# ON THE ORIGIN OF $\delta$ SPOTS

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**Abstract.** Mount Wilson sunspot drawings from 1966 through 1980 were used in conjunction with H$\alpha$ filtergrams from Big Bear Solar Observatory to examine the origin of $\delta$ spots, spots with bipolar umbrae within one penumbra. Of the six cases we studied, five were formed by the union of non-paired spots. They are either shoved into one another by two neighboring growing bipoles or by a new spot born piggy-back style on an existing spot of opposite polarity. Proper motions of the growing spots take on curvilinear paths around one another to avoid a collision. This is the shear motion observed in $\delta$ spots (Tanaka, 1979). In the remaining case, the $\delta$ spot was formed by spots that emerged as a pair. Our findings indicate no intrinsic differences in the formation or the behavior between $\delta$ spots and spots of normal magnetic configuration.

## 1. Introduction

Most sunspots emerge as bipoles. As the bipolar spots grow the distance between them increases, consistent with the model of a rising flux tube with its foot points in the photosphere as the spots. At maximum growth, the distance between bipolar spots varies in general with the spot sizes from under 1 arc min for pores to over 4 arc min for a large spot group.

There are two exceptions to the above simple bipolar $\beta$ configuration. The first is a polarity mix-up. The magnetic classification of a group of spots with completely mixed polarities is called a $\gamma$ configuration. A more common type is called $\beta\gamma$ where only one or more spots are 'out of place'. But this is no more than a small bipole emerging in either the $P$-polarity or the $F$-polarity part of a larger bipolar region.

$\delta$ spots are the second exception. It happens when the normal separation between spots of opposite polarities disappears and the bipolar spots become a bipolar spot!

Ordinarily bipolar spots emerge then move apart from one another by proper motion of the spots. More spots would emerge near the neutral line and move apart again. Spots of the same polarity coalesce. At maximum growth, the spots (the strongest magnetic fields) are in the interior of their respective polarity fields. The field strengths decrease outward from the spots. At the magnetic neutral line the longitudinal field strengths are some 2 orders of magnitude weaker than the umbral field. In the case of $\delta$ spot, however, the strongest fields are brought closer to the neutral line by a factor of 3 to 4, creating high field gradients. In addition, there is a high probability of these $\delta$ spots being inverted-polarity spots, i.e. the polarity axis deviates from the Hale's law by more than 45° (Tanaka, 1979; Tang, 1982).

Delta spots are known to be prodigious producers of great flares. Warwick (1966) found that $\delta$ configuration precedes or accompanies practically all proton flares. Tanaka

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(1979) matched 90% of regions of great activities with regions of $\delta$ spots of inverted polarity selected from over 46 years of sunspot data. Using Dodson and Hedeman's (1971, 1975, 1981) comprehensive flare index (CFI) data, we found that of the 13 greatest flares with CFI $\geq$ 15 from 1966 to 1979, all but one were from regions with $\delta$ spots. The most outstanding of all $\delta$ spots is exemplified by the August of 1972 region. In that case all the spots of the region (except some minor pores) were packed inside one penumbra about 1.5 arc min in width. The great flares produced by that region during its disk passage are well known (Zirin and Tanaka, 1973).

Just how are the $\delta$ spots formed? Do the opposite polarity umbrae that make up the $\delta$ spot belong to the ends of a single flux tube (paired spots) or are they unions of spots from different flux tubes (non-paired spots)? The origin of the $\delta$ spots is the subject of this investigation.

## 2. Data

Data consist of the Mount Wilson sunspot drawings on microfilm from 1966 to 1980. The detailed white-light drawings were done on solar image ~42 cm in diameter from the 150-foot tower telescope. The coordinates of the numbered sunspot groups as well as the polarities and field strengths of each individual spot and pore measured in the Fe I 5250 line are indicated on the drawings. When a $\delta$ spot was found we searched backward in time to learn the history of the each constituent of the $\delta$ configuration. To establish the bipoles from which the $\delta$ spot evolved, we relied on the H$\alpha$ coverage from Big Bear Solar Observatory or Tel Aviv. The arch filament system in early stages of spots emergence revealed in the core of H$\alpha$ supply the pairing information of spots.

