ELECTRIC CURRENTS IN THE SOLAR ATMOSPHERE

P. Venkatakrishnan

Udaipur Solar Observatory & Indian Institute of Astrophysiics

OUTLINE OF THE TALK

- Introduction
- Observations of Neutralized Currents in Active Regions
- Observations of Bi-directional Currents in AR10930
- Observations of evolving current in AR 11158
- Shear and Twist Currents in AR10930
- Shear and Twist Currents in AR 11158

Introduction

Currents in astrophysical plasmas are produced by deformation of frozen magnetic field by external forces. ($j = \mathrm{curl}B/\mu_0$)

If a magnetic flux tube is confined within a finite boundary,then the net current across any cross-section of the tube must vanish, else there will be a magnetic field outside the flux tube according to Biot-Savart law.

Since we do not observe a systematic organized field outside an isolated sunspot, we expect the net current of the sunspot to be zero.

Observations show conflicting results.

Georgoulis, M.K., LaBonte, B.J., Metcalf, T.R.: 2004, Astrophys. J. 602, 446.;

Georgoulis, M.K., Titov, V.S., Miki´c, Z.: 2012, Astrophys. J. 761, 61;

Leka, K. D., canfield, R. C., McClymont, A. N., & van Driel-Gesztelyi L., 1996, ApJ, 462,

Wheatland, M. S., 2000, ApJ, 532, 616

Since currents imply many things for solar eruptions, this controversy must be settled.

Observations of Neutralized Currents in Active Regions

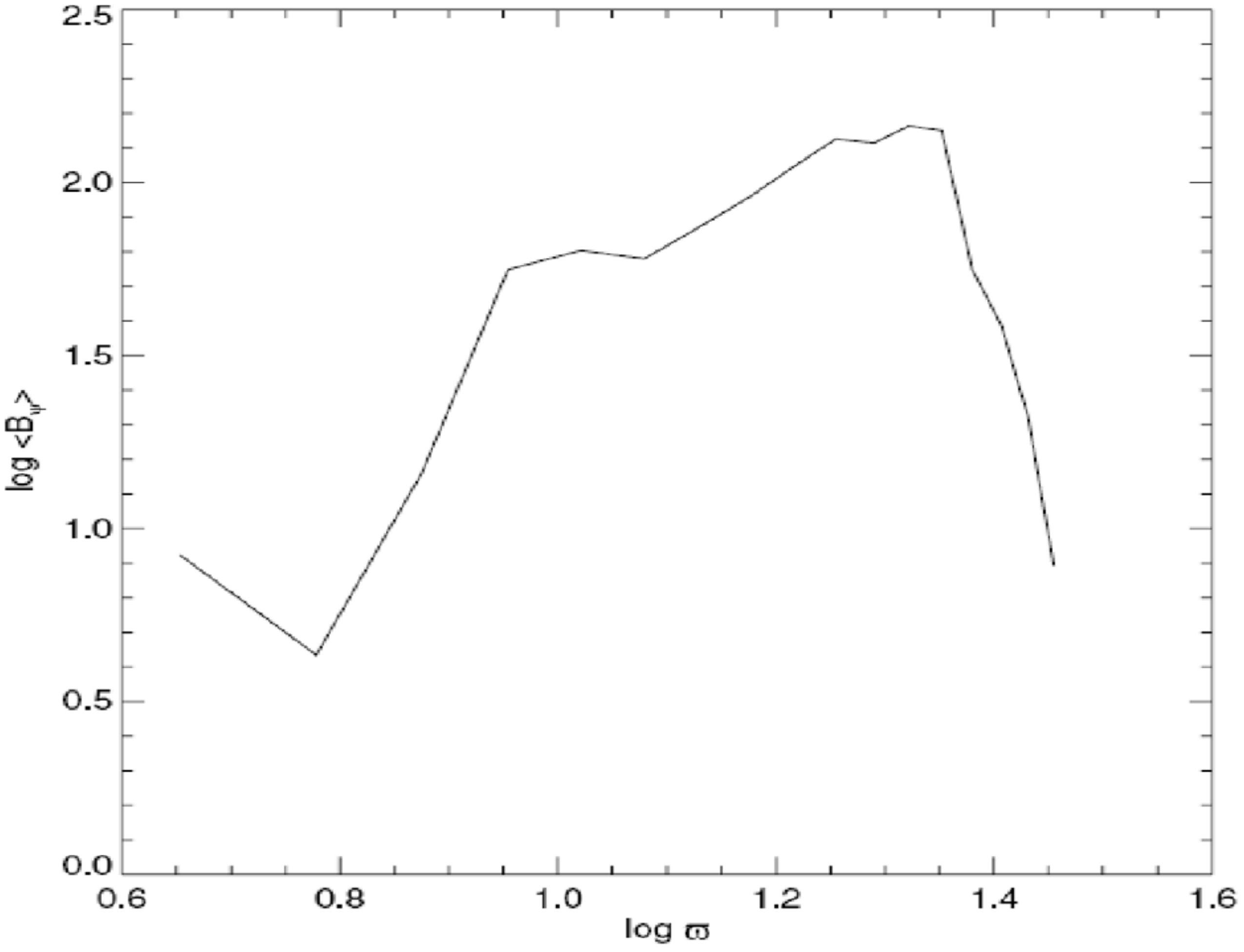
P. Venkatakrishnan and Sanjiv Kumar Tiwari *The Astrophysical Journal*, **706**: L114–L119, 2009 November 20

For a flux tube with cylindrical geometry, the vertical component of the net current obtained by line integral of j along the circumference of the flux tube boundary then becomes:

