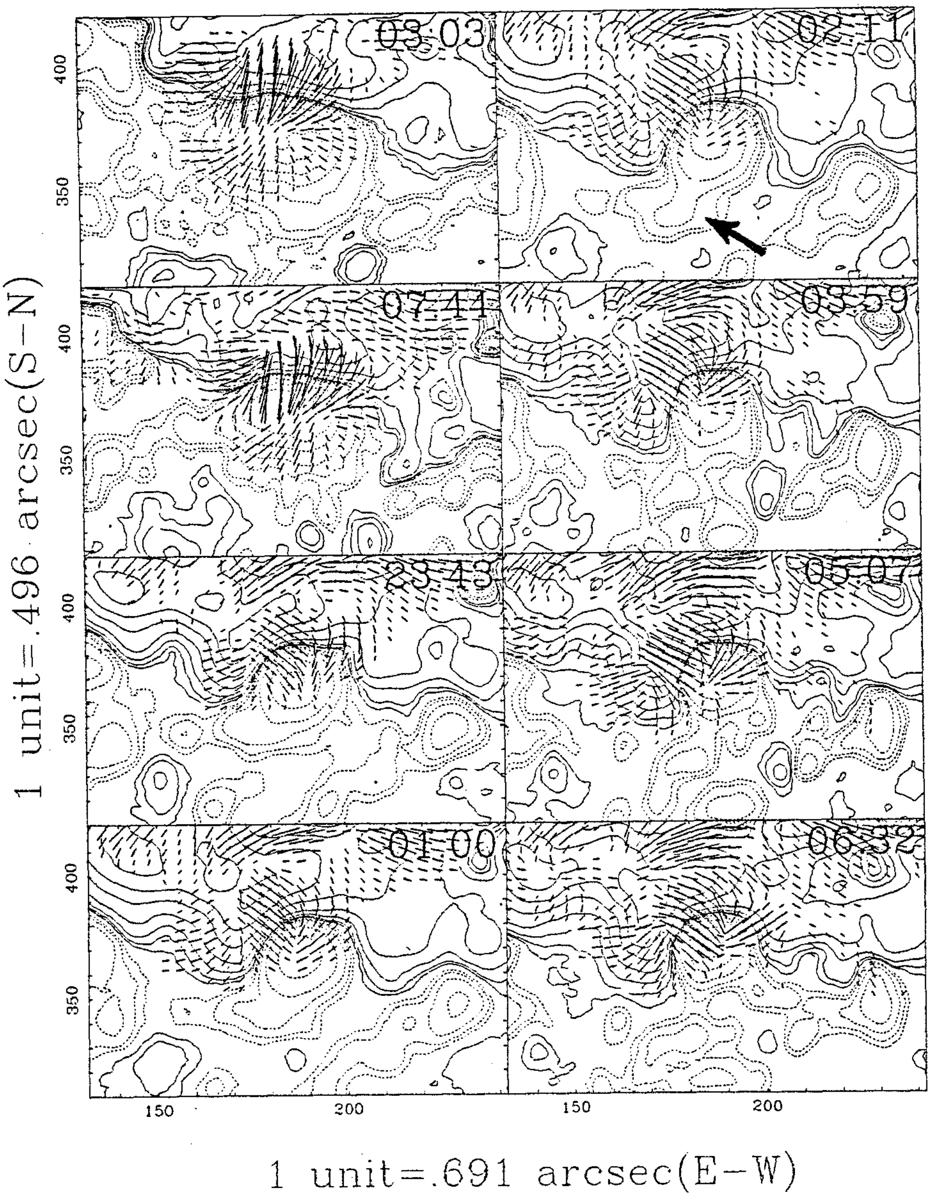


Fig. 2. Time sequence of vector magnetograms of AR 6233 from 03:03 UT of August 29 to 06:32 UT of August 30, 1990. A δ-sunspot, which has been discussed by Wang (1992), is shown in the center of the figure. The transverse field is presented by short line segments with alignment parallel to the field direction and length proportional to relative field strength. Unlike most δ-sunspots, this δ-sunspot maintains basically a potential transverse field. From 23:43 UT of August 29 to 06:32 UT of August 30, a piece of negative flux, marked by an arrow, separated from the δ-sunspot.