We select only those $\delta$ spots with large umbrae. The study yielded six cases where the origin of these spots can be clearly established.

## 3. Results

### 3.1. $\delta$ SPOTS FORMED BY NON-PAIRED SPOTS

We found that most of the $\delta$ spots we studied were formed by the joining of spots from two (or more) different bipolar groups. This is accomplished in two ways.

(1) The non-paired spots are shoved into one another by the growing and expanding of the bipolar groups they each separately belong to. Figure 1 shows an example of this kind. H$\alpha$ filtergrams for this coverage were obtained from Tel Aviv. West is to the right on all filtergrams. On December 6, 1972 two bipolar groups emerged close to one another. $P$ indicates spot(s) of the preceding polarity, $F$ the following polarity. Pairing of the spots at birth, as indicated by the AFS (arch filament system) in center line H$\alpha$, is denoted by the same numeral suffix. On December 8, as the result of the growth and expansion, $P_1$ caught up with $F_2$, and a $\delta$ spot resulted. Spot group 2 continued to grow and $F_2$ finally settled to the north (top) of $P_1$ and stayed there from December 11 through 16, the last day of coverage.

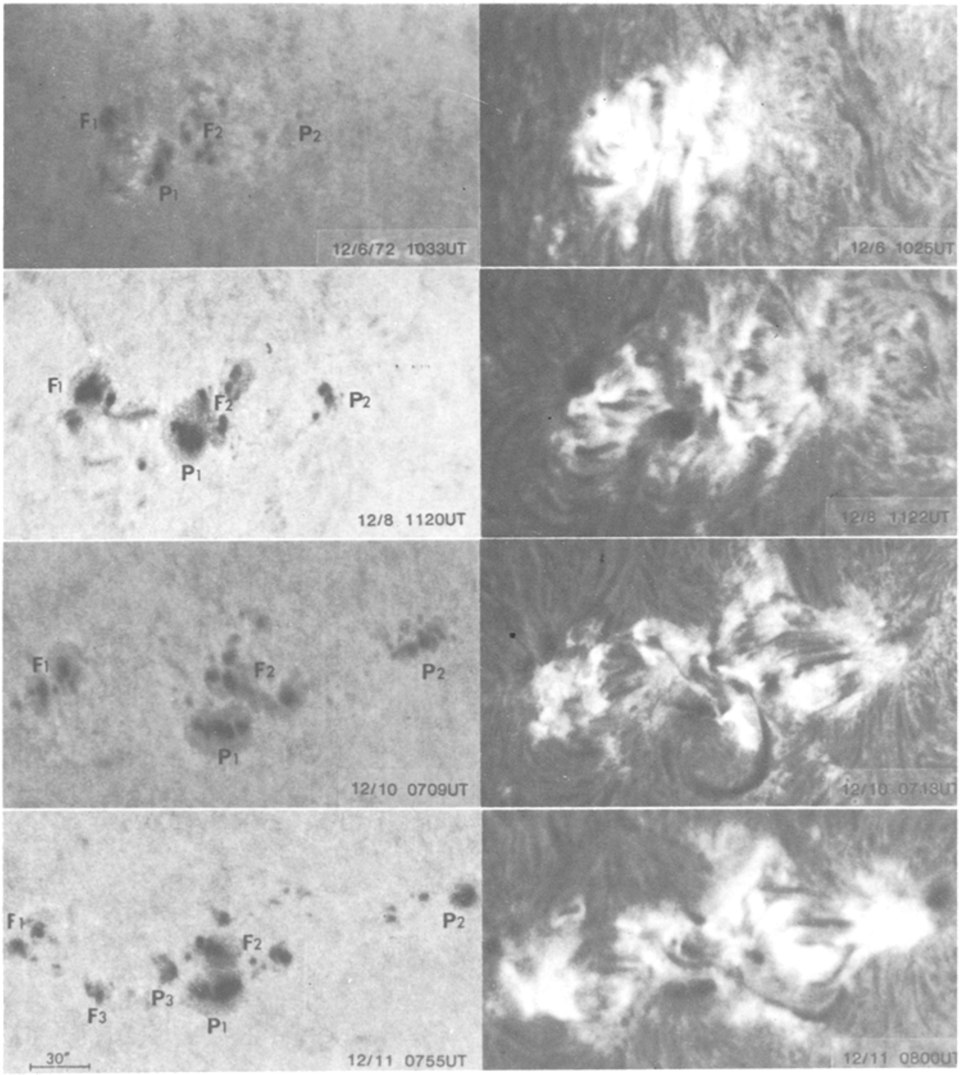


Fig. 1. A δ spot formed by two opposite polarity spots, $P_1$ and $F_2$, being shoved into one another by two neighboring growing bipoles 1 and 2. *P* Denotes preceding polarity, *F* following polarity. Pairing of the spots at birth, as indicated by the arch filament system in center line Hα, is denoted by the same numeral suffix. On and offband Hα filtergrams are from Tel Aviv. West is to the right and north is on top on all filtergrams.

Notice that spot group 2, unlike a typical one, had a dominant *F* spot rather than a dominant *P* spot. This seems to be a frequent occurrence in δ spot as we shall see.

(2) A δ spot is formed by a new spot born piggy-back style on an existing spot of the opposite polarity. Figure 2 shows an example of this type. High resolution Hα and white light coverage were available for this spot. On July 31, 1975 spot group 1 emerged next

