Active-region Tilt Angles from White-light Images and Magnetograms: The Role of Magnetic Tongues

Mariano Poisson1, Pascal Démoulin2, Cristina H. Mandrini1,3, and Marcelo C. López Fuentes1

1 Instituto de Astronomía y Física del Espacio, IAFE, CONICET-UBA, CC. 67, Suc. 28, 1428 Buenos Aires, Argentina; mpoisson@iafe.uba.ar, lopezf@iafe.uba.ar
2 LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, F-92195 Meudon, France; Pascal.Demoulin@obspm.fr
3 Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, 1428 Buenos Aires, Argentina

Abstract

The presence of elongations in active-region (AR) polarities, called magnetic tongues, is mostly visible during their emergence phase. AR tilts have been measured thoroughly using long-term white-light (WL) databases, sometimes combined with magnetic-field information. Since the influence of magnetic tongues on WL tilt measurements has not been taken into account before, we aim to investigate their role in tilt-angle values and to compare them with those derived from LOS magnetograms. We apply four methods to compute the tilt angle of generally bipolar ARs: one applies the k-means algorithm to WL data, a second one includes the magnetic-field sign of the polarities to WL data, and a third one uses the magnetic flux-weighted center of each polarity. The tilt values computed in any of these ways are affected by the presence of magnetic tongues. Therefore, we apply the newly developed Core Field Fit Estimator (CoFFE) method to separate the magnetic flux in the tongues from that in the AR core. We compare the four computed tilt-angle values, as well as these with the ones reported in long-term WL databases. For ARs with low-magnetic-flux tongues, the different methods report consistent tilt-angle values. But for ARs with high-flux tongues, there are noticeable discrepancies between all methods, indicating that magnetic tongues differently affect WL and magnetic data. However, in general, CoFFE achieves a better estimation of the main bipole tilt because it removes both the effect of tongues as well as the emergence of secondary bipoles when it occurs in between the main bipole magnetic polarities.

Unified Astronomy Thesaurus concepts: Bipolar sunspot groups (156); Solar active-region magnetic fields (1975); Sunspots (1653); Solar active regions (1974)

Supporting material: animations

1. Introduction

The simplest manifestation of an active region (AR) is in the form of a magnetic bipolar configuration—made of a main positive and a main negative polarity (van Driel-Gesztelyi & Green 2015). Furthermore, ARs with two sunspots or sunspot groups of opposite magnetic polarity, called a β configuration, form the large majority of ARs along the solar cycle (Jaeggli & Norton 2016); therefore, it is worthwhile to study and understand general AR properties using mainly bipolar ARs. Large sets of observational data, theoretical developments (i.e., dynamo models; see, e.g., the reviews of Charbonneau 2014; Brun & Browning 2017, and references therein), as well as magnetohydrodynamic (MHD) simulations (see the reviews by Fan 2009a; Cheung & Isobe 2014; Toriumi 2014, and references therein) support the idea that bipolar ARs are the consequence of the emergence of magnetic flux tubes. These flux tubes, which have been called Ω loops (Zwaan 1987), originate in the toroidal magnetic field created by the dynamo mechanism in the convection zone. Their field is amplified and deformed by differential rotation and convective motions until they become buoyant and emerge in the form of twisted flux tubes or flux ropes (FRs; Fan 2009b; Nelson et al. 2013). However, other MHD simulations explain the formation of ARs due to the local amplification and structuring of the magnetic field in the upper layers of the convective zone (see the review by Brandenburg 2018).

As the toroidal magnetic flux rises through the convection zone, the Coriolis force acts on the FRs so that they emerge slightly inclined relative to the east-west (E-W) direction (see, e.g., D’Silva and Choudhuri 1993; Fan et al. 1994; Caligari et al. 1995; Fisher et al. 1995; Karak & Miesch 2017). This tendency to have the leading polarity of an AR located toward the solar Equator relative to the following polarity was first studied by Hale et al. (1919) and is referred to as Joy’s law (van Driel-Gesztelyi & Green 2015). Observationally, this law implies that the axis joining the centers of the main polarities of an AR forms an angle, called a tilt angle, with respect to the E-W direction.

The existence of tilt angles in ARs plays a central role in flux-transport dynamo models, as Joy’s law is a fundamental ingredient for the formation and evolution of the polar field (see the review by Wang 2017 and references therein). Therefore, obtaining a good estimation of tilt angles, their evolution, and spatial variation on the Sun surface plays a key role in constraining this kind of dynamo models.

Tilt angles have been derived for a long time using databases from white-light (WL) photographic observations taken at Mount Wilson Observatory from 1917 to 1985 and Kodaikanal Solar Observatory from 1906 to 1987 (see, e.g., Howard et al. 1984; Sivaraman et al. 1993). The longest existing catalog of sunspots is the Greenwich Photoheliographic Results (1874–1976; see, e.g., Willis et al. 2013). After 1976, Debrecen Heliophysical Observatory developed another WL catalog. The
Debrecen Photographic Data is compiled using WL full-disk observations taken at Debrecen Observatory and its Gyula Observing Station (Győri et al. 2011; Baranyi et al. 2016). There are also two extensions of this database that include magnetic-field information. The Solar and Heliospheric Observatory (SOHO)/Michelson Doppler Imager (MDI) Debrecen data (SDD) includes magnetic and continuum images taken by the SOHO (Scherrer et al. 1995) with the MDI instrument, while the Solar Dynamics Observatory (SDO) / Helioseismic and Magnetic Imager (HMI) Debrecen Data uses the magnetic and WL images taken by the HMI (Schou et al. 2012) instrument on board the SDO (Pesnell et al. 2012).

The evolution of photospheric magnetograms is the main source of information on the characteristics of subphotospheric FRs. In particular, a noticeable feature is the presence of magnetic tongues (see Poisson et al. 2016 and references therein). They appear as elongations of the main AR polarities and are mainly observed during the emergence of the top part of Ω-shaped flux ropes (FRs). They are produced by the line-of-sight (LOS) projection of the azimuthal component of the FR magnetic field. López Fuentes et al. (2000) were the first to report their existence, and progressively, they were noticed in many other examples (see, e.g., Luoni et al. 2011; Mandrini et al. 2014; Valori et al. 2015; Yardley et al. 2016; Vemareddy and Démoulin 2017; Dicie et al. 2018; López Fuentes et al. 2018). These elongated features are also present in MHD simulations of FR emergence (Archontis & Hood 2010; Cheung et al. 2010; MacTaggart 2011; Jouve et al. 2013; Rempel & Cheung 2014; Takasao et al. 2015). The presence of magnetic tongues naturally modifies the photospheric magnetic distribution of flux concentrations and, therefore, tilt-angle measurements done directly on LOS magnetograms. Furthermore, since sunspots and pores are present in the strongest magnetic fields, magnetic tongues are also expected to modify WL images.

In several articles, we have qualitatively and quantitatively investigated the presence and role of magnetic tongues during the emergence of bipolar ARs. Poisson et al. (2015) presented a systematic method, based on the evolution of the photospheric inversion line (PIL), to quantify the influence of magnetic tongues in emerging FRs. The method allowed us to estimate their average twist, assuming that the emerging magnetic field can be represented as a uniformly twisted half torus (see also Luoni et al. 2011). Poisson et al. (2016) studied how the tongues affect the evolution of the magnetic flux distribution of bipolar ARs, extending the analysis to ARs observed along more than a solar cycle. Since it was found that emerging ARs have a wide set of twist profiles, a more sophisticated FR emergence model was developed that considered FR cross-sections with non-uniform twists (both in the radial and azimuthal directions).