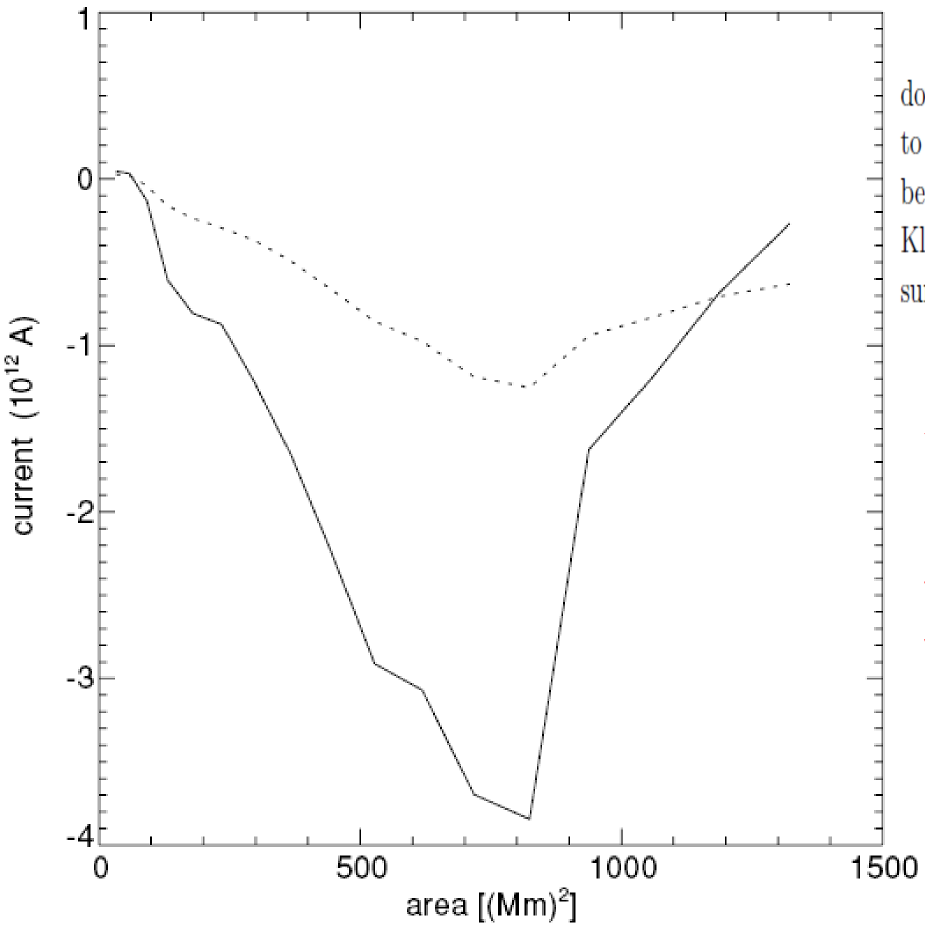
$$I_z(\varpi) = \frac{\varpi}{\mu_0} \int d\psi B_\psi(\varpi, \psi) \longleftarrow 2\pi < B_\psi >$$

We analyzed several ARs as seen in table:

AR No. (NOAA)	Date of Observation	Slope δ	Shear Angle (SSA: deg)	Twist Angle ($tan^{-1}(B_\psi/B_r)$: deg)	Position
10969	29 Aug 2007	7.514	−4.488	−4.009	S05W33(t)
10966	07 Aug 2007	4.349	−5.120	−7.028	S06E20(t)
10963(−)	12 Jul 2007	4.366	−5.123	41.873$^\sharp$	S06E14(t)
10963(+)	12 Jul 2007	4.210	−4.495	−5.112	S06E14(t)
10961	02 Jul 2007	4.976	−4.973	29.451$^\sharp$	S10W16(t)
10960	07 Jun 2007	3.267	3.182	−24.012$^\sharp$	S07W03
10953	29 Apr 2007	8.249	−3.382	7.200$^\sharp$	S10E22(t)
10944	03 Mar 2007	2.407	−4.635	−5.130	S05W30(t)
10940	01 Feb 2007	2.281	−4.726	−7.950	S04W05
10933	05 Jan 2007	9.584	−2.283	−2.689	S04W01
10926	03 Dec 2006	2.750	−1.538	6.001$^\sharp$	S09W32(t)
10923	10 Nov 2006	3.175	0.785	−9.010$^\sharp$	S05W30(t)



2.5
2.0
1.5
1.0
0.5
0.0
0.6
0.8
1.0
1.2
1.4
1.6
log <B_ψ>
log ϖ



Parker (1996) also mentions the possibility of net currents in the corona, continuing down to the height where the first cleaving takes place. It would therefore be imperative to look for net currents at higher reaches of the solar atmosphere. This is very important because several theories of flares (Melrose 1995) and CME triggers (Forbes & Isenberg 1991; Kliem & Török 2006) rely heavily on the existence of net currents in the corona above the sunspots.

At this point in my research, I had assumed that confinement of field, with consequent neutralization of the net current really works, at least in the photosphere, but I was in for a rude shock when we looked at net currents in emerging flux regions, which I will next discuss

Evolution of Currents of Opposite Signs in Active Region NOAA 10930

B. Ravindra, P. Venkatakrishnan, Sanjiv Kumar Tiwari and R. Bhattacharyya The Astrophysical Journal, Volume 740, 19-26, (2011)

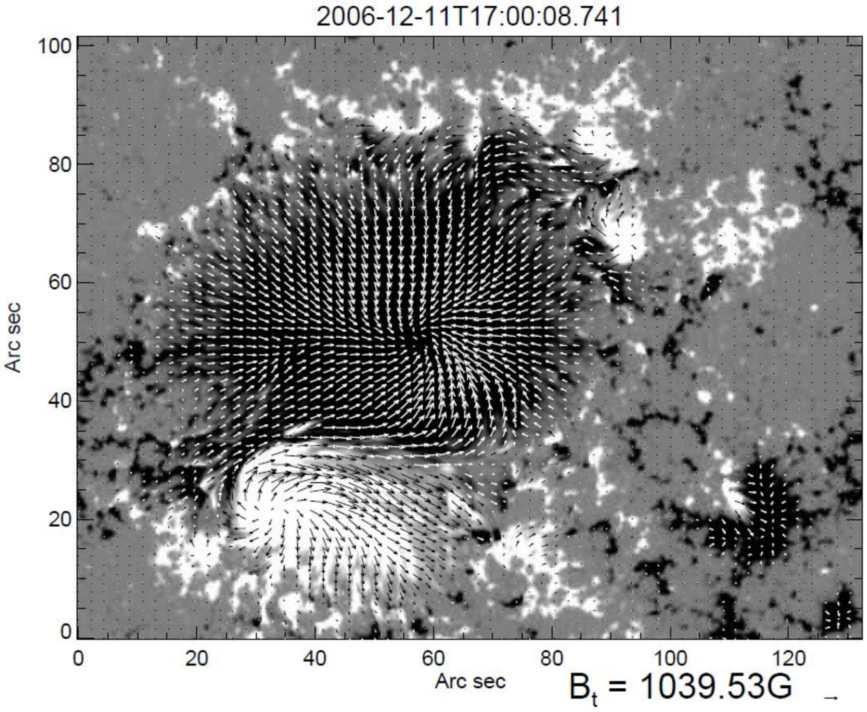
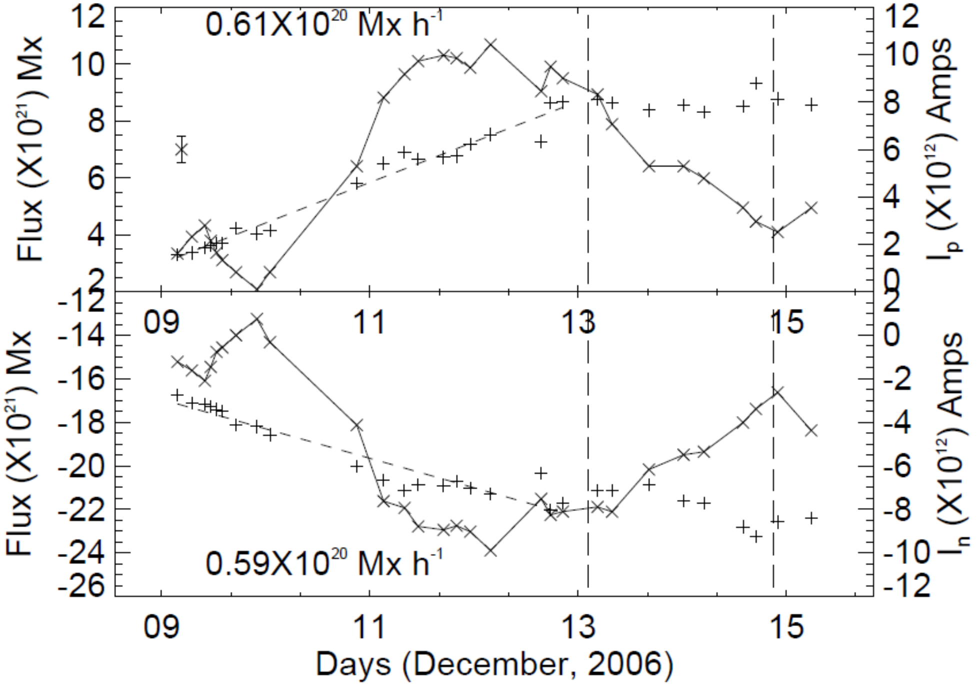


