Characterizing the Umbral Magnetic Knots of δ-Sunspots

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Abstract

Delta (δ) spots are active regions (ARs) in which positive and negative umbrae share a penumbra. They are known to be the source of strong flares. We introduce a new quantity, the degree of δ (Doδ), to measure the fraction of umbral flux participating in the δ-configuration and to isolate the dynamics of the magnetic knot, i.e., adjacent umbrae in the δ-configuration. Using Helioseismic and Magnetic Imager data, we analyze 19 δ-spots and 11 β-spots in detail, as well as 120 δ-spots in less detail. We find that δ-regions are not in a δ-configuration for the entire time but spend 55% of their observed time as δ-spots with an average, maximum Doδ of 72%. Compared to β-spots, δ-spots have 2.6× the maximum umbral flux, 1.9× the flux emergence rate, 2.6× the rotation, and 72× the flare energy. On average, the magnetic knots rotate 17° day⁻¹, while the β-spots rotate 2° day⁻¹. Approximately 72% of the magnetic knots present anti-Hale or anti-Joy tilts, contrasting starkly with only 9% of the β-spots. A positive correlation exists between Doδ and the flare energy emitted by that region. The δ-spots obey the hemispheric current helicity rule 64% of the time. A total of 84% of the δ-spots are formed by single flux emergence events, and 58% have a quadrupolar magnetic configuration. The δ-spot characteristics are consistent with the formation mechanism signatures as follows: 42% with the kink instability or Sigma effect, 32% with multisegment buoyancy, 16% with collisions, and two ARs that are unclassified but consistent with a rising O-ring.

Unified Astronomy Thesaurus concepts: Delta sunspots (1979); Solar flares (1496); Magnetohydrodynamics (1964); Solar magnetic flux emergence (2000)

Supporting material: animations

1. Introduction

Sunspot regions that contain both positive and negative magnetic polarity umbrae within 2° of each other and within a shared penumbra are defined as δ-spots by Küntzel (1965). They appear in observations as a type of magnetic knot (Tanaka 1991) with polarities that do not separate in time in contrast to simpler active regions (ARs). We use the term “magnetic knot” to refer to the umbrae in an AR that satisfy the criteria of being in a δ-configuration and are participating in the δ-configuration. There can be multiple magnetic knots in a single AR classified as δ, and not all of the umbrae in δ-spots need to be part of a knot, as some umbrae are not participating in the δ-configuration. Due to the fact that δ-spots are disproportionately responsible for the most energetic flares and eruptions during any given solar cycle, they are a topic of interest to solar physics and space weather research (Tanaka 1991; Shi & Wang 1994; Sammis et al. 2000; Guo et al. 2014). In contrast to the relatively uncommon, flare-active δ-spots, β-spots are the most common sunspot group category, composing 64% of all sunspot groups (Jaeggli & Norton 2016). A simple β-region has distinct positive- and negative-polarity umbra that are contained in separate penumbra.

The scenarios put forward to explain the formation of δ-spots include a highly twisted, kink-unstable flux tube (Tanaka 1991; Linton et al. 1996; Fan et al. 1999; Takasao et al. 2015; Knizhnik et al. 2018), convective buffeting of the flux tube, i.e., the Sigma (Σ) effect (Longcope & Klapper 1997; Longcope et al. 1998), the multisegment buoyancy model in which two bipoles emerge at two different locations from a single flux tube (Toriumi et al. 2014), and the collision of two emerging tubes (Murray & Hood 2007; Jouve et al. 2018). The twist and the writhe of the flux tube are predicted to be of the same sign if the formation is due to the kink instability and of the opposite sign if the formation is due to the Σ-effect (Linton et al. 1996).

Zipin & Liggett (1987) categorized the formation of δ-spots in the following three ways based on decades of observations at Big Bear Solar Observatory. The first type is an AR emerging all at once as a dipole with the dipoles intertwined, often compact with a large umbra and known as an “island δ.” The second is a δ-spot produced by emergence of satellite spots near large older spots, and often a small opposite-polarity umbra is within the older, larger spot’s penumbra. Third, a δ-configuration is formed by the collision between two separate but growing bipoles that emerged nearly simultaneously, such that the overall area has a quadrupolar configuration and the follower spot of one bipolar region collides with the preceding spot of the other. Toriumi et al. (2017) nicely illustrate these three observed formations and the possible subsurface flux tube structures, naming the categories as spot–spot (“island”-δ); spot satellite, and quadrupole; see Figure 1 for illustrations of the δ-spot types. Lastly, interacting ARs that supposedly are not connected below the surface can collide and form δ-spots. Using observations to distinguish between the formation mechanisms is challenging, as the scenarios shown in Figure 1(b) and (d) would appear nearly identical unless one could confidently measure current or kinetic helicity to differentiate them. Toriumi & Wang (2019) provide a comprehensive review of flare-productive ARs, including a summary of δ-spots.
Figure 1. Flux tube geometries that could lead to the formation of δ-spots are shown: (a) An “island”-δ that is the first category of Zirin & Liggett (1987), also known as the “spot–spot” type by Toriumi et al. (2017), formed by a kink instability acting on a twisted, rising Ω-loop or convective buffeting; image reproduced from López Fuentes et al. (2000). (b) An inverted kink instability; reproduced from Poisson et al. (2013). Bottom row: two multisegment buoyant configurations with different subsurface connectivity; images reproduced from Toriumi et al. (2017), who named them (c) “spot satellite” and (d) “quadrupole.” These last two multisegment buoyancy configurations represent the second and third categories of Zirin & Liggett (1987). The configuration in panel (a) would appear in a magnetogram as a primarily bipolar magnetic configuration, whereas the other three would present as quadrupolar. These schematics do not show crucial aspects of flux emergence such as the buildup of flux at the shoulders of the rising loops, moving dipolar features, etc.

We simplify the observational categorization of regions to be a single emergence event bipole (SEEB), a single emergence event quadrupole (SEEQ), or a multiple flux emergence event quadrupole or multipole (MEEQ). Figure 1(a) represents an SEEB, while the other three panels represent an SEEQ.

δ-spots are classified by observers using the Mount Wilson system via the following method: if a line can easily be drawn between the two polarities, it is classified as a βδ-configuration; if the polarity spatial distribution is more complicated and no such neutral line can easily be drawn, it is classified as a βγδ-configuration. Most δ-spots are complicated and classified as βγδ, with only 16% of δs between 1992 and 2016 being the simpler βδ classification (Jaeggli & Norton 2016). Jaeggli & Norton (2016) reported a variation in AR complexity as a function of solar cycle in that complex ARs (including all groups with a δ or γ classification) composed a larger percentage of ARs during late solar maximum and the declining cycle phase. Nikbaksh et al. (2019) confirmed this finding. One interpretation of the cycle trend is that complex ARs (including δs) are produced by the collision of different magnetic systems when the frequency of flux emergence is high. Jaeggli & Norton (2016) found no significant difference in latitude distribution for complex ARs during the solar cycle. See material in the Appendix for a list of all δ-regions in Solar Cycle 24 and their time–latitude distribution. Sammis et al. (2000) showed that larger flares were well correlated with more complicated sunspot structure, with βγδ-spots hosting the strongest flares.

If the kink instability were crucial in forming δ-spots, it is expected that they would have certain observational signatures. The tilt angle may deviate significantly from Hale’s law or Joy’s law. Hale’s law describes that the ordering of the group magnetic polarity in the east–west direction is opposite in the northern and southern hemispheres for a given sunspot cycle and that this ordering changes from one cycle to the next (Hale et al. 1919). Joy’s law describes the tendency for the follower spot in a sunspot group to be located more poleward, i.e., at a higher latitude, than the preceder spot and for that poleward displacement to be greater at higher latitudes than near the equator (Hale et al. 1919). Tian et al. (2005) found that 34% of δ-spots, in a sample of 104, violated Hale’s law or Joy’s law but the majority of the 104 spots still followed the hemispheric current helicity rule, i.e., the dominance of negative (positive) current helicity in the northern (southern) hemisphere.
(Pevtsov et al. 1995). Knizhnik et al. (2018) modeled kink-stable and kink-unstable flux ropes and found that quantities that can be observed in the photosphere, such as footpoint separation (compactness), rotation, and anti-Hale orientation, all behaved according to the expectations, with the kink-unstable regions being more compact, having higher rotation, and having a larger percentage of anti-Hale configurations than flux tubes that were not kink unstable. However, Knizhnik et al. (2018) showed that observable quantities such as the force-free parameter alpha, current density, and current neutralization ratio do not easily distinguish between the highly twisted and weakly twisted flux ropes. They argued that this could be due to the force-free parameter alpha being a poor representation of flux rope twist, or due to twist (Fan 2009) and/or current (Török et al. 2014) remaining below the photosphere during emergence (Berger 1984).