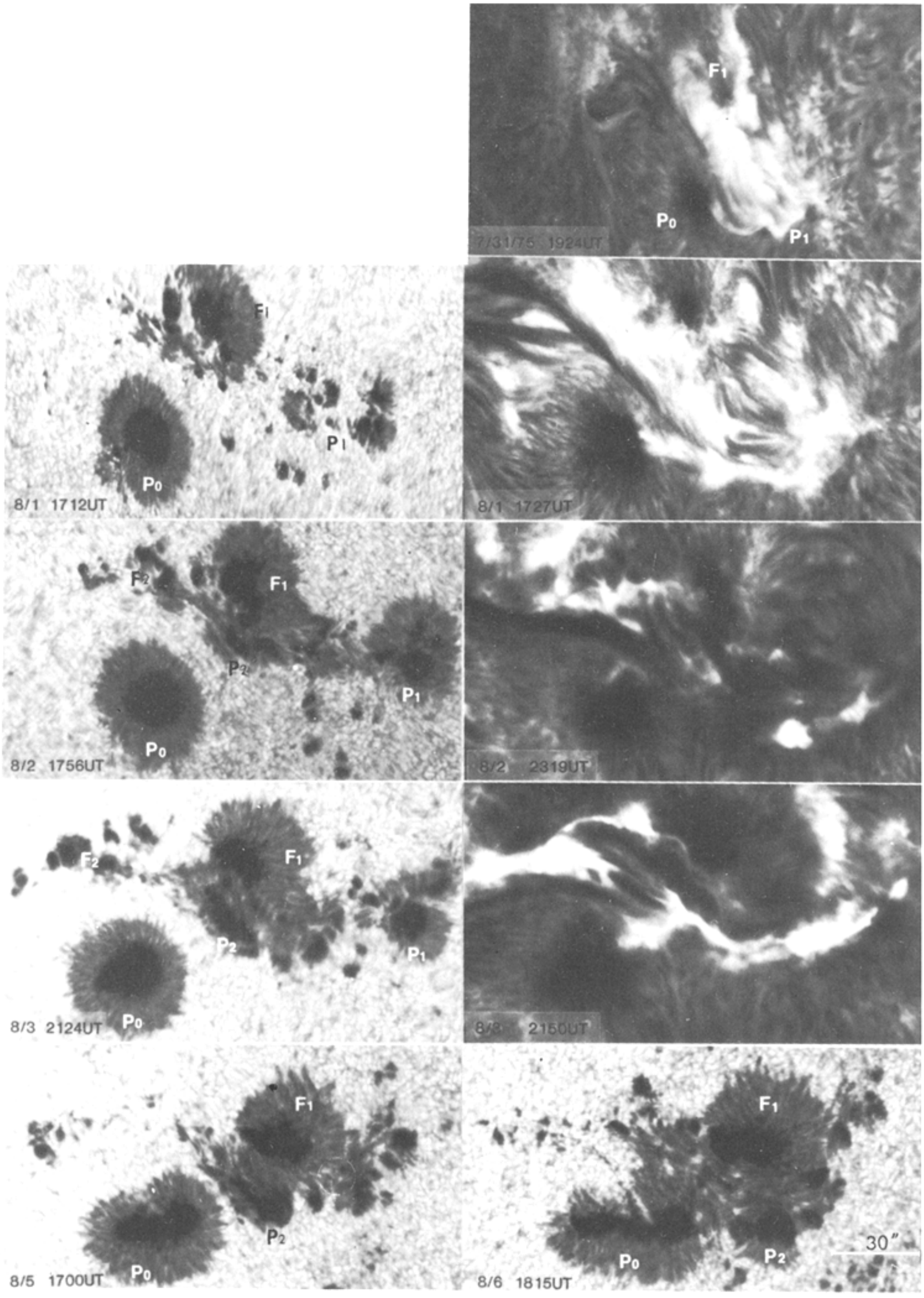


Fig. 2. White-light and center-line Hα filtergrams from Big Bear Solar Observatory show a δ configuration resulting from a *P* spot ($P_2$) emerging on a *F* spot ($F_1$) from a different bipole. On August 6, the δ configuration was joined by a unipolar *P* spot ($P_0$) from yet another bipole of an earlier time.

to $P_0$, a unipolar spot left over from a bipolar region just to the east. $P_1$ and $F_1$ denote the spots of the EFR (emerging flux region) with its characteristic AFS. The next day region 1 grew rapidly and new $P_1$'s replaced old ones at a less inclined angle. On August 2, another EFR with spots $P_2$ and $F_2$ emerged. The AFS linking the spots can be seen once again in the center line. Since $P_2$ emerged on $F_1$, a $\delta$ spot was formed. The proximity did not seem to hamper the growth of either spot – $P_2$ (growing away from $F_1$) was larger than $F_2$; and $F_1$ was larger than $P_1$.

On August 6, while the other spots and pores in spot groups 1 and 2 decayed, the $\delta$ spot was joined by $P_0$ and now it consisted of not 2 but 3 spots evolving from 3 different spot groups.

The manner in which $P_0$ joined the $\delta$ spot is intriguing. A unipolar circular spot left by itself normally decays through weakening and shrinking (Liggett and Zirin, 1983). $P_0$, however, actually actively took part in the development just to the west of it. Normally there would be no more westward proper motion for spots at this late stage of evolution (Waldmeier, 1955). $P_0$ reached westward toward the $\delta$ spot by transforming its shape from circular (see 8/2 frame of Figure 2) to an elongated spot (see 8/6 frame of Figure 2). The final linkage to the $\delta$ spot was then provided by growing an extra portion of penumbra.

The $\delta$ configuration remained until the 9th but the spot was much reduced by then through decay.

Notice in both of the above cases the non-paired spots that formed the $\delta$ spot appeared to rotate about one another. This is the shear motion in the evolution of $\delta$ spots discussed by Tanaka (1979). Since the opposite-polarity spots cannot annihilate one another when they are shoved (or grow) onto one another, the proper motions of the spots take on a curved path to go around one another. Because there is more westward proper motion of the $P$-polarity spot than the eastward motion of the $F$ spot in growing regions (Waldmeier, 1955), the shear motions comprise mostly the westward motion of the $P$ spot as shown in Figure 1. The practical use of this is that one can predict the direction of the shear motions given the geometry of the growing bipoles.

The rotation-like motion, seen in Figure 1, also shows how an inverted polarity $\delta$ spot can result from two normally oriented regions.