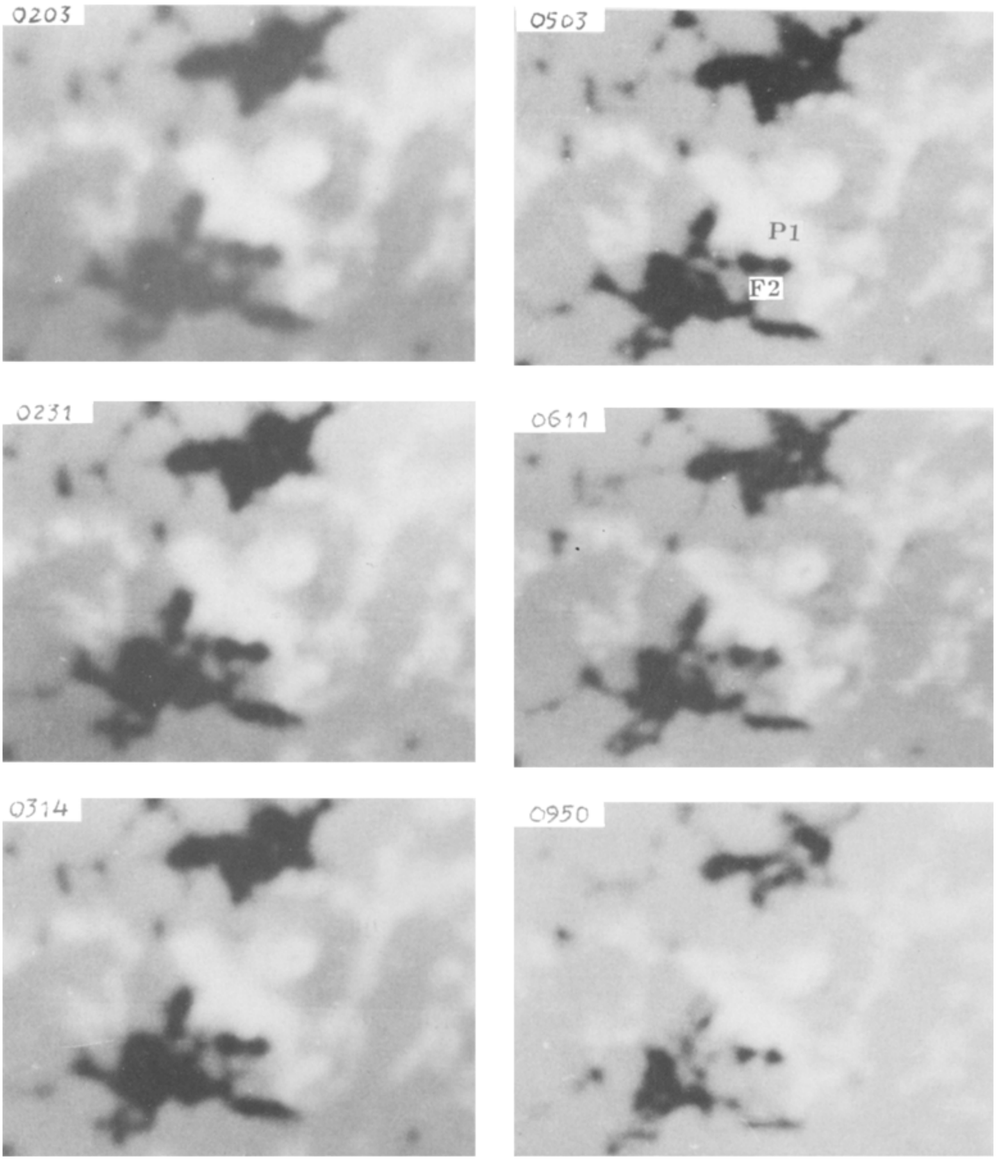


Fig. 3a.