Although numerous studies have shown that $\delta$-spots exhibit higher-than-average compactness and rotation and are often anti-Hale, these values are derived using the entire AR and thus include regions of the AR that are not part of the $\delta$-configuration. The center of mass and total current in the AR (and other properties) are therefore influenced by parts of the AR that are not related to the umbrae in the $\delta$-configuration. We were motivated to study the $\delta$-spots in a different way. We quantify the “degree of $\delta$” ($\delta\delta$), i.e., the fraction of umbral flux that is participating in the $\delta$-configuration, the percentage of $\delta$-regions that are anti-Hale or anti-Joy, the flux emergence rate of $\delta$-spots compared to other ARs, the rotation and footpoint separation of the $\delta$-portions of the ARs, and the correlation between $\delta\delta$ and flare energy.

As an example of the $\delta\delta$, see Figure 2, showing five snapshots in chronological order of the emergence and evolution of NOAA AR 11560, a quadrupole formed by a single flux emergence event. The time of total maximum umbral flux $\phi_{\text{um}}$ is shown third from the top, and the time of maximum umbral flux in the $\delta$-configuration, i.e., $\delta$-umbra-only flux, $\phi_{\text{Do} \delta}$, is shown fourth from the top. This illustrates how the $\delta$-configuration does not exist for the full evolution of a given AR and also shows how the tilt of the umbrae participating in the $\delta$-configuration is anti-Hale but the tilt calculated from all the umbrae in the AR is anti-Joy.

2. Data

The Helioseismic and Magnetic Imager (HMI) instrument on board the Solar Dynamics Observatory (SDO) spacecraft utilizes filtergrams to image the full disk of the Sun at the Fe I $\lambda 6173$ absorption line with a pixel size of $\approx 0.75$ and a $4096 \times 4096$ CCD (Scherrer et al. 2012; Schou et al. 2012). The filtergram images are recorded for six wavelength positions across the spectral line in a combination of polarization states to acquire the Stokes $I$, $Q$, $U$, and $V$ data. The HMI team produces observables of line-of-sight magnetic field values, Doppler velocities, line widths, line depths, and intensities every 45 s while providing vector magnetic field quantities derived from the Very Fast Inversion of the Stokes Vector (VFISV) code every 12 minutes (Metcalf 1994; Borror et al. 2011; Centeno et al. 2014; Hoeksema et al. 2014).

During the Solar Cycle 24 yr that HMI has been recording data (2010–2019), 132 ARs contained a $\delta$-configuration. The classifications are found in the Solar Region Summary (SRS) files in the NOAA database. The SRS is a joint product of NOAA and the US Air Force (USAF) issued daily, providing a detailed daily description of ARs after analysis and compilation of individual reports from the USAF observers using the Solar Optical Observing Network (SOON) that includes ground observatories in Learmonth, Western Australia; San Vito, Italy; and Holloman Air Force Base, New Mexico.

For our research, all days that contained a $\delta$ classified region were noted, and the NOAA AR numbers and dates were used to find the sunspot data as recorded by HMI. HMI AR data are stored both as full-disk images and as smaller cutout regions known as Spaceweather HMI Active Region Patches (SHARPs). Each region is assigned a SHARP number, and these regions are tracked at the Carrington rotation rate and processed within the HMI pipeline (Bobra et al. 2014). The SHARP data contain quantitative parameters describing the regions such as total unsigned flux, flux-weighted longitudinal and latitudinal center of each polarity, etc., that are stored as keywords. The NOAA numbers, SHARP numbers, dates, Mount Wilson categories and maximum flare energy for each $\delta$-spot observed by HMI are found in the tables in the Appendix. The SHARP data products used in this research are the hmi.sharp_cea_720s, which have a Lambert cylindrical equal-area projection. Specifically, the continuum intensity, $I_c$, and the radial field, $B_r$, segments are analyzed. We sample the SHARP data every 2 hr in our analysis, although they are available every 12 minutes and so could be sampled more frequently if desired.

Limb darkening is removed for each continuum intensity image using a second-order polynomial reported in Pierce & Slaughter (1977) with a dependence on the center-to-limb angle as follows: $I = A + B \cos(\theta) + C \cos(\theta)^2$, where $A = 0.36019$, $B = 0.90010$, $C = -0.26029$, and the center-to-limb angle $\theta$ is defined as $\cos(\theta) = 1$ at disk center. The limb darkening is important to include to ensure that umbral boundaries are defined in a consistent manner as the region traverses the solar disk.

Our small sample is composed of 19 $\delta$-spots and 11 $\beta$-spots that act as a control group. We also analyze a large sample of 120 $\delta$-spots, i.e., all those observed by HMI in Solar Cycle 24 within $55^\circ$ of disk center, calculating more limited quantities. We use the GOES catalog to identify flares associated with each NOAA numbered AR. We note every M-class or higher flare, using the sum of these flare X-ray energies as a total flux and the single, highest-energy flare as the maximum X-ray flux.

3. Analysis

We characterize the ARs in two distinctly different manners: (1) values characterizing only the $\delta$-portion of the AR umbra at the time of maximum flux, $\phi_{\text{Do} \delta}$, and (2) values characterizing the entire AR when the region is at its maximum umbral flux, $\phi_{\text{um}}$. We also report on the values of a group of $\beta$-spots at the time of maximum umbral flux, $\phi_{\beta \text{um}}$, to use as a comparison to the $\delta$-spot values at $\phi_{\text{um}}$.

The umbral–penumbral and the penumbral–quiet-Sun boundaries are identified using both the $I_c$ and $B_r$ data in an automated manner after limb darkening is removed. Similar to Norton et al. (2017) and Verbeeck et al. (2013), a threshold value is determined from the mean continuum intensity and the standard deviation of the intensity. On average, using an intensity contrast threshold of 85% for penumbral pixels and 56% for umbral pixels in comparison to quiet-Sun $I_c$ adequately isolated the umbrae in a given image. The magnetic field values, $B_r$, at the same time are used to determine the polarity
Figure 2. NOAA AR 11560 is a δ-spot shown at different times in SDO/HMI continuum intensity (left) and radial magnetic field, $B_r$ (right). The third panel from the top is the time of maximum umbral flux, $f_{\text{um}}$, while the fourth panel from the top is the time of maximum flux in the δ-umbrae only, Do$\delta$ of 56%. The umbral regions participating in the δ-configuration are identified by contours on the continuum intensity image, with yellow (red) contours identifying the negative (positive) umbra and yellow (red) crosses identifying the centroid location for the negative (positive) umbra in the δ. This is a northern hemispheric AR in which the umbrae participating in the δ-configuration present an anti-Hale tilt but a tilt calculated using all umbrae in the AR presents an anti-Joy tilt, since most northern ARs in Solar Cycle 24 have a positive trailing polarity (white) closer to the pole and this one is closer to the equator. The δ-configuration stays compact, and the magnetic knot rotates $70^\circ$ clockwise. The region has a δ-configuration for 29% of the time observed. It is an SEEQ, and its presentation is similar to either the inverted kink configuration, shown in Figure 1(b), or the multisegment buoyancy “quadrupole” configuration, shown in Figure 1(d).
of the umbrae. We use a noise threshold of 575 Mx cm\(^{-2}\) for the vector field strengths such that anything below this value is considered to be noise. This noise threshold is higher than 225 Mx cm\(^{-2}\) recommended by Bobra et al. (2014) and does not affect the identification of umbrae that are participating in the \(\delta\)-configuration since the umbral field values are always higher than 575 Mx cm\(^{-2}\). However, using the threshold of 575 Mx cm\(^{-2}\) does effectively lower values such as the total flux of the region and the flux emergence rate of the region because plage and penumbral fields can fall below 575 Mx cm\(^{-2}\).