### 3.2. $\delta$ SPOTS FORMED BY PAIRED SPOTS

Delta spots formed by paired (conjugate) spot are rarer. We have come across only one instance where a major $\delta$ spot consisted of spots born as a pair. Figure 3 illustrates the case.

A growing region was near the east limb on December 7, 1978. The Mount Wilson sunspot drawing showed the growing $P_1$ and $F_1$ and two $F$ polarity pores in between them the next day. On the 9th, a new $P$ spot, $P_2$, emerged with an extended penumbra connecting it to $F_1$. The arch filament system in the center-line filtergram shows that $F_2$ actually merged with spot $F_1$. On December 14, a $\delta$ configuration resulted once again by virtue of an extra portion of penumbra that linked $P_2$ with $F_2$. Notice that the mature spots of group 1 were at a much smaller separation than that of an ordinary pair of spots

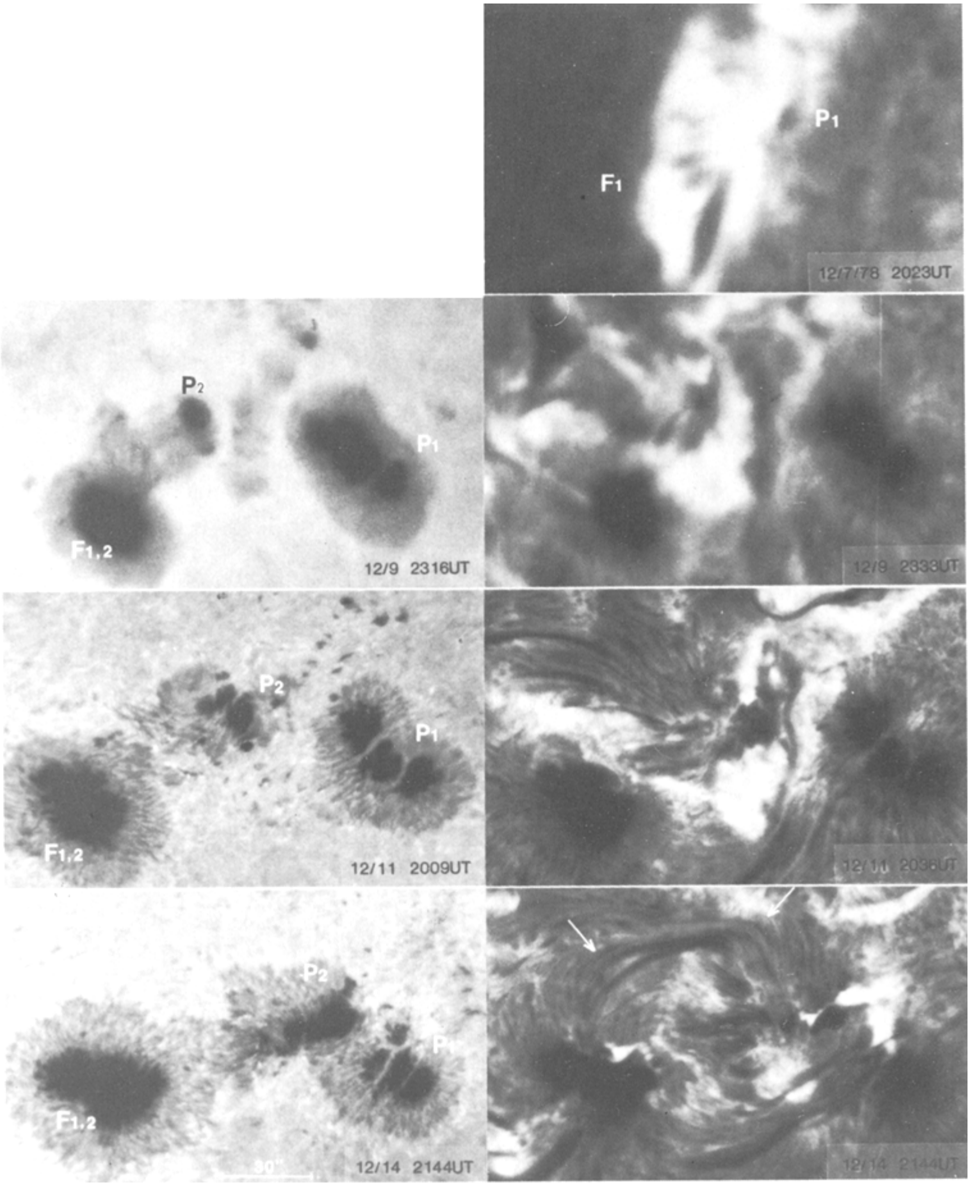


Fig. 3. An example of a rare δ configuration formed with paired-spots, spots at the foot points of a single flux tube. Kinks (arrows) indicate stress in the field lines resulted from the unnaturally close proximity of the pair.

to begin with. The separation between $P_2$ and $F_2$ is shorter than the usual separation between spots of comparable sizes by a factor of 3. The kinks in the field lines, denoted by the arrows in the center-line H$\alpha$, indicate stress caused by the proximity of the bipoles.

The end of the δ configuration came two days later when $P_2$ moved westward (belatedly) and severed the link to its *F* spot. This is different from the previous two cases where decay caused the demise of the δ spots rather than separation along the polarity line. Table I summarizes the δ spots we studied.

TABLE I

The δ spots studied

| No. | Mt. Wilson sunspot No. | Dates | | | Formation | Orientation |
|---|---|---|---|---|---|---|
| 1 | 19596 | 2–9 | Aug. | 1975 | *P* born on *F* | N–S |
| 2 | 20123 | 8–20 | July | 1978 | *F* born on *P* | N–S |
| 3 | 19057<br>19058 | 8–16 | Dec. | 1972 | shoved together | N–S |
| 4 | 19426<br>19427 | 1–9 | July | 1974 | shoved together | N–S |
| 5 | 17192<br>17196 | 23–24 | March | 1969 | shoved together | reversed<br>E–W |
| 6 | 20342 | 9–16 | Dec. | 1978 | born paired | normal |