Fig. 3. Time sequence of line-of-sight magnetograms of AR 5572 from 02:03 to 09:50 UT of July 8, 1989 (a); and vector magnetograms of the same region from 23:56 UT of July 8 to 08:03 UT of July 9; flare ribbons are superposed as thick lines (b).

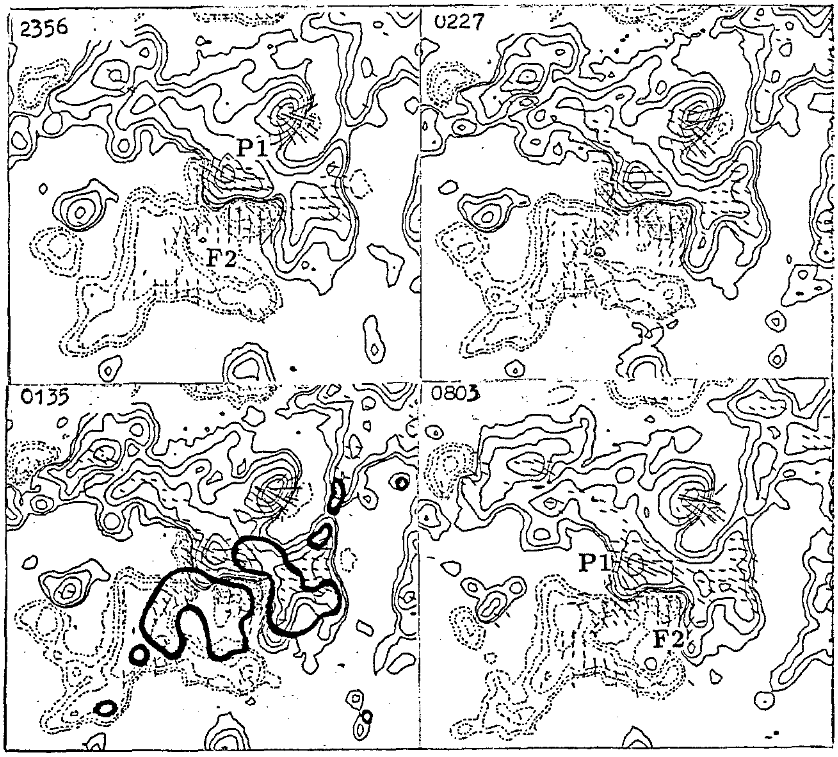
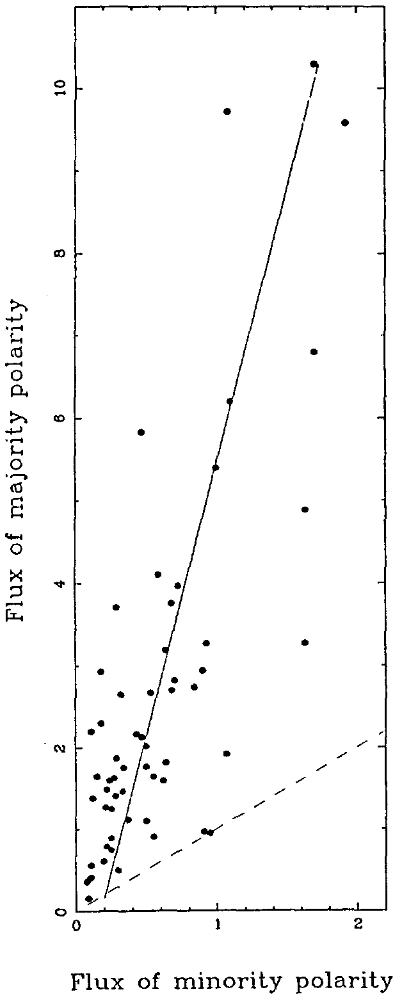


Fig. 3b.