In order to determine whether the \(\delta\)-criterion is satisfied and to identify the umbral areas participating in the \(\delta\), a binary array the same size as the AR image is created in which penumbral pixel values are assigned as 1 and nonpenumbral pixel values are assigned as 0. Any contiguous or neighboring penumbral pixels in that array are placed into their own list, where each list marks a separate contiguous region of penumbra. A similar process is performed on the positive and negative umbral regions. Then, a simple loop through each penumbral region determines whether both a positive and negative umbral region are contained within the aforementioned binary subset of penumbrae. If yes, then the umbral regions are classified as in a \(\delta\)-configuration. We do not implement the criterion that the opposite umbrae are within 2° of each other (24 Mm or 33° at disk center or 66 HMI pixels), as we find that if they are contained within the same penumbra, then the 2° criterion is usually satisfied. There are some instances where the opposite umbrae are farther than 2° apart.

Tilt angles are determined using a full 360° range of values; see Figure 3 for the angle definitions and an example. First, the flux-weighted centroids are calculated for the negative and positive polarities of the radial magnetic field in the umbrae. Second, the tilt angle is determined. Third, we determine which of four quadrants the tilt angle resides in. Only one quadrant represents that of compliance with Joy’s law and Hale’s law, two quadrants represent anti-Hale (AH), and the remaining one represents anti-Joy (AJ); see Figure 3. An angle that is anti-Hale can also be anti-Joy, but we do not assign both AH and AJ to a tilt value, only one or the other. The rotation was initially calculated as the difference between the tilt angle from the final time when it is in a \(\delta\)-configuration and the first time it is in a \(\delta\)-configuration. However, we found that within the \(\delta\)-spot, several knots, i.e., adjacent umbrae in \(\delta\)-configuration, could exist at different times, and if the final tilt referred to a knot that was not present in the beginning of the \(\delta\)-configuration, then the rotation was not meaningful. To better characterize the rotation, we isolated individual magnetic knots within each region and noted the direction and amplitude of their rotation via visual inspection of the movies and tilt angle values as a function of time. Positive (negative) rotation values indicate counterclockwise (clockwise) directions. The separation is calculated as the distance between the magnetic flux-weighted centroids of the negative and positive polarities.

The Do\(\delta\) is determined by summing the total, absolute value of the magnetic flux of the umbrae participating in the \(\delta\)-configuration and calculating the fraction it represents of all the flux in the umbrae of the AR. Figure 4 shows four ARs, NOAA AR 11302, NOAA AR 11429, NOAA AR 12158, and NOAA AR 12673, in \(I_1\) and \(B_z\) at various times with a Do\(\delta\) ranging from 17% to 100%. The negative flux and positive flux are not required to be balanced.

Similar to Norton et al. (2017), we calculate the flux emergence rate as the total flux that emerged from a time nearest 10% and through to 90% of maximum umbral flux divided by the number of hours in which that occurred. Sometimes, we do not sample the entire emergence, so we simply calculate this quantity from the nearest times to 10% or 90%, or for regions whose emergence we do not capture at all, we simply report a rate of zero.

Current helicity is a quantity that describes the structure of ARs. We use current helicity to examine the so-called hemispheric preference of the current helicity sign (hereafter referred to as simply the hemispheric rule (HR); Abramenko et al.
the unsigned total flux of the AR above the threshold, the signed flux emergence rate of all the flux above the threshold in the region from the time the flux is at 10%–90% of \( \phi_{\text{hus}} \), and the polarity separation. In addition to these instantaneous values, we report on the total rotation of the tilt angle over the lifetime, the change in separation distance over the lifetime, the lifetime of the umbrae of the AR, and total flare energy. The \( \beta \) ARs are analyzed in the same manner as the \( \delta \)-spots analyzed at maximum umbral flux. We then use the observed emergence and measured parameters to categorize the ARs into regions whose behavior is consistent with certain formation mechanisms.

For a snapshot of the temporal analysis for the AR in a \( \delta \)-configuration, see Figure 5 of NOAA AR 11158, with the \( I_s \) and \( B_r \) snapshots and the quantities as described above for analyzing the \( \delta \)-umbrae only, i.e., the magnetic knot, plotted as a function of time. The vertical, dashed black line indicates the time in the sequence corresponding to the grayscale images in the top panels. Figure 6 is a snapshot of the same AR (NOAA AR 11158) but showing the result of the analysis of the AR taking into account all umbrae, not just the umbrae in the \( \delta \)-configuration. The contours are drawn around all umbrae, and the corresponding umbral flux, region flux, tilt, and polarity separation are shown.

Movies are available online for the small sample of 19 \( \delta \) and 11 \( \beta \) spots included in this paper. Note that we do not employ any smoothing. For the large sample of 120 \( \delta \)-spots, i.e., all those observed by HMI in Solar Cycle 24 within 55° of disk center, we calculate more limited quantities of maximum Do\( \delta \), maximum total umbral flux, \( \phi_{\text{hus}} \), maximum flare energy, total flare energy, and anti-Hale or anti-Joy tilts.

4. Results

Values characterizing the \( \delta \)-umbra-only portion of the AR (the knot) at its maximum \( \phi_{\text{hus}} \) are found in Table 1, while values characterizing the entire AR when at its maximum umbral flux, \( \phi_{\text{hus}} \), are found in Table 2. The similar characteristics of \( \beta \)-spots at maximum umbral flux, \( \phi_{\text{hus}} \), are shown in Table 3. On the left side of the tables, Columns (3)–(7), are instantaneous values determined at the maximum flux times, while Columns (8)–(11) are time-derived values.

For a summary of whether the tilts are anti-Hale or anti-Joy, see Tables 1–2 or Figure 7.

1. 72% of the small sample of \( \delta \)-spots are anti-Hale (44%) or anti-Joy (28%) when these tilts are determined from only the umbrae participating in the \( \delta \).
2. 53% of the small sample of \( \delta \)-spots are anti-Hale (16%) or anti-Joy (37%) at maximum umbral flux using the traditional method of including all umbrae in the AR to determine the tilt angle.
3. These values contrast with only 10% in the \( \beta \) group (all Anti-Joy).

The large sample confirms these percentages with 74% of the \( \delta \)-umbra-only spots having tilts that are anti-Hale or anti-Joy. This percentage drops down to 50% of the tilts being anti-Hale or anti-Joy when calculating the tilt using all umbrae in the AR at \( \phi_{\text{hus}} \); see Figure 7.

On average, the amount of umbral flux participating in the \( \delta \)-configuration, the Do\( \delta \), was found to be a maximum of 72% ± 19%; see Table 1. When calculating the Do\( \delta \) at maximum total umbral flux, the value was lower at 41% ± 33%; see
Figure 4. Snapshots of NOAA AR 11302 (HARP 892), NOAA AR 11429 (HARP 1449), NOAA AR 12158 (HARP 4536), and NOAA AR 12673 (HARP 7115) are shown from top to bottom in continuum intensity (left) and radial magnetic field, $B_r$ (right). The umbral regions participating in the $\delta$-configuration are identified by yellow (red) contours on the continuum intensity image outlining the negative (positive) umbra. The corresponding Do$\delta$ at each time is written in the continuum intensity image.
Figure 5. This δ-spot is analyzed using the umbral flux participating in the δ-configuration, $\phi_{\delta,0}$; i.e., the umbral flux in the "knot." NOAA AR 11158 (HARP 377) is shown using $I_c$ (left) and $B_r$ (right). The still-frame image is from 2011.02.14 at 06:00:00 UT, while the duration of the movie is 176 hr from 2011.02.10 22:00:00 until 2011.02.18 06:00:00 UT. The negative (positive) umbral areas participating in the δ-configuration are identified by contours on the $I_c$ image in yellow (red). The flux-weighted centroids of the knot are indicated by yellow and red crosses on the $B_r$ image. Below the images are plots as a function of time of the following unsmoothed quantities: the umbral flux in δ-configuration, $\phi_{\delta,0}$, the Do$\delta$ (which is the umbral flux in δ divided by the total umbral flux of the region), flare energy of the entire region, tilt angle of the polarities of the knot, total unsigned flux of the region summed from pixels whose values are above 575 Mx cm$^{-2}$, and the polarity separation of the knot. The dashed vertical line on the graphs indicates the time corresponding to the grayscale images in the top panels.