Fig. 1.— A sample vector magnetogram showing the ambiguity resolved transverse field overlaid upon the vertical magnetic field. The black (white) color represents the S (N) polarity regions. Arrows indicate the direction of the transverse magnetic fields.



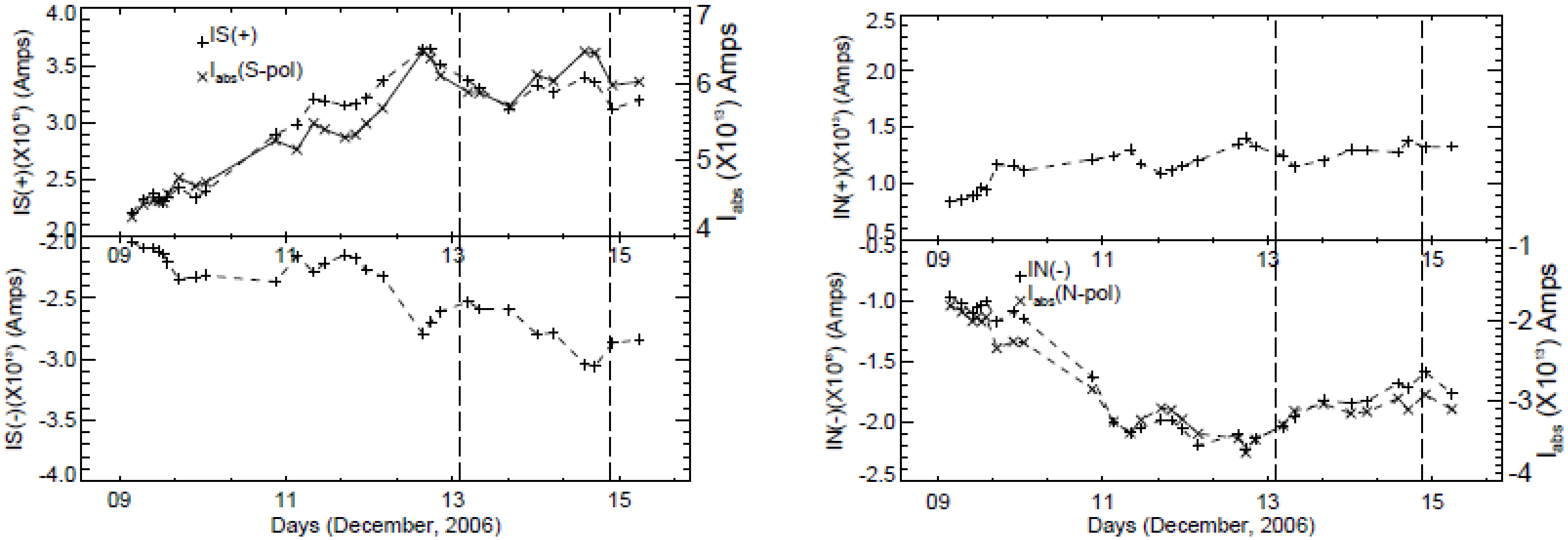


Fig. 5.— Left: The temporal evolution of net vertical currents in S-polarity region (shown by + symbol). Right: Same as left side plot but for N-polarity region. The top and bottom plots show the temporal evolution of positive and negative currents in the same polarity region. The right side scale on the Y-axis is drawn to show the I_{abs} in each of the polarities. The I_{abs} is shown by $\times$ symbol.

- **Both Direct and Return Currents increase asymmetrically along with flux emergence and equalize after complete emergence**
- **Flares occur during episodes of maximum flux emergence**

Flux Emergence in the Solar Active Region NOAA 11158: The Evolution of Net Current