In brief summary, either the formation or disintegration of δ-sunspots represent well the interaction of two topologically separated flux loops. This might be a reason why δ-sunspots are highly flare-productive.

3. Imbalance of Magnetic Flux in Opposite Polarities

It is known that active regions often have an imbalanced flux between leading and following polarities. The imbalance of magnetic flux in δ-sunspots seems more severe. Moreover, the δ-sunspots which produce great flares often have a highly imbalanced flux. In this study, 58 δ-sunspots, in which there are one or more X-class flares, are used to evaluate the flux ratio between the two polarities. Both sunspot data from Shahe Station and magnetograms from Huairou Station are available for these active regions. As the measurements of magnetic field strength for sunspot umbrae suffer from large errors caused by stray light, the estimation of magnetic flux is mainly based on sunspot area as has been done by Sheeley (1966). The flux of the majority polarity vs that of the minority polarity is plotted in Figure 4(a). The distribution strongly deviates from a line with slope 1, which represents a balanced flux between the two polarities. Least-square fitting gives an average flux



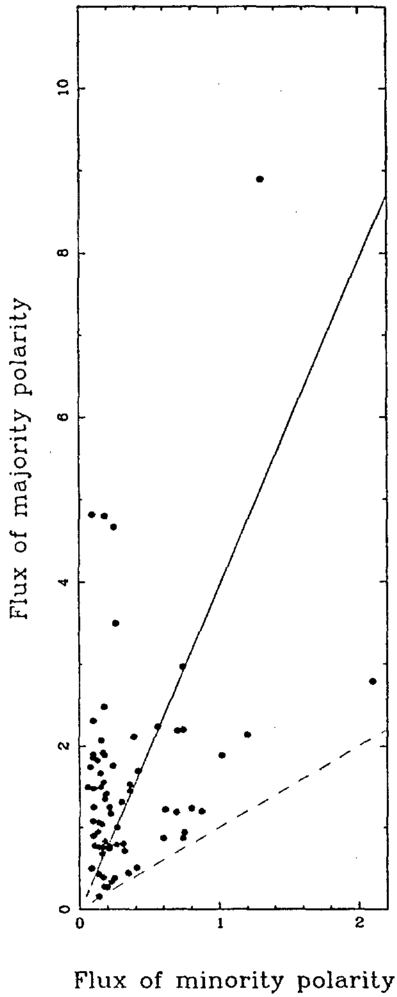


Fig. 4. (a) Flux distribution of majority and minority polarities for a sample of δ-sunspots producing X-class flares in solar cycle 22. (b) Flux distribution for a sample of all δ-sunspots within ± 45 deg in longitude from disc center. The unit of magnetic flux is 10^{22} Mx.

ratio of 6.6 between majority polarity and minority polarity. There is no difference between flux ratios for δ-sunspots located in the north or south hemisphere.

Tang (1983) reported that δ-sunspots appeared to have dominant flux from sunspots of the following polarity. However, for the sample of this study, the preceding polarity seems dominant in flux over the following polarity. Among 58 δ-sunspots studied, 38 ($\sim\frac{2}{3}$) have dominant flux from the preceding sunspots. Only one-third of them have following polarity dominant.

As only the δ-sunspots, which are X-class flare generators, are used to evaluate the flux ratio, a question is naturally raised whether this imbalance of magnetic flux between the two polarities holds for all δ-sunspots, or if it is only a characteristic of δ-sunspots which produce X-class flares. To answer this question, another sample of 73 δ-sunspots in solar cycle 15 is chosen to examine the results found above. All δ-sunspots during the period from 1917 to 1924 which were located with 45 deg of the disc center are included in this sample. From a lack of knowledge about the flare activity of these δ-sunspots, one assumes that this sample represents 'normal' δ-sunspots. The same plot as in Figure 4(a) for this sample of δ-sunspots is shown in Figure 4(b). The data points roughly distribute along two branches. One branch has a steep slope as in Figure 4(a); the other has a rather flat slope; but all the data lie above the dashed line, indicating a balanced flux distribution. A least-square fitting gives a ratio of 4.0. This means that all δ-sunspots do have imbalanced flux between the two polarities. By comparing Figures 4(a) and 4(b), one may conclude that the degree of imbalance of magnetic flux in opposite polarities seems relevant to the activity level of δ-sunspots in producing large flares.