However, though in these articles it was shown that the presence of tongues has a non-negligible effect in the determination of the tilt of ARs, none of them developed a method to remove this effect from the intrinsic characteristics of emerging FRs. A method called Core Field Fit Estimator (CoFFE) has been presented by Poisson et al. (2020). CoFFE succeeds to remove most of the magnetic tongues’ effect on the computation of the location of the flux-weighted centers (magnetic barycenters) of the polarities, and hence it allows us to obtain an AR tilt angle that better represents the FR intrinsic tilt.

In this article, we investigate the role of magnetic tongues on the measurements of tilt angles of sunspot groups derived from WL images. To facilitate the reading of this article in the top block of Table 1, we list the acronyms most used in our text, their meanings, and the databases to which they refer or are applied to, while in its bottom block, we enumerate the different tilt-angle names, the method used to compute them, and the data to which they refer or are applied to. In Section 2, we describe the data we use in our tilt-angle computations. Our methods to compute the tilt values using WL images alone and combining them with magnetic-field data, as well as a summary of the CoFFE method applied to magnetograms, are described in Section 3. Next, Section 4 presents the results of the application of the previous methods to a set of bipolar ARs with different observed photospheric magnetic flux distributions (i.e., from cases in which tongues are not evident to those with clearly elongated tongues and even some examples with more than one bipole present). We compare the results obtained with these different methods and also with those found in the SDD catalog. Finally, in Section 5, we summarize our findings and conclude.

### 1. Data Used

We use continuum intensity images and LOS magnetograms obtained with MDI. The full-disk WL images are constructed with the combination of five filtergrams with wavelengths around the Ni I absorption line. These images have a noise per pixel of 0.3%. The LOS magnetograms are constructed onboard SOHO by measuring the Zeeman effect in right and

### Table 1

| Acronym | Meaning | Refer/Applied to |
|---------|---------|------------------|
| SDD     | SOHO/MDI-Debrecen Data | MDI WL data processed with Debrecen software plus polarity sign |
| TM      | threshold method | MDI WL data |
| k-means | grouping algorithm | MDI WL data to spatially cluster umbrae |
| MB      | magnetic barycenters | MDI LOS magnetograms |
| CoFFE   | Core Field Fit Estimator | MDI LOS magnetograms |
| \(\phi_{WL}\) | | Computed with |
| \(\phi_{U}^M\) | TM + k-means grouping | MDI WL data |
| \(\phi_{U}^W\) | TM + polarity sign grouping | MDI WL data |
| \(\phi_{M}^A\) | magnetic barycenters (apparent tilt) | MDI LOS magnetograms |
| \(\phi_{M}^C\) | CoFFE | MDI LOS magnetograms |
left circularly polarized light. The magnetograms from the 96 minute series, obtained from 5 minute averaged magnetograms, have lower noise levels than the 1 hr series (that includes magnetic and WL data) and an error per pixel of ~9 G (Liu et al. 2004). Both magnetograms and intensity images have a spatial resolution of 1°98 and are digitized with the same CCD with a size of 1024 × 1024 pixels. We use all the available WL images from the 1 hr and 1 minute data sets closer in time to the magnetograms from the 96 minute cadence data set.

As we aim to characterize the tilt-angle evolution in emerging ARs, we selected eight ARs for which we see a clear emergence across their transit through the solar disk. For all the cases, we limit the latitudinal and longitudinal range of the selected ARs within −35° to 35° from the disk center to reduce the foreshortening and limb darkening effects (Green et al. 2003).

We process the WL images and the magnetograms to construct two sets of data cubes for each analyzed AR. Using standard solar software tools, we transform the LOS component of the magnetic field to the solar radial direction. As we study ARs located near the solar disk center, the latter approximation produces no significant effect on the resulting magnetic flux density (Green et al. 2003). Next, we rotate the set of magnetograms and WL images to the time when the AR was located at the central meridian. This procedure corrects the solar differential rotation using the coefficients derived by Howard et al. (1990). Next, we select a subregion that encompasses the AR. Any image presenting evidence of wrong pixels and/or corrupted data is removed from the set.

In order to detect the umbra regions, we apply a few processing tools from the OpenCV Python 3 package to the WL images. First, we rescale the continuum intensity levels of all the WL images corresponding to the evolution of an AR using the global maximum and minimum of the set. Then, we convert the pixel intensities to an unsigned 8 bit integer number; this fixes the number of the intensity levels of the image to 255. This conversion is in line with previous studies, including the method used with SDD (Győri 1998). Pattern recognition algorithms, including the one used here to detect the umbra, also include this conversion to improve the algorithm performance. We increase the image contrast by 10% and reduce the brightness by 50% to desaturate the intensity observed in the photosphere. Finally, we apply a 2D filter to emphasize the differences in adjacent pixel values. This filter performs a linear convolution of the image with a 3 × 3 matrix, or kernel, chosen to increase the image sharpness and thus facilitate the detection of the edges.

We compare our tilt-angle values deduced from WL umbra detection with those reported in SDD. SDD has free access to ftp data requests and an online catalog with sunspot-group information (Győri et al. 2011). The sunspot groups in this catalog are labeled with the same number as the one assigned by the National Oceanic and Atmospheric Administration (NOAA) to ARs. The catalog combines the image processing algorithms, sunspot detection, and area measurements developed earlier for the Debrecen Photoheliographic Data catalog (Győri 1998; Győri et al. 2011; Baranyi et al. 2016). These techniques are also applied to MDI magnetograms (see Section 1); thus SDD also includes the information on the magnetic polarity signs.

### 3. Tilt-angle Estimation Methods

#### 3.1. Tilt Angle from WL Images

Methods to compute the tilt angle from continuum images start with the identification of the umbra areas within a sunspot group. These methods can be separated into two groups. The first group corresponds to the threshold methods (TMs), which are based on the selection of a cutoff value for the image intensity levels (Chapman & Groisman 1984; Steinegger et al. 1996). The second group is comprised of border methods, which use a gradient map to identify the abrupt changes of the image intensity between the umbra-penumbra interface. The method described by Győri (1998) is an example of the latter group and is the one used on SDD to automatically register the information of umbra areas of sunspot groups.

Tilt angles can be determined from WL images using only the sunspot umbrae or including their penumbrae. The penumbra is, in general, easier to detect than the umbra at earlier stages of an AR emergence. However, its detection can be affected by the presence of dark penumbral filaments, granular local minima, and/or background magnetic-field remnants, which can produce dark features around pores. Then, tilt angles obtained from area-weighted penumbra centers are frequently strongly affected by these extra features. To avoid determining erroneous tilts, we only consider the values obtained using umbra areas from images processed as summarized in Section 2. In this way, tilt values are less noisy, though we have more data gaps at the beginning of the emergence.

Many of the past sunspot records have no magnetic polarity information (see, e.g., Howard 1991); therefore, it is necessary to use a proximity-based algorithm first to isolate a sunspot group, and then to identify the leading and the following spots or polarities of an assumed bipolar AR. To do so, an area-weighted umbra center of the group is computed, and then the leading (following) portion of the group is assigned to the spots located to the solar west (east) of this center.

We use a similar procedure based on the k-means clustering algorithm (MacQueen 1967) to explore the consistency between the different grouping procedures. This iterative procedure requires the input of the number of groups, k. In our case k = 2, one corresponding to the leading polarity and one to the following one. Then, each of the separated umbrae are associated with one of these groups. The routine computes the distance between the center of each umbra to assigned group centers. Initially, the group centers are located at random positions within the image; then, the procedure defines new group centers and/or new associations until the global mean distance of each umbra to each group center reaches a minimum. In other words, the routine seeks to minimize the functional defined as the distance between the umbra centers and the group centers. Once an optimal grouping is achieved, we define the group located to the solar west as the leading polarity and the one at the solar east as the following one.