(An animation of this figure is available.)
Table 2. The umbrae were in a $\delta$-configuration 55% of the time they were observed.

The $\delta$-spots show more rotation and less footpoint separation than the control group. The total, average change in rotation of the $\delta$-umbra-only portion of the ARs was $62^\circ$, while it was $23^\circ$ when considering all umbrae in the $\delta$; see Tables 1 and 2. The $\beta$-regions’ total change in rotation was, on average, $9^\circ$; see Table 3. The polarity separations of the $\delta$-only portions of the umbrae were, on average, 32.1 Mm and, on average, converged over time; see Table 1. In contrast, when examining all umbrae in the $\delta$-spot, the average polarity separation was 61.1 Mm and on average separated 9.18 Mm over the lifetime of the region.

Figure 6. The same $\delta$-spot, NOAA AR 11158, as in the previous figure but analyzed using all umbrae of the AR. It is shown using $I_c$ (left) and $B_r$ (right). The still-frame image is from 2011.02.14 at 06:00:00 UT, while the duration of the movie is 176 hr from 2011.02.10 22:00:00 until 2011.02.18 06:00:00 UT. All of the negative (positive) umbral areas are identified by contours on the $I_c$ image in yellow (red). The flux-weighted centroids of all umbral polarities are indicated by yellow and red crosses on the $B_r$ image. Below the images are plots as a function of time of the following unsmoothed quantities: umbral flux in the AR, the total unsigned flux above the threshold of the region, tilt angle as defined by all umbrae, and the polarity separation as defined by the flux-weighted centroids determined using all umbrae. The dashed vertical line on the graphs indicates the time corresponding to the grayscale images in the top panels.

(An animation of this figure is available.)
see Table 2. The $\beta$-spots had an average separation of 66.10 Mm (see Table 3), with an overall change in the separation being a divergence of 31.7 Mm.

The flux emergence rates, $\phi_{\text{em}}$, of the $\delta$-spots, whose values are shown in Table 2, were determined by finding the maximum unsigned flux value above the threshold of all flux in the region at the time of $\phi_{\text{em}}$, then subtracting the flux values at 10% of that maximum flux from 90% of the maximum flux, and dividing through by the time elapsed. This value was divided by two in order to report the signed flux emergence rate. The average flux emergence rate for the full AR of the $\delta$-spots was $10.41 \times 10^{19}$ Mx hr$^{-1}$, and it was $5.45 \times 10^{19}$ Mx hr$^{-1}$ for the $\beta$-spots. Putting the emergence rates into perspective, see Figure 8, where we overlay a fit (dashed line) reported by Otsuji et al. (2011) of a power-law relationship from Hinode observations where maximum flux emergence rates were dependent on maximum flux. Also plotted is the fit (solid line) reported by Norton et al. (2017) of an average flux emergence rate scaling with total signed maximum flux from HMI observations. A value reported for the maximum flux emergence rate by Toriumi et al. (2014) is plotted as a green triangle. Two simulations of AR flux emergence from Rempel & Cheung (2014) and Chen et al. (2017) are also shown using red symbols; see Section 5 for more details and discussion.

In Figure 9, top panel, the maximum flux in $\delta$, $\phi_{\text{Dmax}}$ (black symbols) for the large sample of 120 $\delta$-spots is plotted against the single, maximum flare energy produced by that AR. Also plotted in the top panel is the relationship between the maximum umbral flux in the $\delta$-spot, $\phi_{\text{Dmax}}$ (red symbols), and
the single, maximum flare energy. The fit for the relationship between $\phi_{\text{DoD}}$ and the single maximum flare energy emitted by that region is $E_{\text{FlareMax}} \propto (\phi_{\text{DoD}})^{0.44}$. The fit for $\phi_{\text{max}}$ and the total flare energy emitted by that region is $E_{\text{FlareMax}} \propto (\phi_{\text{max}})^{0.59}$. The Pearson correlation coefficients, known as the $r$-values, are 0.37 (0.39) for the $\phi_{\text{DoD}}$ ($\phi_{\text{max}}$) fits in the top panel, with $p$-values, the probability that the null hypothesis is true, of $10^{-5}$ (10^{-5}).

The same quantities, $\phi_{\text{DoD}}$ and $\phi_{\text{max}}$, are shown in the bottom panel of Figure 9 as a scatter plot against total X-ray flare energy associated with each AR during the times observed. The fits for these have exponents of $c = 0.54$ (0.76), corresponding $r$-values of 0.47 (0.52), and $p$-values of $10^{-5}$ (10^{-5}). All fits provide a positive correlation, but the correlation between maximum umbral flux, $\phi_{\text{max}}$, and total X-ray flux, $E_{\text{FlareTot}}$, has the highest $r$-value of 0.52.

We examine the HR by studying the current helicity for these $\delta$-spots. The current helicity is plotted as a function of hemisphere and time that region is anti-Hale when considering all umbrae in $\delta$-configuration (see Table 1) but anti-Joy when considering all umbrae (as shown here). The last row is the absolute deviation of the median.
regions exhibit the hemispheric current helicity preference (83% in N and 63% in S), as do 60% of the anti-Joy regions (65% in N and 55% in S).

We categorize the δ-regions with regard to how many flux emergence events occur and whether they are bipolar or quadrupolar to find that 58% are SEEQ, 26% are SEEB, and 16% are MEEK; see Table 4. By definition, the β-regions are bipolar.

We then performed a second categorization using the measured parameters and our understanding of the physical mechanisms responsible for forming δ-spots (see Figure 1), to find that the ARs are consistent with the following configurations: kink instability or Σ-effect, inverted kink instability, multisegment buoyancy configurations such as spot satellite or quadrupoles, and colliding ARs. We use the AH, AJ, Doθ, and ΔRot values as determined from the δ-umbrae only, or the “knot”; see Table 1. We note whether the region is a quadrupole. We also note whether there were multiple flux emergence events or only a single one. If there are multiple flux emergence events, defined as emergence events separated by more than 48 hr, the region is immediately classified as being consistent with colliding, or interacting, ARs. If it is a bipole with AH or AJ tilt and a Doθ higher than 50%, it is classified as being consistent with a kink instability or Σ-effect. Single emergent events with quadrupolar configurations could be caused by either a multisegment buoyancy “quadrupole” or an inverted kink configuration. We cannot truly distinguish between the two, but we speculate that a higher rotation of the central umbrae in δ-configuration (>90°) makes it more likely to be an inverted kink configuration because the rotation is consistent with the signature of the writhe of the kink rising through the photosphere, as opposed to the follower spot from one region and the leader spot of the other simply joining together because they are joined below the surface. Some of these ARs, such as NOAA AR 11302 and NOAA AR 12443, do not display AH or AJ. NOAA AR 12158 is compact with an AH tilt with a high Doθ, so it appears consistent with a kink instability but has very little rotation. NOAA AR 12715 is unusual because it is not AH or AJ, shows very little rotation, and emerges with signatures consistent with an arch rising, but then the magnetic polarities do not separate. See Figure 11 for snapshots of NOAA AR 12715 during its evolution. We speculate that this behavior is consistent with the emergence of an O-ring whose flux initially emerges but the polarities stay connected subsurface. The categorization criteria we use show that 42% of the ARs have signatures consistent with formation via a kink instability or Σ-effect, 32% from multi-segment buoyancy, 16% from collisions, and 11% unclassified but consistent with O-rings.

5. Discussion and Conclusions

During the Solar Cycle 24 yr of 2010–2019, 132 distinctly numbered sunspot groups were identified as containing a δ-configuration as determined by forecasters and observers at NOAA and USAF. A total of 18% of the δ-spots were the simpler β category, while the rest were the βγδ-configuration. As there were 1708 ARs numbered during Solar Cycle 24, and 1657 of them were observed by HMI/SDO, our values indicate that 8% of Solar Cycle 24 spots were δ-spots.