P. Vemareddy, P. Venkatakrishnan, and S. Karthikreddy, Research in Astronomy and Astrophysics, Volume 15, Number 9

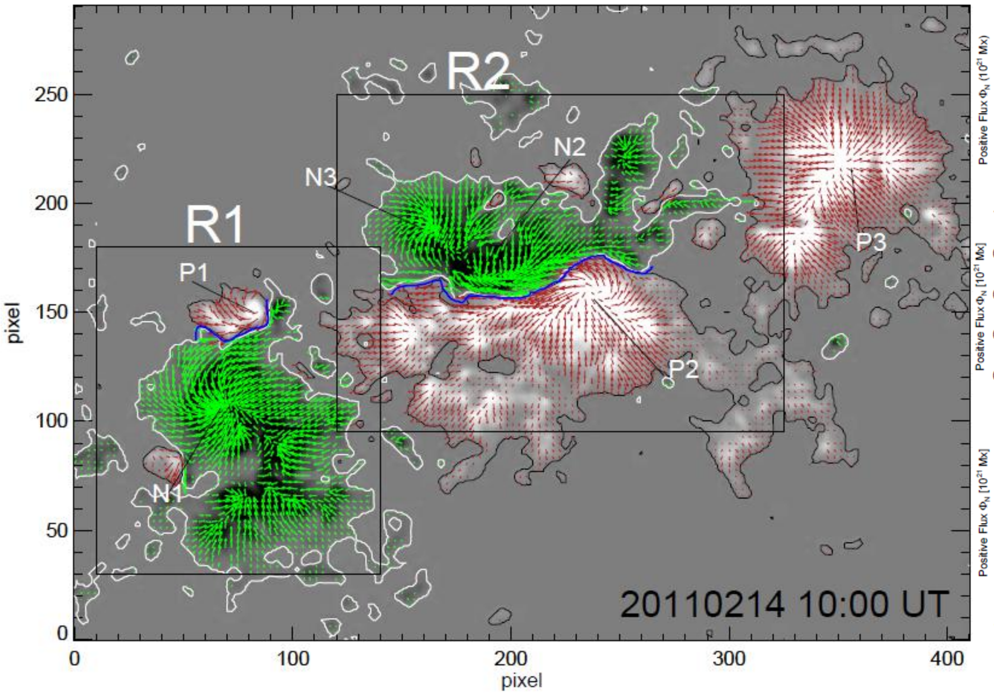


Fig. 1 Typical Vector magnetogram of AR 11158 at 10:00UT on February 14, 2011. The horizontal field vectors in red (green) are over plotted on vertical component of magnetic field map with iso-contours at 150 G (-150 G). The dominant sunspot polarities are marked as P/N* within the rectangular regions of interest R1 and R2 (sub-regions) for further correspondence. The blue solid curves represent the strongly sheared (with shear angle greater than 45°) polarity inversion lines (PILs) separating major positive and negative vertical flux regions. The field of view is 207 × 146 arcsec^2 (1 pixel = 0.5 arcsec).

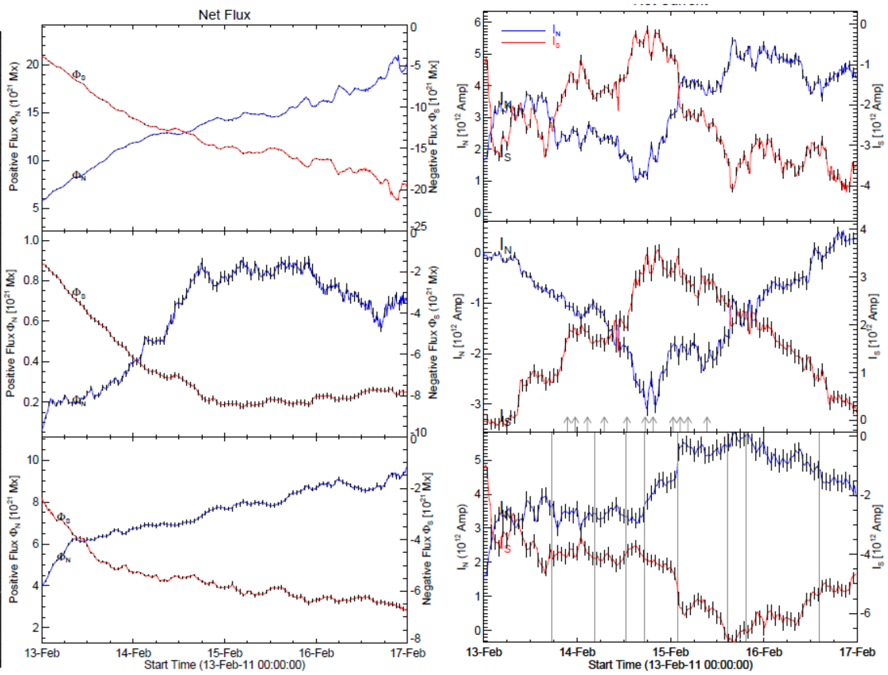


Fig. 4 Evolution of magnetic flux (vertical current) over entire AR 11158, sub-region R1, sub-region R2 in top, middle and bottom panels of first (second) column, respectively (see Figure 1). Vertical lines (Bottom right panel) indicate the initial timings of flares and arrows (middle right panel) are that of CMEs.

In conclusion, we find that Parker's expectation of a neutralized current in an individual sunspot, is valid only for the evolution of a twisted flux bundle with a field free interface between the two spots. The situation changes dramatically, when the flux of one sunspot emerges into an environment with lower confining pressure, close to another sunspot with opposite polarity. The consequent expansion of the twisted flux tube into the domain of a neighboring sunspot will produce a significant length of strongly sheared PIL without any field free plasma in between. It is also possible that this impact of the two legs of a twisted flux tube can drive reconnection and lead to changes in field connectivity. In which case, appearance of net current in the observed field indicates a possible change in the field connectivity in a slow evolution of magnetic fields in the active region. The changes in field connectivity would, in parallel, lead to increased probability for solar eruptions.

Shear and Twist Currents in AR 10930

Yogita Suthar · P. Venkatakrishnan · B. Ravindra ·& S.N.A. Jaaffrey, Solar Phys (2014) 289:2459–2471

$$\boldsymbol{J} = \frac{1}{\mu_0}(\nabla B) \times \boldsymbol{b} + \frac{B}{\mu_0}\nabla \times \boldsymbol{b}$$

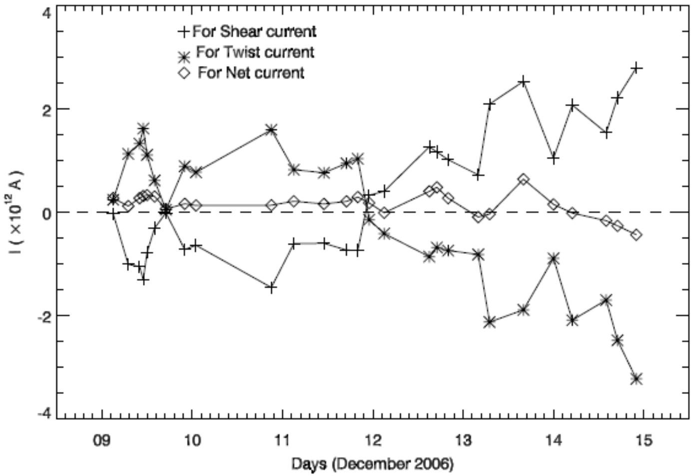


Figure 4 The evolution of net current, NTC, and NSC for the whole AR as a function of time.