SOHO/MDI magnetograms allow us to use the magnetic-field information to separate the leading and the following umbrae. Using the magnetic-field sign grouping helps us understand the limitations and errors of the methods described above. In particular, it can identify inconsistencies between the different catalogs due to a wrong assignment of umbrae to the leading or following group; this can result in tilt values
and indicate the inclination of the bipole from which the values of magnetic algorithm. The red (respectively. The separation of both sunspot groups is done using the contours show the umbra areas of the leading and following sunspots, and after the images shown in the static by the LOS magnetograms. The animation covers approximately 2 days before year-month-day followed by the time in UT. An animation of the AR 9906 LOS magnetograms, dates in the bottom right corner are indicated in the format CoFFE iterative procedure. From now on, in panels showing WL images and (b) the red- and blue-shaded areas represent the positive and the negative LOS magnetic-field component. The black circular contours are drawn at the half-maximum height of the CoFFE Gaussian. Its mark the region in which the magnetic flux of both magnetic polarities is removed in the CoFFE iterative procedure. From now on, in panels showing WL images and LOS magnetograms, dates in the bottom right corner are indicated in the format year-month-day followed by the time in UT. An animation of the AR 9906 evolution is available online. It shows, sequentially, the WL images followed by the LOS magnetograms. The animation covers approximately 2 days before and after the images shown in the static figure at ~22:24 UT on 2002 April 14. (An animation of this figure is available.)

From this point forward, the data of all ARs are plotted with the same drawing convention (see the caption of Figure 1). For each AR, the same subregion is shown for WL images and magnetograms (figure panels and associated animation(s)). The spatial coordinates are relative to the bottom left corner, with the X coordinate growing toward the solar west and Y toward the solar north. When the leading polarity is closer to the equator than the following one, as is the case for most ARs (Joy’s law), we define the tilt angle as positive.

3.2. Tilt Angles from Magnetic Barycenters and Tongues

LOS magnetograms allow us to study the evolution of AR tilt angles. The tilt angle is generally derived from LOS magnetograms using the magnetic barycenters (see López Fuentes et al. 2000). Then, as with the WL area-weighted centers, we define the apparent tilt angle, \( \phi_b^M \), as the acute angle formed between the E-W direction and the segment that joins the barycenters. We call the tilt values derived in this way the magnetic barycenters (MB) method. However, the value of \( \phi_b^M \) is not an exact estimation of the intrinsic tilt angle of the FR that forms the AR (Poisson et al. 2020). As summarized in Section 1, the intrinsic FR tilt angle is modified by the magnetic tongues present during the AR emergence. Indeed, the departure of \( \phi_b^M \) from the intrinsic tilt can be significantly larger than the mean dispersion reported in most of Joy’s law studies (e.g., Wang et al. 2015).

To illustrate the morphology of magnetic tongues and help us understand their influence on tilt-angle measurements, we select AR 9906 that has well-developed magnetic tongues (Figure 1). Magnetic tongues are observed in LOS magnetograms, such as the one shown in Figure 1(b), where the red- and blue-shaded areas indicate the positive and negative magnetic polarities, respectively, and where magnetic isocontours of \( \pm 50 \) G are added with the same color convention. Magnetic tongues are extensions of the leading and following magnetic polarities toward the center of the AR. In this example, the positive polarity (red) extends northward in the direction of the negative polarity (blue), while the negative one has a similar southward extension toward the positive. This pair of elongations are recurrently observed in emerging ARs and are interpreted as due to the emergence of a twisted FR (Poisson et al. 2020, and references therein). Their presence naturally modifies the location of the magnetic barycenters.

3.3. Tilt Angles from the CoFFE

The CoFFE method is based on the identification of two different magnetic flux components that produce the LOS magnetic-field distribution observed in emerging ARs (Poisson et al. 2020). These components are noted as core and tongue fluxes. We associate the core flux to the flux of the axial field of a toroidal FR during its emergence (Poisson et al. 2020). The tongue flux is the magnetic flux in the elongations of the magnetic polarities, due to the FR azimuthal field component, as previously described. The core flux is modeled using a 2D Gaussian. Its fit to the corresponding field distribution in the magnetogram provides the core center of each polarity. Then, the tilt angle, \( \phi_c^M \), is computed using the core centers, as done when using the magnetic barycenters.

More precisely, the CoFFE method simultaneously performs a fit of the field distribution of each polarity with a Gaussian to isolate the core field and removes the tongue component of the computed from sunspots having the same polarity sign (Baranyi 2015).

The umbra areas and their polarity sign information let us derive different estimations of the tilt angle. The tilt angle is obtained as the acute angle formed between the east-west direction and the line that joins the umbra area-weighted centers of the leading and following polarities. We determine two different tilt angles from the umbra areas, depending on the grouping algorithm. We define the tilt angle \( \phi_c^{NL} \) derived from the proximity algorithm (k-means grouping) and \( \phi_c^{WLM} \) as the tilt derived considering the magnetic-field sign of the umbrae. An example is shown in Figure 1(a), with the umbra detection done on an MDI WL image corresponding to AR 9906 observed on 2002 April 14.

(Figure 1. SOHO/MDI observations for the southern hemisphere (SH) AR 9906: (a) WL image; (b) LOS magnetogram. In (a), the green and magenta contours show the umbra areas of the leading and following sunspots, respectively. The separation of both sunspot groups is done using the k-means algorithm. The red (blue) contour corresponds to the positive (negative) magnetic field with a strength of 50 (−50) G. The blue and green segments indicate the inclination of the bipole from which the values of \( \phi_b^{NL} \) and \( \phi_b^{WLM} \) are obtained, respectively (as defined in Section 3.1). The black segment in both panels corresponds to the bipole inclination computed using the magnetic barycenters, \( \phi_b^M \) (see Section 3.2).)
field distribution. To do so, an iterative procedure is designed. An initial fit to each polarity flux provides a rough estimation of the core centers. Then, an exclusion region is defined. This region is delimited with two lines perpendicular to the line joining the core centers and crossing each of them (see the yellow lines in Figure 1(b)). This region is typically located where the tongue contribution is dominant over the core. So in the first iteration, a new fit of the core is completed, removing the points in the exclusion region from the fitting procedure. Finally, iterations are performed until a convergence criteria over \( \phi_c^M \) is fulfilled. In order to improve the performance of the method, a smaller or larger exclusion region can be defined (Poisson et al. 2020). For our aim, in this work, it is enough to use the just-described basic CoFFE method for the studied ARs.

To ensure a good approximation of the core region, we start our computation with the magnetogram that is closer to the AR maximum flux. At this time, we expect that the core flux will be stronger than that of the tongues, and thus easier to identify and constrain. Once the iteration procedure is completed for this magnetogram, we use the obtained Gaussian parameters as an initial estimate for the fit in the previous magnetogram toward the beginning of the emergence. In this way, a progressive procedure is used wherein the core parameters computed at time step \( i + 1 \) are utilized to initiate the computation at time step \( i \).

An example of the application of CoFFE to a LOS magnetogram of AR 9906 is shown in Figure 1(b). The black circles correspond to the isocontours of the Gaussian function fitted to the core flux of each polarity. The level of these contours is set to 50% of their respective Gaussian maximum value. The red segment connecting the center of the positive and negative core regions corresponds to the inclination of the bipole computed with CoFFE, from which we derive the tilt \( \phi_c^M \). The black segment corresponds to the tilt \( \phi_c^M \) computed from the magnetic barycenters or apparent tilt. This segment shows the shift of the magnetic barycenters toward the center of the AR due to the presence of strong magnetic tongues.

A series of tests on FR models and ARs have shown that CoFFE provides a better estimation of the tilt angle since it efficiently removes the effect of the magnetic tongues (Poisson et al. 2020). The correction achieved with \( \phi_c^M \) requires just a little more computational effort than the previously described methods. Finally, the removal of the effect of the tongues allows us to expand the determination of AR tilts to the early stages of their emergences, since magnetic tongues are typically stronger at the beginning of the emergence (dominance of the azimuthal field component at the top of FR; Poisson et al. 2016).