Out of the 132 δ-spots identified, we find that 46 produced flares of M-class strength and 14 produced flares of X-class strength as recorded in the GOES flare catalog. While it is well known that >80% of X-class flares originate in δ-regions (Guo et al. 2014), it is not commonly known that it is a small fraction of the δ-spots that produce X-class flares, ≈10%. To restate: in Solar Cycle 24, 8% of ARs are δ-spots, and only ≈10% of those produce X-class flares, while 35% produce M-class flares. This is on the order of 10–20 ARs producing X-class flares and ≈50 producing M-class flares.

Table 3

| NOAA (HARP) | Time       | AH | AJ | Doθ | φi/φmax | Sep | φi | ΔRot | ΔSep | Life | ΣFlares |
|-------------|------------|----|----|-----|----------|-----|----|------|------|------|---------|
| 11141 (325) | 2010.12.31 | 0  | 0  | 0   | 5.31     | 44.70| 0.92| -6   | 29.40| 108  | 0.06    |
| 11184 (466) | 2011.04.05 | 0  | 0  | 0   | 7.42     | 97.50| 7.42| -17  | 26.90| 86   | 0.02    |
| 11199 (540) | 2011.04.28 | 0  | 0  | 0   | 5.54     | 85.10| 5.54| -2   | 51.90| 70   | 0.18    |
| 11311 (926) | 2011.10.04 | 0  | 0  | 0   | 8.27     | 57.90| 8.27| 0    | 9.50 | 20   | 0.04    |
| 11327 (982) | 2011.10.21 | 0  | 0  | 0   | 4.51     | 54.50| 4.51| 2    | 45.50| 100  | 0.04    |
| 11397 (1312)| 2012.01.13 | 0  | 1  | 0   | 7.68     | 25.70| 7.68| 20   | 25.50| 22   | 0.04    |
| 11428 (1447)| 2012.03.06 | 0  | 0  | 0   | 4.58     | 10.50| 4.58| 5    | 10.50| 138  | 0.16    |
| 11435 (1471)| 2012.03.17 | 0  | 0  | 0   | 4.94     | 65.90| 4.94| 10   | 39.90| 64   | 0.16    |
| 11460 (1578)| 2012.04.21 | 0  | 0  | 0   | 5.97     | 87.00| 5.97| 11   | 56.20| 154  | 0.12    |
| 11512 (1795)| 2012.06.30 | 0  | 0  | 0   | 5.23     | 65.90| 5.23| -14  | 38.10| 154  | 0.14    |
| 11497 (1727)| 2012.06.05 | 0  | 0  | 0   | 3.91     | 60.40| 3.91| 13   | 14.90| 172  | 0.04    |
| Average     |            | 0  | 0  | 0   | 5.45     | 66.10| 5.45| 9    | 31.70| 99   | 0.09    |
| Median      |            | 0  | 0  | 0   | 7.87     | 60.60| 7.87| 10   | 29.42| 100  | 0.06    |
| Med abs dev |            | 0  | 0  | 0   | 4.99     | 15.90| 4.99| 5    | 14.60| 38   | 0.04    |
Small Sample of 19 δ-Spots and 11 β-Spots

![Pie charts showing tilts for small sample](image1)

Large Sample of 120 δ-Spots

![Pie charts showing tilts for large sample](image2)

**Figure 7.** Top row: small sample. Bottom row: large sample. The AR tilts are binned by whether they are in the range of expected values (meaning that they obey Hale’s law and Joy’s law), or whether they have anti-Hale or anti-Joy tilt angles. The pie charts from left to right in the top row represent the tilts of the small sample of 19 δ-spots and 11 β-spots for only the umbrae involved in the δ-configuration at the time of maximum Doβ, then all umbrae in the δ AR at the time of maximum umbral flux, and all umbrae for the β-spots at the time of maximum umbral flux. The tilt values from the large sample of 120 δ-spots are shown in the bottom row. Plotted left to right are tilts determined for umbrae involved in the δ-configuration at the time of maximum Doβ, then all umbrae in that region at the time of maximum umbral flux. One can see that the small and large samples are equivalent in that their pie charts differ only by a few percent for the δ-only analysis. Movies for all regions are found online.

spots, and Solar Cycle 24 is no different, as reported by Chen & Wang (2016), who examines five SARs of Solar Cycle 24, and all of those are also δ-spots. Out of the largest 25 ARs of Solar Cycle 24, 21 were δ-spots; see https://www.spaceweatherlive.com/en/solar-activity/top-25-sunspot-regions/solar-cycle/24.html. As such, the control group of β-spots has much smaller flux, and this is a natural outcome of δ-spots being large, in general. Therefore, we could not curate a control group sample that mirrored the same flux range.

The tilt angles reported in Tables 1–2 and Figure 7 indicate that δ-spot formation processes could be responsible for a significant fraction of all AH regions observed during a solar cycle. The total percentage of ARs in any given cycle that are AH is roughly 4%, as reported by Wang & Sheeley (1989) and Kosovichev & Stenflo (2008), or 8%, as reported by McClintock et al. (2014) and Li (2018). We find that 44% of the small sample of δ-spots are AH when using the δ-umbrae only to determine tilt and 16% of δ-regions are anti-Hale when using all umbrae to determine the tilt. If we use these values of 8% of ARs in Solar Cycle 24 were δ-spots and 16% of those were AH, then the AH δ-spots account for 1.3% of all ARs. Comparing this with 4%–8% of ARs in Solar Cycle 24 being AH indicates that δ-spots account for ≈15%–30% of all AH regions during Solar Cycle 24. We find that our percentage of AJ and AH (when considering all umbrae to determine tilt as in Table 2, as this is the correct comparison for the references above) is 53% in the small sample and 50% in the large sample, which is higher than the 34% reported by Tian et al. (2005). Note that the tilt angles reported in this paper are determined at only the times of δDoβ and δimp. The percentages of δ-spots with AH or AJ tilts may certainly be higher if we considered the tilt values at all times during the δ-spot lifetime.

The ARs spend, on average, just over half of their observed time in the δ-configuration and were seen to exist for only a quarter of the lifetime in a few regions. Since the δ-configuration can exist for a short time (even less than a day) compared to the total AR lifetime, we suggest using an automated analysis code with space-based data as input in order to capture more instances of ARs in δ-configuration. This would also remove operator error when classification is performed by humans or ambiguity is introduced by seeing conditions at ground-based observatories.

It is not unexpected to find a higher rotation rate in the δ-spot sample, as this has been reported previously. The average AR group (not δ) experiences a tilt angle change of ≈5° day−1 and has a 40–50 Mm footpoint separation (McClintock & Norton 2016) within a day of emergence. The values from Table 1 indicate that the δ-portion of the spot averages a 62°
The correlation between maximum umbral flux and discussed in Section 4. All $\delta$-spots and $\beta$-spots shown as blue crosses and triangles, respectively, with the median absolute deviation shown as error bars. We overlay fits using a dashed (solid) line reported by Otsuji et al. (2011; Norton et al. 2017) of a power-law relationship from Hinode (HMI) observations where maximum (average) flux emergence rates were dependent on maximum flux. A value reported for the maximum flux emergence rate by Toriumi et al. (2014) is plotted as a green square, and an average flux emergence rate reported by Norton et al. (2017) is plotted as a green triangle. Two simulations of AR flux emergence from Rempel & Cheung (2014) and Chen et al. (2017) are also shown using red symbols; see Sections 4 and 5 for more details and discussion.

Figure 8. AR flux emergence rates determined from observations (blue and green) and simulations (red) show the trend that regions containing more flux emerge faster. The average values of AR maximum signed flux and average flux emergence rates in this study are the $\delta$-spots and $\beta$-spots shown as blue crosses and triangles, respectively, with the median absolute deviation shown as error bars. We overlay fits using a dashed (solid) line reported by Otsuji et al. (2011; Norton et al. 2017) of a power-law relationship from Hinode (HMI) observations where maximum (average) flux emergence rates were dependent on maximum flux. A value reported for the maximum flux emergence rate by Toriumi et al. (2014) is plotted as a green square, and an average flux emergence rate reported by Norton et al. (2017) is plotted as a green triangle. Two simulations of AR flux emergence from Rempel & Cheung (2014) and Chen et al. (2017) are also shown using red symbols; see Sections 4 and 5 for more details and discussion.