It is interesting to ask what causes this imbalance of magnetic flux in opposite polarities and if this imbalance is a decisive factor in causing high flare activity. First of all, this flux imbalance might itself indicate the different origins of the sunspots that are locked as a δ-spot. Since the opposite polarities belong to two independent magnetic loops, they might be obviously different in geometric size and field strength, as well as evolutionary histories. There is no reason to expect a balanced flux between the two polarities. Even relying solely on this fact, one could expect that δ-sunspots are flare productive; since only at the separatrix surfaces of independent flux loops, are there possibilities for the formation of a strong current sheet, accumulation of non-potential magnetic energy, as well as fast reconnection. All of these are necessary conditions for great flares. Furthermore, the thermodynamic and/or dynamic states of two component sunspots might be different, and their depths rootes by two flux might not be the same. These may further favor the onset of great flares. However, at present no data are available to evaluate if there are intrinsic differences between two-component sunspots in a δ-sunspot.

4. Productivity of X-Class Flares

High productivity of great flares is one of the intrinsic properties of δ-sunspots. For the definitiveness and completeness of the chosen sample, in this paper only X-class X-ray flares in solar cycle 22 are considered. So far, 149 X-class flares have been reported since 1988; 96% of them appear in active regions with δ-sunspots. On the other hand, 282 δ-sunspots are observed in the same period; 23% of them have preceded X-class flares. In Figure 5, the 6-month running average of δ-sunspots and X-class flare numbers are plotted. The solid curve with circles represents the flare numbers, while the dashed with asterisks is for the numbers of δ-sunspot. Their change are roughly in phase. In this sense, the numbers of δ-sunspots might be considered as a global index of activity level of the Sun.

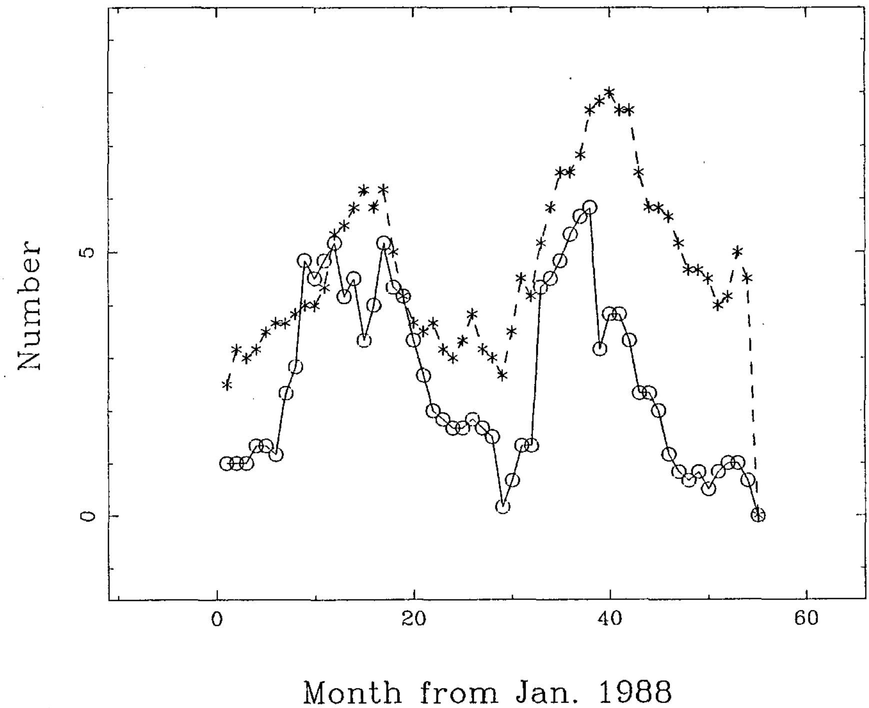


Fig. 5. The 6-month running average of δ-sunspot and X-class flare numbers.