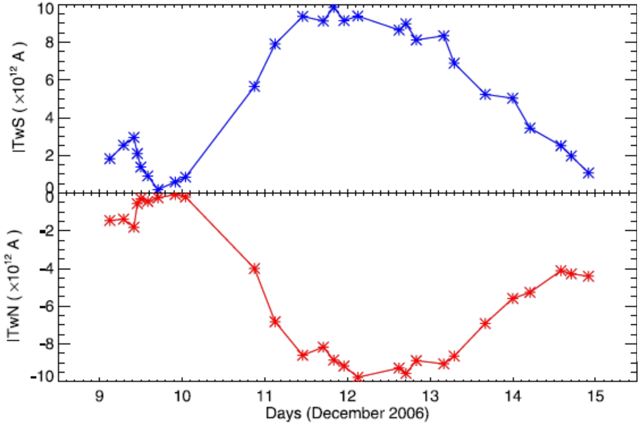


Figure 5 The evolution of NTC in the S-polarity (blue) and N-polarity (red) regions as a function of time.

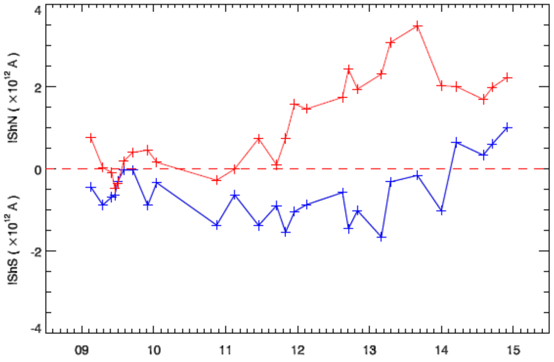
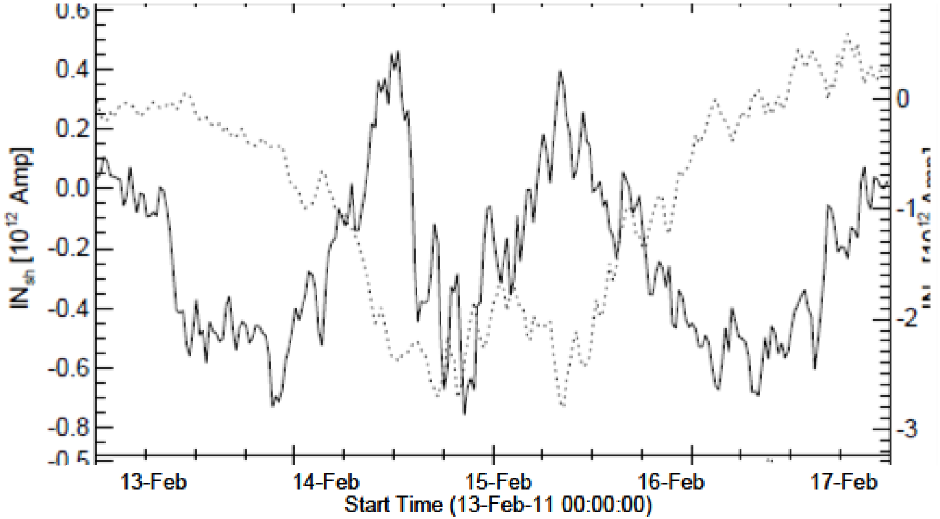
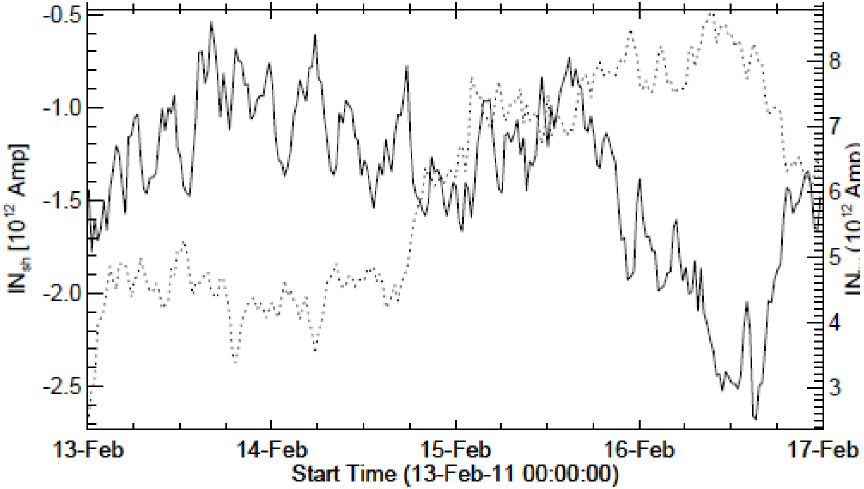


Figure 6 The evolution of NSC in the N-polarity (red) and S-polarity (blue) regions as a function of time.

Shear and Twist Currents in AR 11158

P. Venkatakrishnan , P. Vemareddy & B. Ravindra (in preparation)





Left: Evolution of NTC (dotted) and NSC (filled) for N polarity of R1 Right: Evolution of NTC (dotted) and NSC (filled) for N polarity of R2

Confrontation with Theoretical Simulations

DISTRIBUTION OF ELECTRIC CURRENTS IN SOLAR ACTIVE REGIONS

T. T¨O R¨OK, J. E. LEAKE, V. S. TITOV, V. ARCHONTIS, Z. MIKI´C, M. G. LINTON4, K. DALMASSE, G. AULANIER , B. KLIEM

The Astrophysical Journal Letters, Volume 782, L10, (2014)

There has been a long-lasting debate on the question of whether or not electric currents in solar active regions are neutralized. That is, whether or not the main (or direct) coronal currents connecting the activeregion polarities are surrounded by shielding (or return) currents of equal total value and opposite direction. Both theory and observations are not yet fully conclusive regarding this question, and numerical simulations have, surprisingly, barely been used to address it. Here we quantify the evolution of electric currents during the formation of a bipolar active region by considering a three-dimensional magnetohydrodynamic simulation of the emergence of a sub-photospheric, current-neutralized magnetic flux rope into the solar atmosphere. We find that a strong deviation from current neutralization develops simultaneously with the onset of significant flux emergence into the corona, accompanied by the development of substantial magnetic shear along the active region's polarity inversion line. After the region has formed and flux emergence has ceased, the strong magnetic fields in the region's center are connected solely by direct currents, and the total direct current is several times larger than the total return current. These results suggest that active regions, the main sources of coronal mass ejections and flares, are born with substantial net currents, in agreement with recent observations. Furthermore, they support eruption models that employ pre-eruption magnetic fields containing such currents.