Figure 9. The maximum Do\textsuperscript{2} umbral flux, $\phi_{\text{Do}^2}$ (black symbols), and the maximum total umbral flux, $\phi_{\text{tot}}$ (red symbols), vs. the single, maximum flare energy produced by that region is plotted in the top panel for the large sample of $\delta$-spots. The same quantities, $\phi_{\text{Do}^2}$ and $\phi_{\text{tot}}$, are plotted vs. total observed flare energy over time in the bottom panel. The best fits are given in the legend and discussed in Section 4. All fits provide a positive correlation, but the correlation between maximum umbral flux, $\phi_{\text{um}}$, and total X-ray flux, $E_{\text{flareTot}}$, has the highest $r$-value of 0.52.

rotation over 88 hr, or $17^\circ$ day$^{-1}$. The $\beta$-spot values from Table 3 show a rotation of $9^\circ$ over 99 hr, which is a rotation on the order of $2^\circ$ day$^{-1}$. Therefore, we can say that the $\delta$-only portion, the magnetic knot, of the umbrae rotates at a rate 8--9 times higher than other categories of ARs. However, this result should be confirmed by more sophisticated analysis using careful feature tracking rather than the simple change in tilt angle as we have done.

Another interesting finding is that the polarity separations of the $\beta$-spots and the $\delta$-spots (when considering all umbrae as in Table 2) are similar, i.e., $66 \pm 16$ Mm for $\beta$s and $61 \pm 16$ Mm for $\delta$s. $\delta$-spots are often described in the literature as "compact," but this is a term best used to describe the "island"-$\delta$s. In fact, Zirin & Liggett (1987) only use the term as applied to those types (see Figure 1(a)), and not the quadrupolar regions. In addition, the large flux of $\delta$-spots means that even if a region is compact, the separation distance of the polarity centroids can be sizable owing to the large area of the region.

Because flux emergence rates are dependent on the amount of flux in the system, the $\delta$ flux emergence rate is higher, as expected, than for the $\beta$-spots because the $\delta$s have 2.6 times as much flux as the $\beta$s. The average $\delta$ flux emergence rate can still be considered within the normal range for the maximum flux associated with the ARs since the emergence rate scales as $\phi \propto c_{\text{max}}^{0.36}$ (Norton et al. 2017). This is shown in Figure 8—note that the $\beta$ and $\delta$ emergence rates lie directly on the line.

Simulations of AR flux emergence have been carried out by numerous researchers; see the review by Cheung & Isobe (2014), and for results that easily compare to observations, see the introduction of Norton et al. (2017). In general, simulations show both a faster flux emergence and a shorter flux emergence time period than observations; see Rempel & Cheung (2014), Chen et al. (2022), and K. J. Knizhnik et al. (2022, in preparation). Results from simulations are shown in Figure 8 (red symbols) and are compared to the observational results.
from this paper (blue symbols) and previous observational results (green symbols; Toriumi et al. 2014; Norton et al. 2017). Note that changing the noise limit for inclusion of more flux in the observations and calculating the maximum instantaneous flux emergence rate as reported by Otsuji et al. (2011; dashed line in Figure 8 showing the relationship of $d\phi/dt \propto \phi^{0.57}$ based on Hinode SOT observations of events followed in time for a few hours) appears to close the gap between the observational flux emergence rate and those reported in simulations.

Interestingly, Chen et al. (2017, 2022) found that the depth at which the flux was introduced into their convective simulations affected the emergence rate, with flux introduced in deeper domains emerging slower and generally matching the convective upflow speeds at that depth. Chen et al. (2017) found that less flux emerged in the photosphere when it was initially placed deeper as well. ARs are almost certainly emerging from flux that is generated deeper than 10 or 20 Mm below the photosphere, which is the extent of many simulations whose depths are limited by available computing power for the simulations. However, it is not definitely known at what depth the magnetic field is amplified in the dynamo process. It seems highly coincidental that the size scales of ARs, with polarity footpoint separations of $\approx 40$ Mm in the first few days of emergence and separations of $\approx 70$ Mm in its last days of decay (McClintock & Norton 2016), are the same size as a supergranule or two (Rincon & Rieutord 2018). The depth of the near-surface shear layer, 35 Mm, is also the horizontal extent of a supergranule (Matilsky et al. 2018). We mention these depths and extents in order to encourage modelers to consider the interactions between supergranules and flux tubes in the 20–100 Mm below the surface.

The difficulties of simulating flux rising throughout the bulk of the convection zone and coupling it to the uppermost 50 Mm below the photosphere are due to the change from anelastic approximations to fully compressible realizations, as well as the rapid change of pressure scale heights, which is many orders of magnitude. Therefore, the full story of magnetic field amplification and emergence is not known, and the near-surface shear layer’s role remains a mystery.

We had hoped that the Do$\delta$ and $\phi_{\text{Do}}$ would be positively correlated with single maximum or total flare energy of that AR. While the correlation was positive, the maximum flux of all umbrae, $\phi_{\text{max}}$, provided a slightly higher $r$-value (0.52) in
the fit to total flare energy than the fit using $\phi_{\text{Do}\delta}$ ($r = 0.47$); see Figure 9. This was disappointing, but it has been pointed out previously by Fisher et al. (1998) that X-ray luminosity of a nonflaring AR is best correlated with total unsigned magnetic flux of an AR as opposed to other magnetic quantities. Sammis et al. (2000) showed that both the spot group area and the increasing magnetic complexity of an AR were positively correlated with the single highest maximum flare energy associated with that region. The panels of Figure 9 are a representation of the upper right portion of the plot by Sammis et al. (2000), which showed maximum flare energy for all classifications of sunspot, but our plot shows only the Solar Cycle 24 data. If we isolated the source region of the flare to specific umbrae, it is possible that the flux participating in the $\delta$ and the Do$\delta$ would be more flare-rich than the umbrae not participating in the $\delta$, but this is left to a future study.

Our finding that the $\delta$-spots obey the HR for current helicity is in agreement with many other studies on this topic, i.e., that ARs obey the HR roughly one-half to three-quarters of the time (Pevtsov et al. 1995). Our results also agree that the northern hemisphere adheres to the rule slightly more often than the southern hemisphere in the last several cycles. We speculated that the anti-Hale or anti-Joy regions might not obey the HR as often, but the bottom panel of Figure 10 debunks this hypothesis. As the current helicity measure is not determined for the $\delta$-only umbrae, we may find a higher deviation from the HR if we were able to calculate the current helicity for the $\delta$-umbrae distinct from the entire AR.

We find that ARs classified as $\delta$ often contain a significant fraction of umbrae that are not participating in the $\delta$. On average, the regions have a maximum Do$\delta$ of 72% and spend only 55% of their time on the disk as a $\delta$. The calculated tilt angles of the $\delta$-portion are found in 37% of the regions to be in completely different quadrants than the tilt angles calculated using all umbrae of the region. As an example, see the fourth panel from the top in Figure 2, in which the $\delta$-configuration is composed of the opposite polarities with an anti-Hale tilt in the middle of an extended quadrupolar region presenting an anti-Joy tilt. These geometries could arise owing to the fact that a kink instability is acting on only a portion of the flux tube or there is interaction between the following and leading polarities of a multisegment buoyancy.