4. Comparing the Tilt Angle Estimation Methods

To illustrate the effect of magnetic tongues on the estimation of tilt angles computed using LOS magnetograms, both \( \phi_s^M \) and \( \phi_c^M \), and WL observations, both \(\phi_U^WL \) and \( \phi_U^WLM \), we select a series of ARs. In Section 4.1, we start by analyzing the emergence of bipolar ARs in which tongues are small and weak (Section 4.1.1) and continue with ARs that have extended and strong tongues all along their emergence phase (Section 4.1.2). Next, in Section 4.1.3, we summarize the main characteristics and results obtained for bipolar ARs. Finally, we deal with two ARs in which the evolution of the main bipole is accompanied by the emergence of secondary bipoles (Section 4.2). This variety of examples lets us explore the performance of the methods described in Section 3 for the computation of AR tilts, as well as their validity and consistency.

4.1. Bipolar ARs

4.1.1. ARs with Small and Weak Tongues

In this section, we show two examples of ARs with small and weak (low magnetic-field intensity) tongues, AR 11027 and AR 10879. Both ARs emerge in the northern hemisphere in a low background field region. In these cases, tongues are visible only in the first days of the emergence, and sometimes they are clear in only one of the two main polarities.

Panels (a) and (b) in Figures 2 and 3 show snapshots of the evolution of AR 11027 and AR 10879, respectively, as seen in WL images (panels a) and MDI LOS magnetograms (panels b). The green segments in panels (a) join the location of the leading and the following umbra centers computed using the magnetic-field polarity information for clustering. In both figures, the blue segments that join the umbra centers, computed using the TM and \( k \)-means grouping, completely agree with the green segments (which mask them). The black segments in panels (a) and (b) of Figures 2 and 3 join the magnetic barycenters, while the red segments in panels (b) connect the polarities core centers computed using CoFFE. The evolution of these segments as the ARs emerge can be followed in the WL and MDI LOS magnetogram animations found in Figures 2 and 3 of the online version.

Panels (c) in Figures 2 and 3 illustrate the evolution of the four tilt-angle measurements described in Section 3 and Table 1. For values derived using LOS magnetograms, the coincidence between \( \phi_s^M \) and \( \phi_c^M \) is evident in the associated animations (i.e., both black and red continuous lines globally follow the same behavior). Furthermore, the tilt values are generally positive, which agrees with Joy’s law. There are only a few negative values of \( \phi_c^M \) in the early emergence of AR 10879 (Figure 3(c)) that are due to the disperse core flux. (Its center cannot be clearly determined when fitting the Gaussian function.) \( \phi_s^M \) is more stable for this early emergence phase (\( \phi_s^M \approx 0 \)). Finally, AR 10879 is an example where an intrinsic clockwise rotation of the bipole is well identified.

Concerning WL tilt-angle measurements for AR 11027, they closely agree (see the blue squares and green dots in Figure 2(c)). Generally speaking, the four tilt values remain close during the entirety of the emergence phase. The same is true for AR 10879, except for several WL tilt values (blue squares), as we explain in the next paragraph.

Figure 3(c) shows several values of \( \phi_U^WL \) that are not accompanied by the corresponding ones of \( \phi_U^WLM \). For these cases, all umbra centers belong to the same polarity, producing fake bipolar identifications from unipolar configurations. The disperse flux of the following polarity forms weak umbrae that are not detected during a few time intervals of the AR evolution, while umbrae are always present in the leading polarity. This implies that WL tilt determinations should be limited to those ARs in which the magnetic flux density is large enough to form umbrae in both polarities. This introduces a strong bias in a large number of tilt-angle measurements that only use WL data (Baranyi 2015).
4.1.2. ARs with Extended and Strong Tongues

We select AR 9906 and AR 9574 to illustrate the influence of extended and strong (high magnetic-field intensity) tongues on tilt-angle measurements. Both ARs emerge in the southern solar hemisphere and have tongues all along their emergence, even when reaching their maximum magnetic flux. In both cases, the most extended and strongest tongue is the one with the leading polarity.

Figures 1(a), (b) and Figures 4(a), (b) show snapshots of the evolution of AR 9906 and AR 9574, respectively, as seen in MDI WL (panels (a)) and LOS magnetograms (panels (b)). Notice that in both cases, tongues are so strong that umbrae are present in WL images at these elongated regions. The blue, green, black, and red segments in Figures 4(a), (b) are equivalent to those defined in Figures 1(a), (b) (see also Section 4.1.1). The evolution of these segments as the ARs emerge can be followed in the WL and MDI LOS
magnetogram animations found in Figures 1 and 4 of the online version. The black and red continuous lines in Figures 5(a), (b), (c) and (d) show the evolution of the apparent tilt angle, \( \phi_a^M \) (black curve), and that derived using the core flux centers, \( \phi_c^M \) (red curve), for AR 9906 (shown in Figure 1). Conversely, to what is observed in the case of ARs with small and weak tongues, these values do not agree. On one hand, \( \phi_c^M \) always remains negative, contrary to what is expected from Joy’s law, and on the other hand, a counterclockwise rotation of around 10° is present all along the AR emergence. These two behaviors are induced by the presence of the extended and strong tongues, and as shown by the evolution of the red curve, they disappear when \( \phi_c^M \) is computed using the CoFFE method. The values of \( \phi_c^M \) stay close to 0°, and their variations do not indicate any clear bipolar rotation along the AR emergence.

In the case of AR 9574, the value of \( \phi_a^M \) (black curve) is positive during a short time at the beginning of the emergence in agreement with Joy’s law (Figures 4(c), (d)). It then turns to be negative changing by about 14°, implying a clockwise rotation of the bipolar forming the AR. This rotation changes to be counterclockwise by \( \approx 10° \) after the first emergence day, returning to 0° by the end of the emergence period. This behavior would imply that the AR is formed by an FR having first an FR axis with a negative writhe and later a positive one (see, e.g., López Fuentes et al. 2003, for the link between tilt rotation and writhe). However, the values of \( \phi_c^M \) stay always positive in agreement with Joy’s law, and the evolution of \( \phi_c^M \) implies a consistent clockwise rotation by around 15°. We conclude that magnetic tongues affect the determination of the tilt angle derived from LOS magnetograms, changing both its value and the rotation direction of AR 9574.

The examples with extended and strong tongues give us the chance to explore the influence of the grouping algorithms in the case of using only WL observations. Indeed, as shown in Figure 1(a) and Figure 4(a), umbrae are present at tongue locations, affecting algorithms based on either proximity (k-means) or magnetic-field grouping work.

The blue squares in Figure 5(a) depict the results derived from the proximity algorithm used by SDD to group umbrae, while the same symbols illustrate the results for the TM and k-means grouping in Figure 5(b). The grouping done using k-means assigns large umbra areas located on each of the magnetic tongues to the opposite magnetic polarity group; see the southern (northern) umbrae with magenta (green) contours at the center of Figure 1(a). The grouping algorithm used by SDD also presents a similar association. For both grouping algorithms, the tilt results (blue squares) are closer to those found with CoFFE, compared with the red continuous line in

![Figure 4](image-url)
values estimated with CoFFE (red continuous curve in Figures 4(c), (d)).

4.1.3. Summary of Bipolar ARs Characteristics

ARs with small and weak tongues are the easiest to analyze, since similar tilt values are expected to be obtained using the four described methods: those derived from LOS magnetograms ($\phi^M_U$ and $\phi^M_c$) and those from WL images ($\phi^{WLM}_U$ and $\phi^{WLM}_c$). This is illustrated by the global agreement shown in Figures 2(c) and 3(c) of the four tilt-angle values.