However, the correlation between numbers of δ-sunspots and large flares is not a one-to-one correspondence. Without the running average, the correlation between numbers of and large flares is rather noisy. It is found that the X-class flares are mainly associated with superactive regions in which huge δ-sunspots with long lifetimes are present; whereas a small δ-sunspot is often not productive of large flares. Keeping this in mind, the lifetime of δ-sunspots might be considered as a measure of how big and how strong the δ-sunspots are. To get a more quantitative idea, the dependence of X-class flare productivity on the lifetime of δ-sunspots is examined.

The lifetime of δ-sunspots varies from less than 1 day to more than 10 days. For the sample of 282 δ-sunspots, an average lifetime of 4.2 days is found; however, for δ-sunspots which are X-class producers, the average lifetime is 7.8 days. The detailed lifetime distribution of all 282 δ-sunspots is shown by the histogram in Figure 6. The productivity of X-class flares is defined as the mean number of X-class flares per region for a given lifetime of δ-sunspots. For all of the 282 δ-sunspots, the relationship between the flare productivity and δ-sunspot lifetime is illustrated in Figure 7. A least-square fit gives

$$P_{xxf} = -0.12 + 0.02T_\delta^2 \,, \qquad (1)$$

where P_{xxf} is the productivity and T_δ is the lifetime of δ-sunspots. This equation

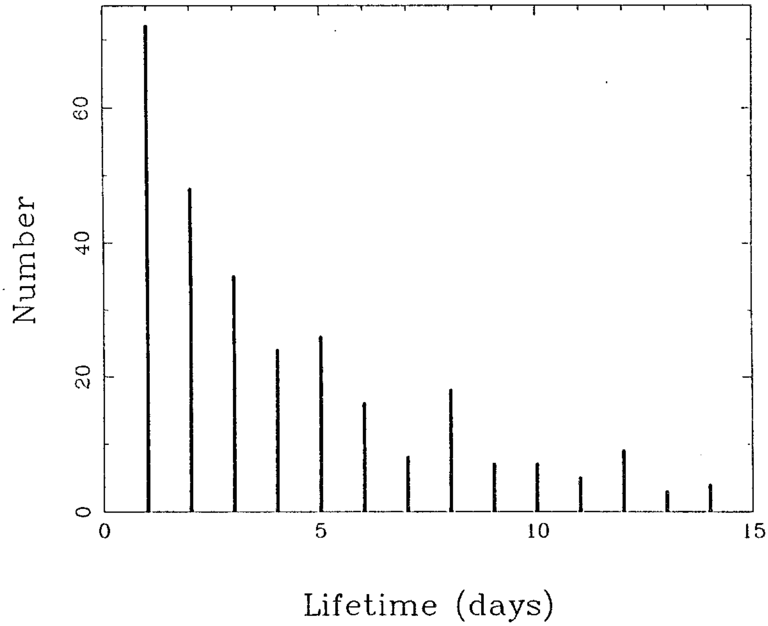


Fig. 6. The histogram of lifetime distribution of all 282 δ-sunspots in solar cycle 22.