## 4. Conclusion and Discussion

Of the 6 δ spots we studied, 5 were formed by non-paired spots either shoved into one another by two neighboring growing bipoles or by a new spot growing on an existing spot of the opposite polarity. Proper motions of the growing spots that formed the δ configuration take on a curvilinear path around one another to avoid a collision. This rotation-like motion is the shear motion observed in δ spots. The rotation also causes normally-oriented groups to produce inverted-polarity δ spots. The fact that there is a high probability of δ spots having inverted-polarity is consistent with the result from our small sample of data that more δ spots are formed by non-paired spots.

In only one of the six cases was the δ spot formed by spots at the ends of the same flux tube.

The formation of δ spots is consistent with the flux tube model for sunspot. The findings from this investigation indicate, or imply, the following: (1) The umbra, the moste concentrated part of the field lines at the heart of a flux tube, is incompressible. (At their closest, the bipolar umbrae are still separated by a truncated penumbra.) The penumbra, on the other hand, is compressible and expandable. (2) The growth of spots is not hindered by the close proximity of one another. They simply grow toward the direction of less concentration of fields, less magnetic pressure. (3) Under rare conditions, a fully risen flux tube (with large bipolar spots) may be ~1.5 arc min apart at the foot points in the photosphere and still remains stable and relatively unstressed ($P_1$ and $F_1$ in Figure 3).

The formation process of $\delta$ configuration shows the behavior of spots under different circumstances from those of normal bipoles. From the standpoint of the flux tube model (Parker, 1955; Babcock, 1961), however, there does not seem to be inconsistentcy between spots of normal configuration and their anomalous counterpart.

What seemed different is that the *F*-polarity umbra of the $\delta$ configuration in our sample seemed to come frequently from bipolar spot groups with dominant *F* spot. Often the resulting $\delta$ spot itself is *F*-polarity dominant. (One recalls that the August 1972 spot was also one of them.) It is not clear what this means. Usually the *F*-polarity spots emerge later, are smaller at maximum growth and decay sooner than the *P*-polarity spots.

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