However, even for those simple ARs, tilt measurements using WL data could be incorrect because one of the AR polarities could have no umbra. This results in WL tilt measurements done only on one magnetic polarity, which has no meaning. This happens mostly at the beginning of the AR emergence, while it could be also present later on. This problem should be solved when measuring the tilt using LOS magnetograms.

Conversely, tilt measurements could be strongly modified (up to $\approx 20^\circ$) by magnetic tongues if they are extended and strong. The examples in Section 4.1.2 show that magnetic tongues can have umbrae in WL. This implies that tongues can affect tilt-angle estimations derived from WL data. Tongues also affect the tilt measurements derived from the computation of the magnetic barycenters. This leads to false tilts that can even be in disagreement with Joy’s law. Furthermore, these wrong determinations can also lead us to infer a spurious rotation of the AR bipole, which can even change direction during the AR emergence. In contrast, the CoFFE method successfully removes the influence of magnetic tongues in the measurements of tilt angles derived from LOS magnetograms. However, one should bear in mind that for the CoFFE method to be applicable and useful, one needs to have the emergence evolution as complete as possible in order to efficiently identify the FR core at some point and proceed backward in time with the analysis.

We have illustrated the results just discussed using four ARs with well-defined tongue characteristics (see Sections 4.1.1 and 4.1.2). Still, AR emergences have a broad range of tongue morphologies and evolutions, as shown by Poisson et al. (2016) in their study of mainly bipolar ARs covering a full solar cycle. To get a glance of this variety, we present in the Appendix the results using two additional ARs. Our analysis shows that the previous results are quite general, except that the fake or biased deduced tilts could evolve in different ways according to the tongue evolution during the AR emergence. However, CoFFE, in general, gives more stable tilt values and, in particular, eliminates the spurious bipole rotations inferred when using WL data or the barycenter method applied to magnetograms.

4.2. Multipolar ARs

In most works (e.g., Tlatov et al. 2010; Li & Ulrich 2012; Stenflo & Kosovichev 2012; Illarionov et al. 2015; Tlatova et al. 2018), tilt angles are measured using either a single LOS magnetogram or WL image per day, thus without studying the evolution of the AR. In these articles, all ARs are included, despite being monopolar, bipolar, or multipolar. In this section, we test the different methods summarized in Section 3 and apply them to multipolar ARs for which defining a tilt angle is very difficult. We present two examples of ARs. In the first

![Figure 5](image_url)

**Figure 5.** Evolution of the tilt angle along the emergence of the southern hemisphere AR 9906. Comparison between the $\phi^M_U$ and $\phi^{WLM}_U$ using the data from the SDD catalog in (a) and the umbra detection using a threshold method in (b). The black and red continuous lines in both panels have the same meaning as those in Figure 2(c). In (a), the blue squares correspond to the tilt values obtained from the SDD proximity grouping method, and in (b), these values are obtained using k-means clustering (Section 3.1). The green dots in both panels show the tilt angles $\phi^{WLM}_U$ computed, including the magnetic-field sign information to both grouping algorithms. An animation of this AR evolution is available in Figure 1 of the online version.
November 2.

The Astrophysical Journal, 11007:

An animation of the AR 11007 evolution is available in the online version. It shows, sequentially, the WL images followed by the LOS magnetograms. The animation covers approximately 2 days before through 1 day after the images shown in the static figure at ~15:59 UT on 2008 November 2.

(An animation of this figure is available.)

Figure 6. SOHO/MDI observations of the northern hemisphere (NH) AR 11007: (a) white-light image and (b) LOS magnetogram. The arrow in panel (a) points to the secondary emerging bipolar. (c) Evolution of the tilt angles along the emergence of AR 11007. The drawing convention is the same as in Figures 1 and 2. An animation of the AR 11007 evolution is available in the online version. It shows, sequentially, the WL images followed by the LOS magnetograms. The animation covers approximately 2 days before through 1 day after the images shown in the static figure at ~15:59 UT on 2008 November 2.

Despite the disperse magnetic flux and small concentrated polarities, AR 11007 has clear magnetic tongues that are visible during the first half of the emergence. Toward its end, when tongues have almost retracted, a delta group emerges between both polarities (see Figures 6(a), (b), and the online animations of the WL images and LOS magnetograms).

The values of $\phi^M_c$ (black continuous curve in Figure 6(c)) are strongly affected by the flux in the tongues, as well as by the presence of the central bipole from its early emergence in the late hours of 2008 November 1 (at around 19:15 UT). The evolution of $\phi^M_c$ shows two successive rotations of the AR—first clockwise and later counterclockwise. The second rotation is just a spurious effect due to the evolution of the central bipole and is not related to either the presence of tongues or the intrinsic rotation of the main bipole. Next, close to the beginning of the emergence, some $\phi^M_c$ measurements (red continuous curve in Figure 6(c), on 2008 October 31 from $\approx$04:45 UT to $\approx$12:45 UT) are affected by the stronger flux in the tongue compared to that in the core of the following polarity. This shifts the position of its Gaussian center and provides lower $\phi^M_c$ values. After this period of time, the CoFFE method provides a more stable tilt because the exclusion region, defined to remove the tongues, also removes the emerging bipole around the AR center. Tilt values derived from CoFFE agree with what is expected from Joy’s law and indicate no clear rotation of the main bipole.

AR 11007 provides the opportunity to illustrate several problems of tilt-angle measurements using WL data. From the first four measurements (see blue squares and green dots in Figure 6(c) and the evolution in the online WL animation), only the first one corresponds to correct groupings using either $k$-means or polarity signs. The other three measurements have a wrong bipole determination, and even a monopolar region is present for the middle one. These types of problems were already encountered in Section 4.1.1 and in the Appendix. After that, none of the two polarities have detectable umbrae (notice the large gap in the WL data) until the field intensity in the leading polarity is enough to produce umbrae, while this is not the case for the disperse polarity that follows. This happens at around November 2 at 03:10 UT. Then, the umbra group center of the preceding negative polarity of the main bipole is falsely associated with the single positive umbra of the new bipole. This happens up to the end of the emergence, resulting in wrong estimations of $\phi^M_c$ and $\phi^M_{WLM}$ (Figure 6(c)).

Six snapshots of the evolution of AR 9748—two WL images and four MDI magnetograms—are shown in Figure 7. The AR is clearly bipolar in its early emergence with elongated and weak tongues. The tongue flux, mainly that of the preceding polarity, is fragmented in the first stages of the emergence. By the second half of December 21, a secondary bipole emerges in between the main one (see panel (d)). At the beginning of the AR emergence, the distribution of the flux in the tongues indicates a positively twisted FR; but by mid-December 22, the flux distribution is rather compatible with a negatively twisted FR. This apparent change in the FR twist is produced by false tongues due to new flux emergence (compare panels (c) and (e) of Figure 7). Next, there is a third bipole emergence seen at around December 22 at $\approx$21:00 UT, when a positive polarity starts distorting the shape of the negative elongated false tongue (see panel (f) and the LOS magnetic-field animation in the online version) and a negative polarity appears later to its east. The flux in the third bipole is lower than in the second one and does not alter the evolution of the total unsigned magnetic flux (positive flux plus absolute value of the negative one divided by 2), shown in panel (h). It is, however, noteworthy that the clear alignment between the direction of tongues (original and false) with that of the core would have made this AR to be considered by any tilt-angle computation algorithm as a single FR, at almost any time of its emergence, if observations at only one time would have been analyzed.