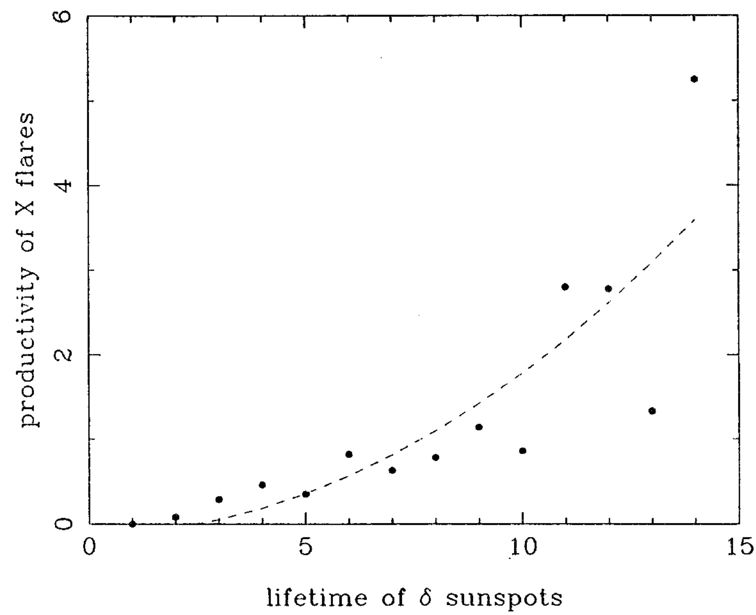


Fig. 7. The relationship between flare productivity and δ-sunspot lifetime for all 282 δ-sunspots in solar cycle 22.

shows that only δ-sunspots with lifetimes longer than 2 days may be productive in X-class flares.

5. Conclusion and Discussion

Delta-sunspots in this solar cycle are used as a sample to investigate the statistical properties of δ-sunspots, particularly those relevant to X-class X-ray flares. The previous discoveries of the patterns of δ-sunspot formation and disintegration are basically confirmed. As a new result, it is found that a δ-sunspot can be separated simply into two unlocked sunspots by individual proper motions of each component sunspot. Examples of the disappearance of δ-sunspots by flux cancellation with occurrence of large flares are also identified.

An intriguing characteristic of δ-sunspots is the highly imbalanced flux between the two opposite polarities. For 58 δ-sunspots, which precede X-class flares, the average ratio of majority flux to minority flux is 6.6. For the other 73 δ-sunspots in solar cycle 15, whether flare-productive or inactive, the average ratio is 4.0.

It is also revealed that the productivity of δ-sunspots in X-class flares is closely correlated to the lifetime of δ-sunspots. For δ-sunspots with lifetimes of only one day, no X-flares were even observed in this solar cycle. The productivity of X-class flares seems to be roughly proportional to T_δ^2.

With regard to the questions why δ-sunspots have such an imbalanced flux between the two polarities, and what makes δ-sunspots highly energetic in causing great flares, the answer is still not clear. The authors suggest that a key fact could lie in the origins of δ-sunspots. As Tang (1983), Zirin and Liggett (1987), and this investigation illustrated, δ-sunspots form from different dipoles which have their own identity in the topological connectivity. The component sunspots locked as a δ-sunspot are often of different size, source, and evolutionary history, so that they may also have different dynamic and thermodynamic, as well as topological properties. Once they are locked together somehow, a very steep magnetic gradient and magnetic shear are set up in the interface, so are strong current sheets. Meanwhile, the characteristic scale for field changes becomes comparable with the width of their interface, but not that of sunspots, so that Ohmic diffusion can no longer be neglected. As long as a huge amount of magnetic flux is involved in the δ-sunspots, great resources of free energy will be available. Continuously, major activity will certainly take place. On the contrary, there is ample evidence that a single set of magnetic loops (see the example in Figure 2) can last a long time without any activity, except for possible coronal heating, high above. In brief, the δ-sunspots present well the interaction of two or more intense flux loops, which is the basic magnetic environment for the appearance of large flares.

The proper motions of sunspots seem to play an important role in the formation and disintegration of δ-sunspots. It is the magnetic buoyancy that drives the proper motions of sunspots. Many examples demonstrate that different dipoles often have different orientations and separation speeds. This, sometimes, might cause sunspots to shove into one another, and result in strong magnetic shear on their common boundary.