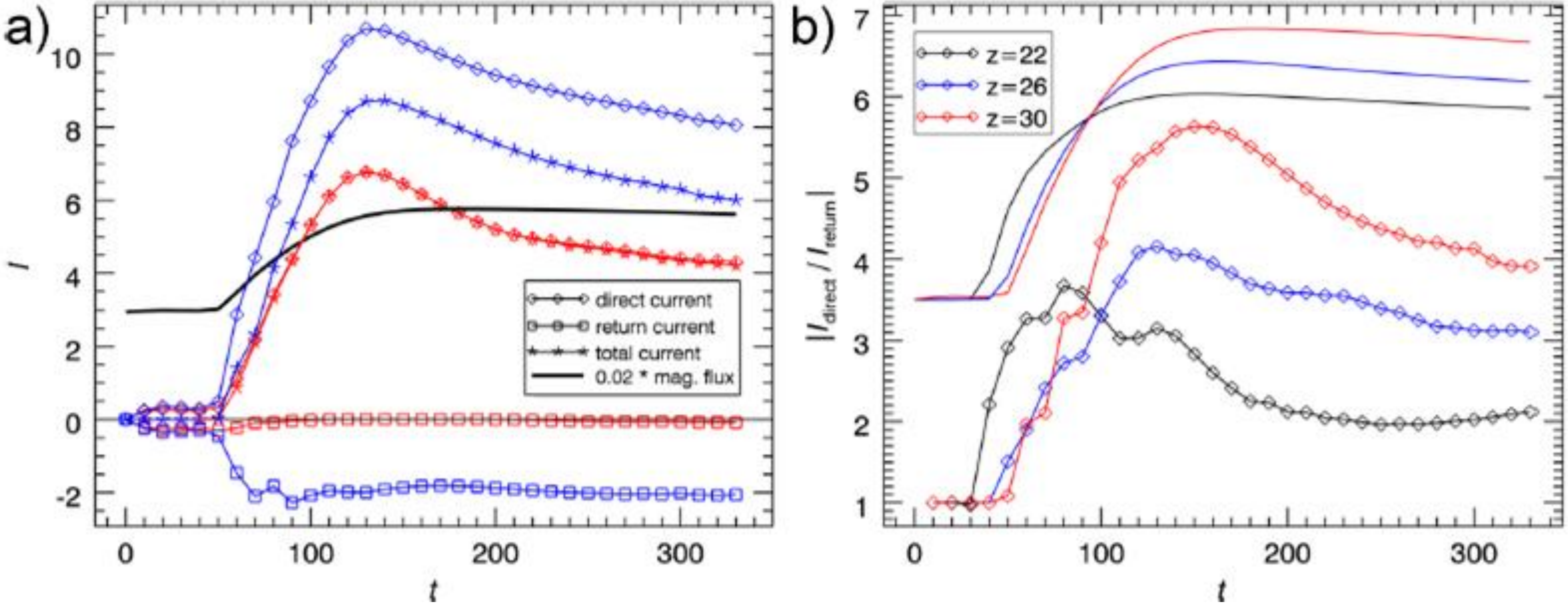


FIG. 4.— Electric currents integrated over the positive polarity region, $B_z(z) > 0$. (a) Integration at $z = 30$ over the whole polarity (blue symbols) and over the polarity center ($B_z > B_{z_{max}}/3$; red symbols). The total positive magnetic flux is shown by a black line (scaled to fit into the plot). (b) Ratio of total direct and total return current integrated over the whole positive polarity at heights $z = 22$, 26, and 30 (red, blue, and black diamonds, respectively). The total positive magnetic flux at these heights is shown by solid lines of the same color, scaled to the same initial value.

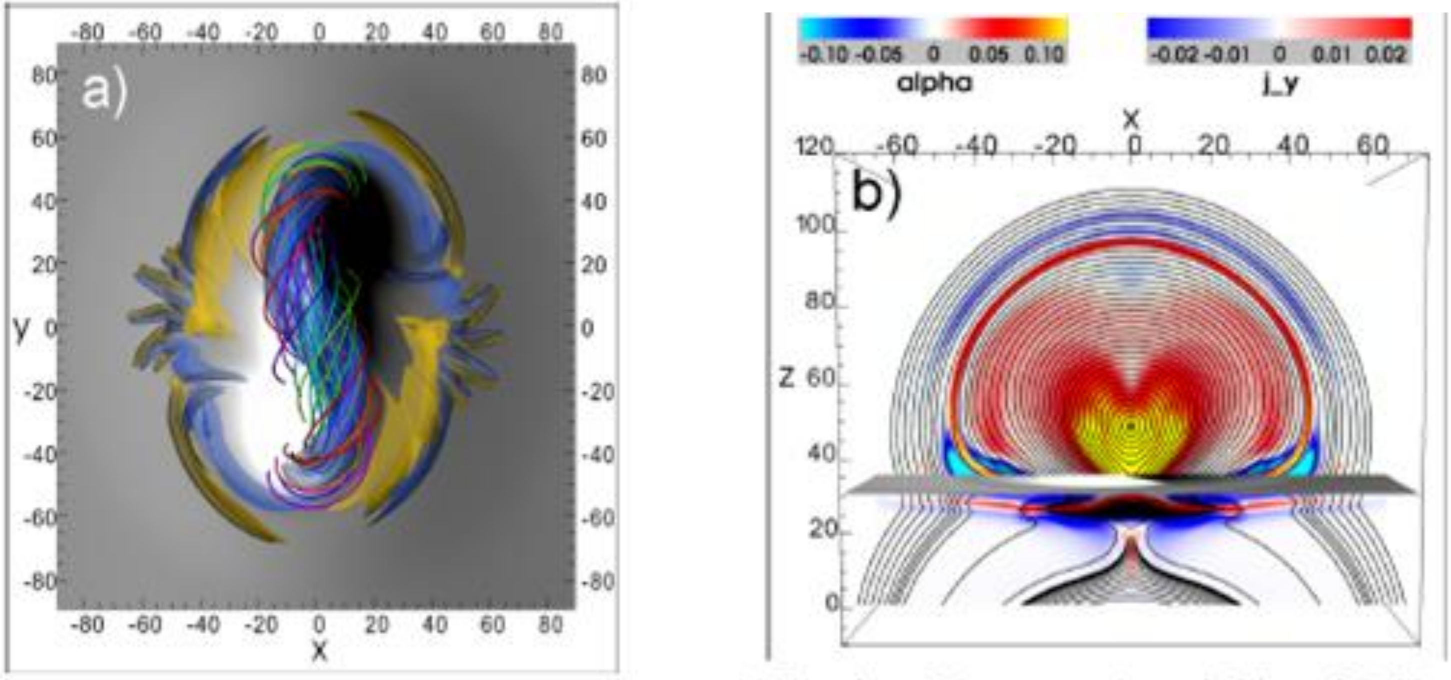


FIG. 3.— (a) Top view of the system shown in Figure 2 (without arcade field lines). Direct (return) currents are visualized by a blue (orange) transparent iso-surface of $\alpha = 0.12$ (-0.08). Note that the flux rope is right-handed ($\alpha > 0$), while the flux rope in Figure 1(a) is left-handed ($\alpha < 0$). (b) Perspective view along the rope axis, showing field lines of $(B_x, 0, B_z)$ and color-scales of α (for $z > 30$) and j_y (for $z < 30$) in the plane $\{y = 0\}$ (j_y is used to visualize the current direction for $z < 30$ since the field is far from a force-free state there).