The four tilt estimations for AR 9748 are shown in Figure 7(g). The values of $\phi^M_c$ (black continuous curve) are positive, as expected from Joy’s law, but its variation changes from increasing values to decreasing ones by December 22 at $\approx$17:30 UT, close to the time when the distribution of the tongue flux changes from positive to apparent negative twist.
This change indicates first a counterclockwise rotation and later a clockwise one. As in the other examples, CoFFE shows more stable estimation until the end of December 24, which agree with Joy’s law (red continuous line in Figure 7(g)). The change of position of the preceding polarity core observed during the last day (seen approximately during 2001 December 24 20:00 UT to 2001 December 25 24:00 UT in 9748_CoFFFe.mp4) is due to the increase of the flux of the second emergence, affecting also the value of $\phi_c^M$. In fact, the correction provided...
by CoFFE is affected both by the spatial location and the flux of the secondary bipole relative to the first bipole.

The blue squares and green dots in Figure 7(g) depict the evolution of $\phi_U^{WL}$ and $\phi_U^{WL}$. Some dispersion exists in $\phi_U^{WL}$ and $\phi_U^{WL}$, around the end of December 21 and the beginning of December 22, when the tongue umbrae are present in the first bipole (see the white-light animation in the online version). The morphology of the tongues forces a wrong grouping in the case of $\phi_U^{WL}$; this is somehow corrected when including the polarity sign and $\phi_U^{WL}$ becomes closer to $\phi_M$. After the second bipole emergence, both measurements are closer to the red curve corresponding to $\phi_M$, indicating that the flux in the core produces the largest umbrae.

From the two examples described in this section, in the first one, AR 11007, we observe a clear new emergence in between the polarities of the first emerging bipole. This emergence produces a false rotation of the original bipole when measuring tilt values from LOS magnetograms using the magnetic barycenters, as well as wrong tilt values when using WL data. The second example, AR 9748, illustrates how a secondary barycenters, as well as wrong tilt values when using WL data. The morphology of the tongues forces a wrong grouping in the case of $\phi_U^{WL}$; this is somehow corrected when including the polarity sign and $\phi_U^{WL}$ becomes closer to $\phi_M$. After the second bipole emergence, both measurements are closer to the red curve corresponding to $\phi_M$, indicating that the flux in the core produces the largest umbrae.

The Astrophysical Journal, 894:131 (14pp), 2020 May 10

by CoFFE is affected both by the spatial location and the flux of the secondary bipole relative to the first bipole.

The blue squares and green dots in Figure 7(g) depict the evolution of $\phi_U^{WL}$ and $\phi_U^{WL}$. Some dispersion exists in $\phi_U^{WL}$ and $\phi_U^{WL}$, around the end of December 21 and the beginning of December 22, when the tongue umbrae are present in the first bipole (see the white-light animation in the online version). The morphology of the tongues forces a wrong grouping in the case of $\phi_U^{WL}$; this is somehow corrected when including the polarity sign and $\phi_U^{WL}$ becomes closer to $\phi_M$. After the second bipole emergence, both measurements are closer to the red curve corresponding to $\phi_M$, indicating that the flux in the core produces the largest umbrae.

From the two examples described in this section, in the first one, AR 11007, we observe a clear new emergence in between the polarities of the first emerging bipole. This emergence produces a false rotation of the original bipole when measuring tilt values from LOS magnetograms using the magnetic barycenters, as well as wrong tilt values when using WL data. The second example, AR 9748, illustrates how a secondary barycenters, as well as wrong tilt values when using WL data. The morphology of the tongues forces a wrong grouping in the case of $\phi_U^{WL}$; this is somehow corrected when including the polarity sign and $\phi_U^{WL}$ becomes closer to $\phi_M$. After the second bipole emergence, both measurements are closer to the red curve corresponding to $\phi_M$, indicating that the flux in the core produces the largest umbrae.

The correct determination of the tilt angle of ARs is fundamental to understand the underlying processes that take place during the transit of magnetic FRs through the convection zone. Moreover, flux-transport dynamo models rely on the precise estimation of the latitudinal dependence of the tilt angle, known as Joy’s law, to predict the progression of one solar cycle to the next (see Cameron et al. 2010; Bhowmik & Nandy 2018). Tilt-angle values, and consequently Joy’s law, have shown significant variation and dispersion depending both on the observable and the method used to measure them. In this article, we test four different methods to measure AR tilts. We also explore the implications on the measured tilt of typical characteristics of flux emergence—namely the evolution of magnetic tongues and the emergence of secondary bipoles.

A standard method is to use LOS magnetograms, and to compute the tilt angle, $\phi_M$, from the flux-weighted centers (or magnetic barycenters) of the magnetic polarities (Section 3.2). However, Poisson et al. (2016) have shown that the elongation of the polarities produced by the magnetic tongues can affect significantly the position of magnetic barycenters during the emergence of ARs and, consequently, the value of $\phi_M$. In Section 4.1.2, we have shown that the magnetic tongues can produce spurious rotations of the AR bipole and values of $\phi_M$ that oppose Joy’s law. Therefore, these measurements can contribute to increasing the dispersion found in statistical studies of Joy’s law, in which the stage of the AR evolution is not taken into account.

The earliest and largest databases used to compute tilt-angle values are those based on WL images. Then, these databases have been the ones mostly used in statistical studies of Joy’s law (Howard et al. 1990; Baranyi 2015; Wang et al. 2015). Tilt values obtained from WL data depend, first, on the method to identify umbra areas and, second, on the algorithm used to assign each umbra to the corresponding magnetic polarity (see Section 3.1). We find that the tilt values, $\phi_U^{WL}$, derived using SOHO WL images in SDD (Győri et al. 2011), could differ from those derived by us using the k-means clustering method (e.g., Figures 4 and 5). Furthermore, as recognized before (Baranyi 2015), the WL data include ARs that have all their spots with the same magnetic polarity. Then, in these unipolar regions, all clustering algorithms wrongly define tilt angles. This implies a strong bias on ARs, which are in their early stage of emergence and/or posses low magnetic flux.

The previously presented problems with $\phi_U^{WL}$ can be detected using the information of the magnetic-field sign to properly group the umbrae and obtain values that we call $\phi_U^{WL}$. However, the use of WL data cannot guarantee that the effect of the magnetic tongues is removed, since in some ARs, we found that the flux associated with the tongues can still produce large umbrae (e.g., Figure 1). Therefore, WL tilt values have the same problems as $\phi_U^{WL}$ in ARs with strong magnetic tongues, independently of the grouping algorithm used (e.g., Figures 4 and 5). All these imply that the most common methods used to compute tilts cannot, in general, give precise estimations of tilt angles in young ARs.

In Poisson et al. (2020), we developed a method, called CoFFE, based on the identification of the LOS field distribution and designed to isolate the axial field of the emerging FR (i.e., the core flux). This method allows us to eliminate the effect of magnetic tongues on tilt measurements, as well as the presence of secondary emergences, and then to obtain corrected tilt values, called $\phi_M$ (Section 3.3). We test the consistency of $\phi_M$ in cases where the magnetic tongues are weak (low magnetic flux), and for bipolar ARs, we find no significant differences between the values achieved with the other three methods (Figures 2 and 3 in Section 4.1.1). In cases where the tongues are strong, we find that CoFFE effectively reduces the flux associated with the magnetic tongues from the tilt estimation, removing the spurious rotation of the bipole, as well as the deviation of the tilt, from Joy’s law predictions (Figures 4, 5 and A1).

We compare the performance of CoFFE with the standard methods to estimate the tilt angle for the particular cases of multipolar ARs. Although the tilt angle is only defined for ARs formed by the emergence of a single FR, most of the statistical studies use standard methods without considering the AR characteristics, which may lead to a larger dispersion of tilt-angle values and/or inconsistent results. The CoFFE method can still estimate the tilt angle of the main bipole in regions with multiple emergences, provided that these emergences are located within the main AR bipole—that is, in the band defined between the main bipole polarities that is excluded by CoFFE by method design (to minimize the effects of magnetic tongues). Presently, we cannot generalize the application of CoFFE to all multipolar ARs, since the correction achieved depends on the spatial location and the flux strength of the secondary emergences. Nevertheless, we find that for the analyzed ARs, CoFFE significantly reduces the effect of secondary flux emergences on $\phi_M$ (see Section 4.2). This implies that CoFFE can be used to improve the estimation of the tilt angle in studies using large samples with statistical purposes. In fact, in order to treat more correctly multipolar
CoFFE is the only method giving the most precise tilt-angle values during an AR evolution. This further allows us to study how emerging ARs are rotating and to further study its physical origin (e.g., due to the writhe of the FR axis or to the action of a convective vortex). This will extend previous studies done on the long-term evolution of ARs (e.g., López Fuentes et al. 2003) to the emerging phase, with the potential to reveal more information on the sub-photospheric FRs.