There are several common characteristics in almost all δ-sunspots. They are: (1) two intense interacting flux loops; (2) vigorous collisional motion or shoving into one another of two polarity components; (3) very steep magnetic gradient; (4) very strong magnetic shear on the neutral lines: (5) highly imbalanced magnetic flux between two polarities; (6) very great activity. It should be pointed out that these elements are also quite common for the configuration of cancelling magnetic features, either in active regions, or in the quiet Sun (Livi, Wang, and Martin, 1985; Martin, Livi, and Wang, 1985; Wang *et al.*, 1987; Wang and Shi, 1993), although the magnetic field strength and field gradient for cancelling features are not always as strong as that in δ-sunspots. In fact, some δ-sunspots themselves cancel, see the example in Figure 3. A rather broad concept 'δ-configuration', with all the above common characteristics, seems of interests to be introduced. This concept, in fact, has been interchangeably used with the term δ-sunspots in the solar literature. Here, the authors suggest that one consider the δ-configuration as a broader concept to describe the magnetic environment which satisfies the basic elements listed above, but one which does not necessarily contain a δ-sunspot.

Finally, it should be mentioned that the calculation of the magnetic flux of δ-sunspots is based on the estimation of sunspot areas. Hence, the results would certainly suffer from some degree of error. However, as regards to the estimation of the flux ratio between the two polarities, the basic results would be reliable.

It seems of great importance to study the physics of δ-sunspots. The measurements of vector magnetic fields in δ-sunspots will be of great help in understanding all the intriguing properties of δ-sunspots, perhaps also the whole physics of flares. For this, further studies of δ-sunspots are underway.

Acknowledgements

This work is supported by National Natural Science Foundation of China under grant 1880608, 19133010, and 19133104. The authors thank the Huairou staff for providing very good magnetograms, the Shahe staff for providing sunspot data. The authors are grateful to Prof. Zirin, for his valuable comments and suggestions.

References

Hale, G. E. and Nicholson, S. H.: 1938, *Magnetic Observations of Sunspots*, Carnegie Institution of Washington, Washington, D.C.
Künzel, H.: 1960, *Astron. Nachr.* **285**, 271.
Livi, S. H. B., Wang, J., and Martin, S. F.: 1985, *Australian J. Phys.* **38**, 855.
Martin, S. F., Livi, S. H. B., and Wang, J.: 1985, *Australian J. Phys.* **38**, 929.
Sheeley, N. T., Jr.: 1966, *Astrophys. J.* **144**, 723.
Tang, F.: 1983, *Solar Phys.* **89**, 43.
Wang, H.: 1992, in K. L. Harvey (ed.), *Solar Cycle*, ASP Conference Series 27, p. 97.
Wang, H., Tang, F., Zirin, H., and Ai, G.: 1991, *Astrophys. J.* **380**, 282.

Wang, J. and Shi, Z.: 1993, *Solar Phys.* **143**, 119.
Wang, J., Shi, Z., Martin, S. F., and Livi, S. H. B.: 1987, *Vistas Astron.* **31**, 79.
Warwick, C.: 1966, *Astrophys. J.* **145**, 215.
Xu, A-a, Yin, C-l., Zhang, H-q., and Wu, S. T.: 1991, *Acta Astron. Sinica* **32**, 36.
Zirin, H.: 1988, *Astrophysics of the Sun*, Cambridge University Press, Cambridge.
Zirin, H.: 1993, in H. Zirin, G. Ai, and H. Wang (eds.), *Solar Magnetic and Velocity Fields.*
Zirin, H. and Liggett, M.: 1987, *Solar Phys.* **113**, 263.
Zirin, H. and Marquette, W. H.: 1991, *Solar Phys.* **131**, 149.
Zirin, H. and Wang, H.: 1990, *Solar Phys.* **125**, 45.