THE ORIGIN OF NET ELECTRIC CURRENTS IN SOLAR ACTIVE REGIONS

K. Dalmasse, G. Aulanier, P. Demoulin, B. Kliem, T. T¨or¨ok, E. Pariat, Astrophysical Journal 810, 17-31 (2015)

There is a recurring question in solar physics about whether or not electric currents are neutralized in active regions (ARs). This question was recently revisited using three-dimensional (3D) magnetohydrodynamic (MHD) numerical simulations of magnetic flux emergence into the solar atmosphere. Such simulations showed that flux emergence can generate a substantial net current in ARs. Another source of AR currents are photospheric horizontal flows. Our aim is to determine the conditions for the occurrence of net vs. neutralized currents with this second mechanism. Using 3D MHD simulations, we systematically impose line-tied, quasistatic, photospheric twisting and shearingmotions to a bipolar potentialmagnetic field. We find that such flows:
(1) produce both direct and return currents, (2) induce very weak compression currents—not observed in 2.5D —in the ambient field present in the close vicinity of the current-carrying field, and (3) can generate force-free magnetic fields with a net current. We demonstrate that neutralized currents are in general produced only in the absence of magnetic shear at the photospheric polarity inversion line — a special condition rarely observed. We conclude that, as magnetic flux emergence, photospheric flows can build up net currents in the solar atmosphere, in agreement with recent observations. These results thus provide support for eruption models based on pre-eruption magnetic fields possessing a net coronal current.

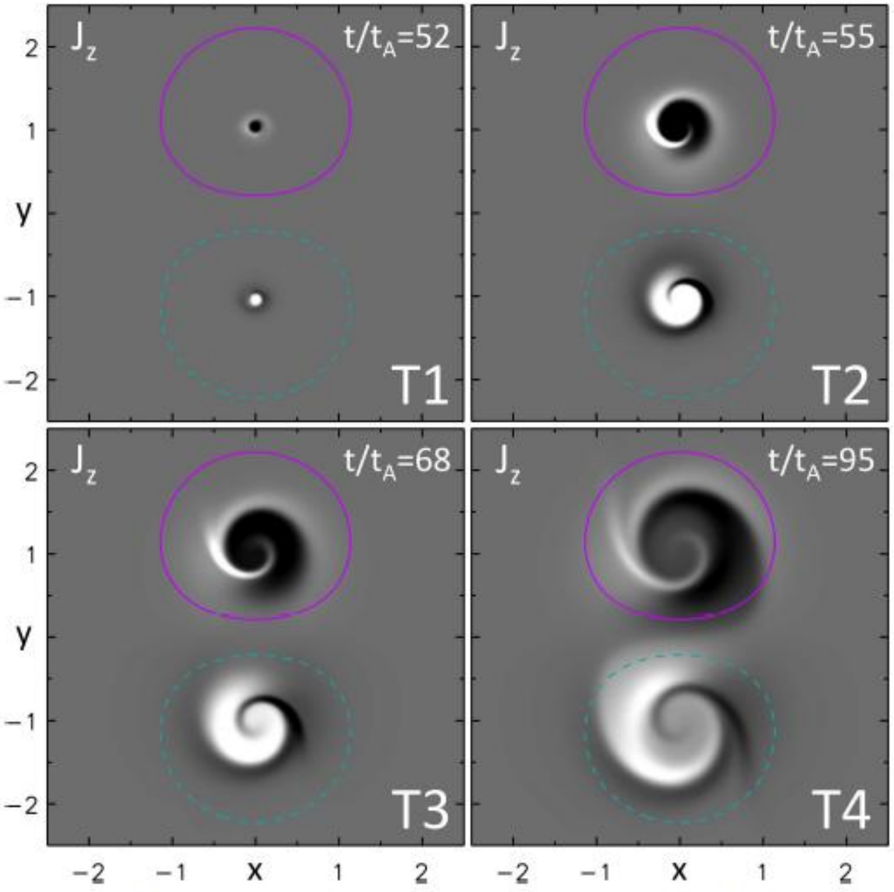


FIG. 3.— Photospheric ($z = 0$) current maps, j_z, at the end of each simulations for the symmetric twisting of two opposite magnetic polarities (Section 2.2), for T{1; 2; 3; 4}. White and black display positive and negative currents respectively. Values are saturated at ±1.5. Solid purple and dashed cyan lines represent ±0.25 isocontours of B_z.

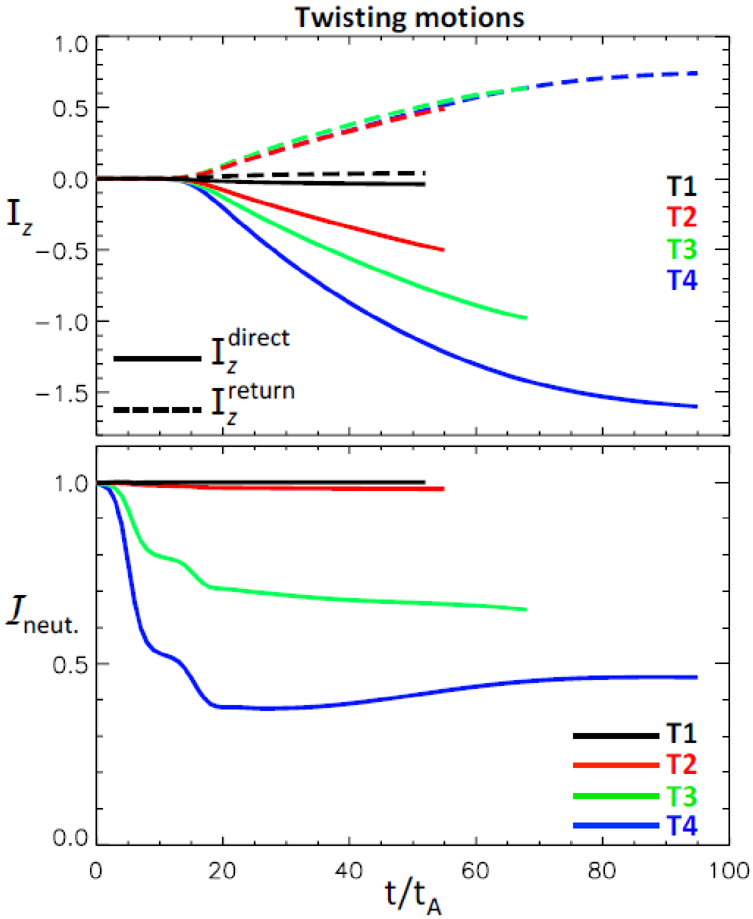


FIG. 4.— Evolution of the electric current, I_z, at $z = 0$ in the positive polarity for the photospheric twisting motions. Top: negative-direct ($I_z^{\rm direct}$) and positive-return ($I_z^{\rm return}$) currents (respectively displayed in solid and dashed lines). Bottom: neutralization ratio.