The authors thank the anonymous reviewer for very useful comments and suggestions. M.P., M.L.F., and C.H.M. acknowledge financial support from Argentine grants PICT 2016-0221 (ANPCyT) and UBACyT 20020170100611BA. M. L.F. and C.H.M. are members of the Carrera del Investigador Científico of the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). M.P. is a fellow of CONICET. This work was supported by the Programme National PNST of CNRS/INSU co-funded by CNES and CEA. The authors acknowledge the use of data from the SOHO (ESA/NASA) mission. These data are produced by the MDI international consortia.

A Variety of Tongue Morphologies and Evolutions

Poisson et al. (2016) studied the characteristics of magnetic tongues for 149 bipolar ARs observed along a full solar cycle. Though, in general, tongues have a tendency to be stronger at the start of the emergence and become weaker as the magnetic flux of the AR reaches its maximum, there are many cases in which tongues stay strong and extended, even at the time of maximum flux (see the examples in Section 4.1.2). Furthermore, observed tongues present a large variety of morphologies and evolutions, even appearing at any stage of an AR emergence. This large variety could be only reproduced when using a broad range of twist profiles when comparing the data with the emergence of a twisted FR. This is shown in Figure 10 of Poisson et al. (2016), where observations are compared with the results of FR models with varying radial and azimuthal twist profiles. In this section, we discuss two examples in which tongues evolve differently; they appear, develop, and almost disappear in AR 10268, while they are mostly present and very elongated during the full evolution of AR 8760.

AR 10268, which emerges in the northern hemisphere, has a clear bipolar configuration in which tongues are strong and do not appear to be clearly separated from the core flux (see the LOS magnetic-field animation in the online version). The effect of tongues is evident when comparing the black and red curves in Figure A1(a). The black curve, $\phi^M_a$, shows that AR 10268 evolves as it emerges toward a high tilt value that opposes to Joy’s law ($\phi^M_a < 0$), while by the beginning of 2003 January 23, there is a sudden change in the apparent bipole rotation toward tilt values agreeing with this law ($\phi^M_a > 0$). This variation implies that the bipole would first rotate counterclockwise by around 20° and later clockwise by around 45°. A different tilt evolution is shown by the red curve depicting the values of $\phi^M_a$ computed with CoFFE. In this case, most values agree with what is expected from Joy’s law, and the evolution of the corrected tilt angle indicates a consistent clockwise rotation of $\approx 20^\circ$. Summarizing, in this AR, we observe a typical behavior of the tongues (i.e., they appear in the first stages of the emergence, evolve, and almost disappear by its

ARs, CoFFE will need to be improved to include an algorithm that first identifies, and then separates, different emerging bipoles in a similar way as done by Leka et al. (1996). ARs formed by a series of significant emergences will ultimately have tilt angles associated with each identified bipole.

In summary, the aforementioned standard methods, using either WL data or LOS magnetograms (or a combination of both) to measure tilt angles, strongly depends on the stage of the AR evolution, given the presence of magnetic tongues is the main problem that affects tilt-angle estimations during the emerging phase. That is why CoFFE is designed to correct their effect. However, to correctly apply CoFFE, we need at least one magnetogram along the AR evolution in which the core region can be detected and isolated from the tongues in both polarities. Therefore, each AR has to be treated individually if we want to extend the computation of tilt angles as far as the early stages of the AR emergence. This more involved treatment of the data somehow reduces the applicability of the method in automatic procedures that deal with a large number of cases. Despite this limitation, we still find that

Figure A1. Evolution of the tilt angles along the emergence of (a) AR 10268 and (b) AR 8760, both located in the northern hemisphere. The black and red continuous lines, as well as the blue squares and green dots, have the same meaning as those in Figure 2(c). An animation of the evolution of AR 10268 and AR 8760 is available in the online version. The animation shows, sequentially, the WL images followed by the LOS magnetograms for AR 10268, and then the WL images and LOS magnetograms of AR 8760. The animation spans the full range of time for both AR shown in the static image(s).

(An animation of this figure is available.)
end); this is shown by the coincidence between \( \phi_a^M \) and \( \phi_c^M \) in Figure A1(a) at the end of the emergence phase.

Concerning tilts derived from WL data, Figure A1(a) shows that the blue squares, \( \psi_W^{WL} \), and the green dots, \( \psi_W^{WL} \), are quite scattered and do not clearly follow either the black or red curves. In this AR, tongues are so strong that they have umbrae and affect the WL tilt measurements. Next, we observe four wrong \( \psi_W^{WL} \) values derived from unipolar umbra measurements (as in the case of AR 10879, Figure 3). After the beginning of January 23, both \( \psi_W^{WL} \) and \( \psi_W^{WL} \) roughly follow the evolution of \( \phi_c^M \) until the time when tongues start retracting on January 24. By this time, both WL measurements follow the evolution of \( \phi_c^M \). Finally, at the end of the emergence, all four tilt values agree (see the WL animation in the online version).

AR 8760 emerges in the northern solar hemisphere. This is a mainly bipolar AR that shows a series of minor emergences in between the two main bipole polarities almost all along the period of time shown in Figure A1(b) (see the LOS magnetogram animation in the online version). These minor bipoles can be interpreted as the resistive emergence of an undulatory FR in which the upper part is fragmented by a Parker instability and then reformed by magnetic reconnection at the photospheric layer (Pariat et al. 2004; Cheung et al. 2010). Despite its complex evolution, these minor bipoles do not significantly affect tilt-angle measurements. At the beginning of the emergence, tongues are not clearly visible due to the presence of a secondary bipole. Next, by 1999 November 8 at \( \approx 19:10 \) UT, a clear elongated tongue pattern, corresponding to a negatively twisted FR, is present. After a fast increase, a comparable evolution of \( \phi_a^M \) and \( \phi_c^M \) (clockwise rotation) is present. The largest difference of, around 5° in \( \phi_a^M \) above \( \phi_c^M \), is evident at \( \approx 14:25 \) UT on November 9. By the beginning of November 11, tongues are smaller and weaker, though still present. It is this distribution of the flux that now makes \( \phi_a^M \) and \( \phi_c^M \) both follow the same behavior until the end of the period shown in Figure A1(b). The values of the tilt angles derived from magnetograms agree with what is expected from Joy’s law.

Umbrae are present in the core regions, as well as in the tongues, once they become clearly visible (see the WL animation in the online version; notice also that there are several gaps in these data). The blue squares and green dots, \( \psi_W^{WL} \) and \( \psi_W^{WL} \), follow the increase in tilt-angle values as \( \phi_a^M \) and \( \phi_c^M \) in Figure A1(b). At around the time of the largest difference between \( \phi_a^M \) and \( \phi_c^M \), \( \approx 14:25 \) UT on November 9, umbrae are very dispersive and the \( k \)-means algorithm fails to group them correctly, locating some of them on the wrong polarity region, giving the largest difference between the blue squares and green dots. This failure has, in fact, a positive effect, since it decreases the effect of the tongues, as in AR 9906 (Figure 5), and then \( \psi_W^{WL} \) values are closer to the red continuous curve of \( \phi_c^M \) at that time. After a gap in the WL data, ending at around the beginning of November 10, both WL measurements follow the same behavior with differences between them of less than 5°. The largest differences happen when \( k \)-means clustering groups umbrae located in the wrong polarity sign region. Later on, both WL tilt values \( \psi_W^{WL} \) and \( \psi_W^{WL} \) stay closer to the black continuous line corresponding to \( \phi_a^M \), showing again the effect of magnetic tongues.