### Table 4

| NOAA (HARP) | AH | AJ | Do$\delta$ | $\Delta$ Rot | Quad. | Em. Events | Categorization 1 | Categorization 2 |
|-------------|----|----|------------|-------------|-------|------------|-----------------|-----------------|
| 11158 (377) | 0  | 0  | 61         | 53          | 1     | 1          | SEEQ Inverted kink (quadrupole) |
| 11166 (401) | 0  | 1  | 50         | 57          | 1     | >1         | MEEQ Colliding   |
| 11261 (750) | 1  | 0  | 78         | 120         | 1     | 1          | SEEQ Quadrupole (inverted kink) |
| 11263 (753) | 1  | 0  | 40         | 55$^\circ$  | 1     | >1         | MEEQ Colliding   |
| 11267 (764) | 1  | 0  | 77         | –40         | 1     | 1          | SEEQ Inverted kink (quadrupole) |
| 11302 (892) | 0  | 0  | 83         | –85         | 1     | 1          | SEEQ Quadrupole  |
| 11429 (1449)| 1  | 0  | 100        | 35          | 1     | 1          | SEEQ Quadrupole  |
| 11465 (1596)| 0  | 1  | 76         | –35         | 0     | 1          | SEEB O-ring      |
| 11476 (1638)| 0  | 1  | 93         | 100$^\circ$ | 1     | 1          | SEEQ Multiple kink |
| 11520 (1834)| 0  | 1  | 79         | 5           | 0     | 1          | SEEB Kink or $\Sigma$-effect |
| 11560 (1993)| 1  | 0  | 56         | 77$^\circ$  | 1     | 1          | SEEQ Quadrupole (inverted kink) |
| 11598 (2137)| 0  | 1  | 99         | …           | 0     | 1          | SEEB Kink or $\Sigma$-effect |
| 12158 (4536)| 1  | 0  | 100        | 10          | 0     | 1          | SEEB Kink or $\Sigma$-effect |
| 12192 (4698)| 0  | 0  | 95         | 30          | 1     | 1          | SEEQ Spot satellite|
| 12205 (4781)| 1  | 0  | 65         | 88$^\circ$  | 1     | 1          | SEEQ Inverted kink (quadrupole) |
| 12443 (6063)| 0  | 0  | 39         | …           | 1     | 1          | SEEQ Quadrupole  |
| 12671 (7107)| 1  | 0  | 30         | –180        | 1     | 1          | SEEQ Inverted kink (quadrupole) |
| 12673 (7115)| 0  | 1  | 94         | …           | 1     | >1         | MEEQ Colliding   |
| 12715 (7275)| 0  | 0  | 93         | 20          | 0     | 1          | SEEB O-ring      |

**Note.** Columns (2)–(5), the AH, AJ, Do$\delta$, and $\Delta$Rot values, are determined from the $\delta$-umbrae only, or the “knot,” as shown in Table 1. The $\Delta$Rot is for individual knots, which is positive (negative) if it is counterclockwise (clockwise); an asterisk indicates an average of several knots rotating in both directions, and ellipsis points indicate that there was no measurable rotation. Column (6) indicates whether it is a quadrupole (1, yes). Column (7) indicates whether there are single or multiple flux emergence events, defined as emergence events separated by more than 48 hr that increase the flux by more than 30%. Column (8) is the first categorization indicating whether the regions are formed with SEEB, SEEQ, or MEEQ. Column (9) is the second categorization indicating in which regions observational signatures are consistent with the formation mechanisms seen in Figure 1. Categorization 1 shows that 58% are SEEQ, 26% SEEB, and 16% MEEQ. Categorization 2 shows that 42% have signatures consistent with the kink (or inverted kink) instability or $\Sigma$-event, 32% with multisegment buoyancy, 16% with collisions, with 11% unclassified but consistent with O-rings. The quadrupole shows a higher rotation of the central umbrae in $\delta$-configuration $\geq 90^\circ$, we classify it as inverted kink configuration with (quadrupole) as a secondary classification and vice versa if the rotation is less.
Figure 11. NOAA AR 12715 snapshots are shown because its configuration and behavior are somewhat anomalous for a δ-spot. The region is not AH or AJ. It is an SEEB with very little rotation whose opposite polarities emerge with some separation but remain close, converging somewhat over time. We speculate that this could be the signature of flux emerging as an Ω-loop initially, but the legs of the region have reconnected beneath in an O-ring and hence the polarities converge, or the region is confined by strong subsurface flows. Neither mechanism is considered to be a formation mechanism for δ-spots. NOAA AR 11465 is another AR consistent with an O-ring.
In our first categorization, we quantify how many regions are single or multiple emergence events and how many are bipoles or quadrupoles; see Table 4. It is surprising to find that 84% of the \( \delta \)-spots are formed in a single flux emergence event and over half, 58%, of \( \delta \)-regions are formed as quadrupoles, SEEQ. There are fewer bipoles, 26%, and fewer collisions, 16%, than we expected.

Some of these ARs, such as NOAA AR 11302 and NOAA AR 12443, do not display AH or AJ. NOAA AR 12158 is compact with an AH tilt with a high Do\( \delta \), so it appears consistent with a kink instability but has very little rotation. NOAA AR 12715 is unusual because it is not AH or AJ, shows very little rotation, and emerges with signatures similar to an arch, but the polarities do not separate. We speculate that this behavior is caused by a loop connected underneath the surface.

Our second categorization of the \( \delta \)-regions into probable formation types is more speculative since we cannot with confidence distinguish between several formation types using our current measures. The categories are kink instability or \( \Sigma \)-effect, multisegment buoyancy (labeled as “quadrupole” or “spot satellite” in Table 4), or interacting/colliding ARs using observed characteristics reported herein. Our percentages of categorization roughly agree with Toriumi et al. (2017), with our percentages being 42% kink instability or \( \Sigma \)-effect, 32% multisegment buoyancy, and 16% collision, while Toriumi et al. (2017) found 39% kink instability, 55% multisegment buoyancy, and 6% collision. Toriumi et al. (2017) used measures such as the location and length of the polarity inversion line, flare ribbons, and proper motion for categorization. Our sample contained eight of the same sunspots (out of 31 in the Toriumi et al. 2017 study and 19 herein), and we only categorized half of those in the same manner. We categorized NOAA AR 11158 and NOAA AR 11476 as likely formed by a kink instability when Toriumi et al. (2017) labeled them as multisegment buoyancy, and vice versa for NOAA AR 11429 and NOAA AR 12192. Interestingly, NOAA AR 11465 and NOAA AR 12715 behave in a manner that is consistent with a \( \delta \)-spot being formed by a rising, subsurface O-ring, with no anti-Hale tilt, but the bipole emerges as an arch similar to other rising flux loops. However, once that arch has emerged, there is no separation of the polarity footpoints over time and no real rotation, as if the regions are still connected subsurface via a flux tube with very little writhe (see Spruit et al. 1987 for a sketch of a “repairing” AR loop whose legs reconnect to form an O-ring). This raises the question as to how commonly this type of \( \delta \)-spot is seen.

The difference between an inverted kink instability (top right, Figure 1) and a multisegment buoyancy configuration such as a quadrupole (bottom right, Figure 1) is uncertain. While numerical simulations of the kink instability do not produce structures with inverted kinks, observations of emerging flux regions are highly suggestive of such a configuration. Takizawa & Kitai (2015) identify “downward knotted structures in the middle part of the magnetic flux tube” in a dozen \( \delta \)-spots.

In order to more confidently identify that a kink instability is responsible for the formation of a \( \delta \)-configuration, one should examine the twist (using either the current helicity measure or another parameter) and writhe. The kink instability is implicated as the formation mechanism when the twist and the writhe have the same sign. This is in contrast to the \( \delta \)-configuration being formed during magnetic flux tube interactions with turbulent convection (\( \Sigma \)-effect), in which case the twist and writhe would have opposite signs. Previous research has concluded that \( \delta \)-spots are formed by multiple mechanisms since only a portion of the studied regions have the same sign of twist and writhe. López Fuentes et al. (2011) found that 6 out of 10 island-\( \delta \) regions had the same sign of twist and writhe and therefore were consistent with a kink instability, while the remaining 4 regions had opposite signs of twist and writhe. Tian et al. (2005) reported a similar result, with \( \approx 65\% \) of 107 \( \delta \)-spots having similar signs of twist and writhe.

Knizhnik et al. (2018) simulated the emergence of kink-unstable flux ropes and found that while the writhe was identifiable from surface measurements in the simulations and was consistent with the kink formed in the convection zone, the twist parameter alpha was not coherent and did not give a clear signature either consistent or inconsistent with the kink. The conclusion they drew was that the dramatic dynamics of emergence and expansion into the corona distort the field enough that the twist parameter signature is not representative of the flux rope’s twist.

A more in-depth study on the twist, writhe, and current helicity of the magnetic knots of \( \delta \)-spots is warranted. However, it is unwise to measure the twist and writhe of the entire AR when only small portions of the AR are participating in the \( \delta \)-configuration. Out of the 19 \( \delta \)-spots in our small sample, only 2 of them (not including the O-ring regions) could be considered to have the majority of the AR be participating in the magnetic knot. This means that these can be considered an island-\( \delta \)-type configuration in which the AR rotates bodily instead of having several small knots within the region with distinctly different rotations and dynamics. Those two regions are NOAA AR 12158 and NOAA AR 11520 with magnetic knot separations of 30–50 Mm and low total rotations of 5°–10° in which the total AR rotates the same amount as the magnetic knot. Most of the magnetic knots are smaller than the entire AR. For example, NOAA AR 11267, NOAA AR 11560, and NOAA AR 12671 have knot separations on the order of 5–15 Mm with rotations ranging from 40° to 180°. These knots should be studied individually and distinct from the behavior of the AR in which they are embedded, as the kink instability may be acting on small flux tubes within the AR. We hope to do this in a subsequent publication, as it is beyond the scope of this paper.

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Appendix

Delta Sunspots in Solar Cycle 24 Observed by HMI

This appendix contains lists of all \( \delta \)-regions in Solar Cycle 24 as classified by NOAA observers. The regions are found in Tables 5–14 organized by year with NOAA numbers and corresponding HARP number, date of observations, classification, and maximum single flare energy. To put the \( \delta \)-regions in context of the progression of the solar cycle, we plot their location on a butterfly diagram created using HMI SHARP data; see Figure 12.
### Table 5
Delta Sunspots of 2010

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 11045| ...  | 20100209-10  | βγδ   | C3    |
| 11087| 86   | 20100713     | βγδ   | C2    |

### Table 6
Delta Sunspots of 2011

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 11158| 377  | 20110216-19  | βγδ   | X2    |
| 11161| 384  | 20110220     | βγδ   | C4    |
| 11164| 393  | 20110302-09  | βγδ   | C6    |
| 11165| 394  | 20110308-09  | βγδ   | C5    |
| 11166| 401  | 20110308-13  | βγδ   | X1    |
| 11224| 622  | 20110530     | βδ    | C3    |
| 11226| 637  | 20110529-30  | βδ    | C4    |
| 11236| 667  | 20110616-17  | βδ    | C7    |
| 11260| 746  | 20110729     | βγδ   | M1    |
| 11261| 750  | 20110731-0805| βγδ   | M9    |

### Table 7
Delta Sunspots of 2012

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 11429| 1449 | 20120305-12  | βγδ   | X5    |
| 11440| 1484 | 20120322     | βγδ   | C2    |
| 11465| 1596 | 20120425-28  | βγδ   | C2    |
| 11476| 1638 | 20120509-14  | βγδ   | M5    |
| 11504| 1750 | 20120614-15  | βγδ   | M1    |
| 11515| 1807 | 20120704-07  | βγδ   | M5    |
| 11520| 1834 | 20120710-16  | βγδ   | X1    |
| 11560| 1993 | 20120904-06  | βγδ   | C5    |
| 11589| 2109 | 20121014     | βγδ   | C3    |
| 11598| 2137 | 20121024-28  | βδ    | C4    |
| 11613| 2191 | 20121114     | βγδ   | M6    |
| 11618| 2220 | 20121122-28  | βγδ   | M3    |
| 11620| 2227 | 20121128-30  | βγδ   | M1    |

### Table 8
Delta Sunspots of 2013

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 11640| 2337 | 20130104-08  | βγδ   | C1    |
| 11654| 2372 | 20130116-17  | βγδ   | C5    |
| 11678| 2469 | 20130220-22  | βγδ   | C8    |
| 11719| 2635 | 20130412     | βγδ   | M6    |
| 11726| 2673 | 20130422-26  | βγδ   | M1    |
### Table 9 (Continued)

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 12157 | 4530 | 20140906-12 | βγδ   | C9    |
| 12158 | 4536 | 20140907-10 | βγδ   | X1    |
| 12172 | 4580 | 20140922    | βδ    | M2    |
| 12175 | 4591 | 20140927-30 | βγδ   | C5    |
| 12192 | 4698 | 20141020-30 | βγδ   | X3    |
| 12205 | 4781 | 20141106-12 | βγδ   | X1    |
| 12209 | 4817 | 20141116-26 | βγδ   | C8    |
| 12216 | 4851 | 20141122-24 | βγδ   | C2    |
| 12219 | 4868 | 20141130    | βδ    | C6    |
| 12241 | 4941 | 20141218-22 | βγδ   | M6    |
| 12242 | 4920 | 20141216-22 | βγδ   | X1    |

### Table 10

#### Delta Sunspots of 2015

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 12253 | 5011 | 20150103-06 | βγδ   | M1    |
| 12255 | 5022 | 20150112    | βγδ   | C1    |
| 12257 | 5026 | 20150110-14 | βγδ   | C9    |
| 12259 | 5039 | 20150115-16 | βγδ   | C2    |
| 12280 | 5144 | 20150209-11 | βγδ   | C8    |
| 12293 | 5249 | 20150228    | βδ    | C4    |
| 12297 | 5298 | 20150309-19 | βδ    | X2    |
| 12305 | 5354 | 20150325-26 | βγδ   | C8    |
| 12320 | 5415 | 20150408-11 | βδ    | M1    |
| 12321 | 5447 | 20150413-14 | βγδ   | C7    |
| 12371 | 5692 | 20150619-24 | βδ    | M7    |
| 12403 | 5885 | 20150823-30 | βδ    | M5    |
| 12422 | 5983 | 20150927-1003| βδ | M7    |
| 12434 | 6015 | 20151018    | βδ    | C4    |
| 12436 | 6027 | 20151021-22 | βδ    | C7    |
| 12443 | 6063 | 20151031-1110| βδ | M3    |
| 12445 | 6052 | 20151104    | βδ    | C2    |
| 12473 | 6206 | 20151223-29 | βγδ   | M1    |

### Table 11

#### Delta Sunspots of 2016

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 12494 | 6320 | 20160205-08 | βγδ   | C5    |
| 12497 | 6327 | 20160212-18 | βγδ   | M1    |
| 12552 | 6599 | 20160610-11 | βδ    | C6    |
| 12567 | 6670 | 20160716    | βδ    | C2    |
| 12585 | 6731 | 20160909-11 | βδ    | B3    |

### Table 12

#### Delta Sunspots of 2017

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 12645 | 6975 | 20170403-06 | βγδ   | C5    |
| 12644 | 6972 | 20170404    | βγδ   | C3    |
| 12661 | 7034 | 20170606    | βδ    | B5    |
| 12671 | 7107 | 20170817    | βδ    | B6    |
| 12673 | 7115 | 20170905-10 | βδ    | X9    |

### Table 13

#### Delta Sunspots of 2018

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 12715 | 7275 | 20180624    | βδ    | B8    |

### Table 14

#### Delta Sunspots of 2019

| NOAA | HARP | Date         | Class | Flare |
|------|------|--------------|-------|-------|
| 12736 | 7350 | 20190322    | βγδ   | C4    |
| 12740 | 7357 | 20190506-07 | βδ    | M1    |
Figure 12. The $\delta$-regions listed in Tables 5–14 are shown on a butterfly diagram where ARs are plotted as a function of time and sine latitude. $\delta$-regions are shown in yellow and are not colored for polarity or anti-Hale orientation. All non-$\delta$-regions observed during this cycle are also plotted, with the leading spot polarity shown in red (blue) and with total flux indicated by symbol marker size. Anti-Hale regions are obvious as the nondominant color in each hemisphere. The data used to generate this figure are the HMI SHARPS data summarized in the Solar Photospheric Ephemeral and Active Region (SPEAR) catalog (Norton 2021), which is an easy-to-read tabulated text file, SPEAR-CR.txt, available at http://Sun.stanford.edu/~norton/SPEAR/. The catalog currently contains information on nearly 4000 magnetic regions at their nearest central meridian crossing time for Carrington Rotations 2096–2239. For reference, the northern hemispheric sunspot number peaked in late 2011 and the southern hemispheric sunspot number peaked in early 2014, information available from multiple sources and found at http://users.telenet.be/jjanssens/SC24web.

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