This section shows how diverse tongues can be, both in morphology and evolution. In AR 10268, tongues are strong enough at the start of the emergence to affect the apparent tilt evolution as well as measurements using WL data. It is only when they start to retract that a fair agreement of the four tilt-angle values is observed. In the second example, AR 8760, tongues are present all along the emergence with a varying intensity. WL measurements are clearly affected by the dispersion of the umbrae that are present both in the core and tongue regions. Despite some differences between \( \psi_W^{WL} \) and \( \psi_W^{WL} \), mainly caused by a wrong grouping, they generally follow the tilt values given by the magnetic barycenters method.

ORCID iDs
Mariano Poisson @ https://orcid.org/0000-0002-4300-0954
Pascal Démoulin @ https://orcid.org/0000-0001-8215-6532
Cristina H. Mandrini @ https://orcid.org/0000-0001-9311-678X
Marcelo C. López Fuentes @ https://orcid.org/0000-0001-8830-4022

References

Archontis, V., & Hood, A. W. 2010, A&A, 514, A56
Baranyi, T. 2015, MNras, 447, 1857
Baranyi, T., Györi, L., & Ludmány, A. 2016, SoPh, 291, 3081
Bhowmik, P., & Nandy, D. 2018, NatCcs, 9, 5209
Brandenburg, A. 2018, JPP, 84, 73584004
Brun, A. S., & Browning, M. K. 2017, LRSP, 14, 4
Caligari, P., Moreno-Inertis, F., & Schussler, M. 1995, ApJ, 441, 886
Cameron, R. H., Jiang, J., Schmitt, D., & Schüssler, M. 2010, ApJ, 719, 264
Chapman, G. A., & Greissman, G. 1984, SoPh, 91, 45
Charbonneau, P. 2014, A&AA, 52, 251
Cheung, M. C. M., & Isobe, H. 2014, LRSP, 11, 3
Cheung, M. C. M., Rempel, M., Title, A. M., & Schüssler, M. 2010, ApJ, 720, 233
Dacie, S., Török, T., Démoulin, P., et al. 2018, ApJ, 862, 117
D’Silva, S., & Choudhuri, A. R. 1993, A&A, 272, 621
Fan, Y. 2009a, ApJ, 697, 1529
Fan, Y. 2009b, LRSP, 6, 4
Fan, Y., Fisher, G. H., & McClymont, A. N. 1994, ApJ, 436, 907
Fisher, G. H., Fan, Y., & Howard, R. F. 1995, ApJ, 438, 463
Green, L. M., Démoulin, P., Mandrini, C. H., & Van Driel-Gesztelyi, L. 2003, SoPh, 215, 307
Györi, L. 1998, SoPh, 180, 109
Györi, L., Baranyi, T., & Ludmány, A. 2011, in IAU Symp. 273, Physics of Sun and Star Spots, ed. D. P. Choudhary & K. G. Strassmeier (Cambridge: Cambridge Univ. Press), 403
Hale, G. E., Ellerman, F., Nicholson, S. B., & Joy, A. H. 1919, ApJ, 49, 153
Howard, R., Gilman, P. I., & Gilman, P. A. 1984, ApJ, 283, 373
Howard, R. F. 1991, SoPh, 136, 251
Howard, R. F., Harvey, J. W., & Forghach, S. 1990, SoPh, 130, 295
Ilariacionov, E., Tlatov, A., & Sokoloff, D. 2015, SoPh, 290, 351
Jaeggli, S. A., & Norton, A. A. 2016, ApJL, 820, L11
Jouve, L., Brun, A. S., & Aulanier, G. 2013, ApJ, 762, 4
Karab, B. K., & Miesch, M. 2017, ApJ, 847, 69
Leka, K. D., Canfield, R. C., McClymont, A. N., & van Driel-Gesztelyi, L. 1996, ApJL, 462, 547
Li, J., & Ulrich, R. K. 2012, ApJ, 758, 115
Liu, Y., Zhao, X., & Hoekema, T. J. 2004, SoPh, 219, 39
López Fuentes, M., Mandrini, C. H., Poisson, M., et al. 2018, SoPh, 293, 166
López Fuentes, M. C., Démoulin, P., Mandrini, C. H., Pevtsov, A. A., & van Driel-Gesztelyi, L. 2003, A&AA, 397, 305
López Fuentes, M. C., Démoulin, P., Mandrini, C. H., & van Driel-Gesztelyi, L. 2000, Apl, 544, 540
Luoni, M. L., Démoulin, P., Mandrini, C. H., & van Driel-Gesztelyi, L. 2011, SoPh, 270, 45
MacQueen, J. 1967, in Proc. Fifth Berkeley Symp. on Mathematical Statistics and Probability, Volume 1: Statistics (Berkeley, CA: Univ. California Press), 281, https://projecteuclid.org/euclid.bsmsp/1200512992
MacTaggart, D. 2011, A&AA, 531, A108
Mandrini, C. H., Schmieder, B., Démoïlín, P., Guo, Y., & Cristiani, G. D. 2014, SoPh, 289, 2041
Nelson, N. J., Brown, B. P., Brun, A. S., Miesch, M. S., & Toomre, J. 2013, ApJ, 762, 73
Pariat, E., Aulanier, G., Schmieder, B., et al. 2004, ApJ, 614, 1099
Poisson, M., Démoïlín, P., López Fuentes, M., & Mandrini, C. H. 2016, SoPh, 291, 1625
Poisson, M., López Fuentes, M., Mandrini, C. H., & Démoïlín, P. 2015, SoPh, 290, 3279
Poisson, M., López Fuentes, M. C., Mandrini, C. H., Démoïlín, P., & MacCormack, C. 2020, A&A, 633, A151
Rempel, M., & Cheung, M. C. M. 2014, ApJ, 785, 90
Scherrer, P. H., Bogart, R. S., Bush, R. I., et al. 1995, SoPh, 162, 129
Schou, J., Scherrer, P. H., Bush, R. I., et al. 2012, SoPh, 275, 229
Sivaraman, K. R., Gupta, S. S., & Howard, R. F. 1993, SoPh, 146, 27
Steininger, M., Vazquez, M., Bonet, J. A., & Brand t, P. N. 1996, ApJ, 461, 478
Stenflo, J. O., & Kosovichev, A. G. 2012, ApJ, 745, 129
Takasao, S., Fan, Y., Cheung, M. C. M., & Shibata, K. 2015, ApJ, 813, 112
Tlatov, A. G., Vasil’eva, V. V., & Pevtsov, A. A. 2010, ApJ, 717, 357
Tlatova, K., Tlatov, A., Pevtsov, A., et al. 2018, SoPh, 293, 118
Toriumi, S. 2014, PASJ, 66, S6
Valori, G., Romano, P., Malanushenko, A., et al. 2015, SoPh, 290, 491
van Driel-Gesztelyi, L., & Green, L. M. 2015, LRSP, 12, 1
Vemareddy, P., & Démoïlín, P. 2017, A&A, 597, A104
Wang, Y. M. 2017, SSRv, 210, 351
Wang, Y.-M., Colaninno, R. C., Baranyi, T., & Li, J. 2015, ApJ, 798, 50
Willis, D. M., Coffey, H. E., Henwood, R., et al. 2013, SoPh, 288, 117
Yardley, S. L., Green, L. M., Williams, D. R., et al. 2016, ApJ, 827, 151
Zwaan, C. 1987, ARA&A, 25, 83