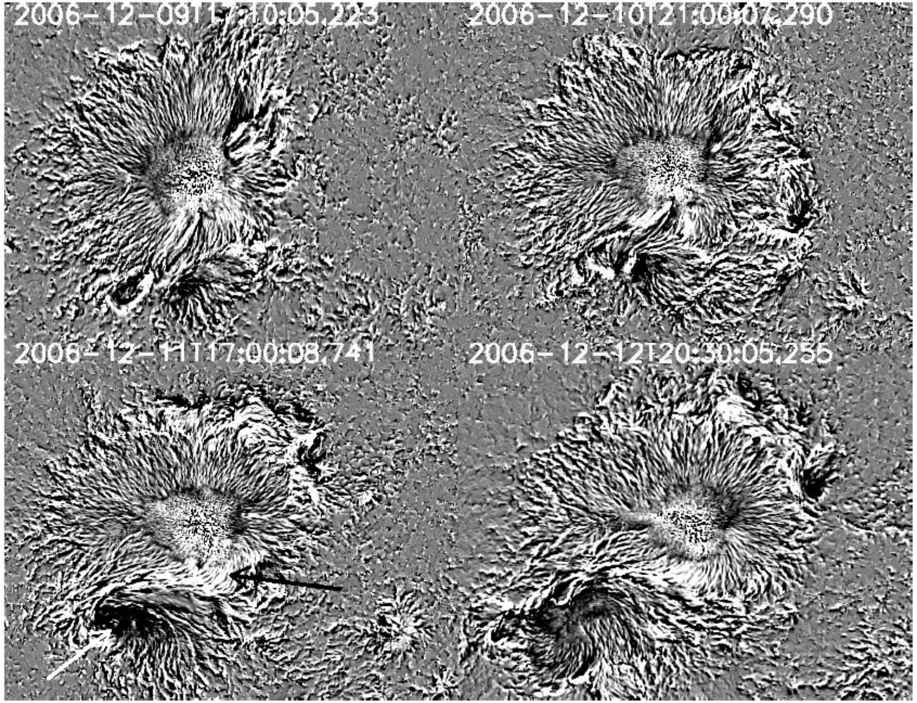


Fig. 3.— Maps of vertical current density obtained at different time of the epoch. The black and white arrows in the bottom left figure show the dominant regions of vertical current density in two different polarities. The field-of-view of each map is same as in Figure 1.

AR 10930

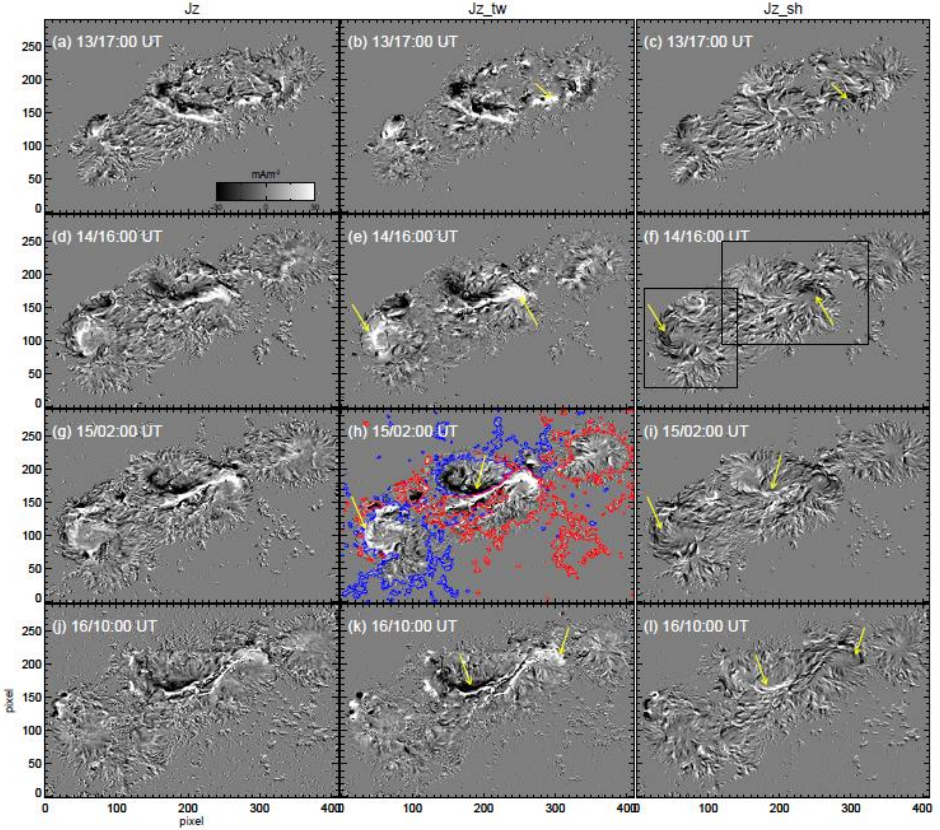


Figure 2. Distribution of vertical current (Jz, First column), chiral/twist current ($Jz_{\rm ch}$, second column), and shear current ($Jz_{\rm sh}$, third column) at different epochs of evolution in AR 11158. Note that the distribution of vertical current and chiral currents similar in almost every location. Identically oriented arrows (yellow) refers to prominent (few to notify) opposite polarity distribution patches of twist and shear currents in respective panels at a given time. Contours (±100G) of LOS magnetic field are plotted in panel (h) and the regions of interest for further analysis are shown in panel (f) with rectangles. All these maps are scaled within $\pm 50 \mathrm{mAm}^{-2}$ as in panel (a).

AR 11158

Discussions & Conclusions

OBSERVATIONS	THEORETICAL SIMULATIONS
Parker's original idea on neutrality of net currents is not valid for emerging or newly emerged sunspots	Demonstrate that net currents can be produced either by flux emergence, shearing motions or twisting motions.
Highly structured maps of current density with positive and negative signs of the vertical component of the current density sometimes appearing close to each othe	No such fine structure is seen.

Questions:

- What is the role of the fine structure in formation of net current and subsequent eruptive activity?
- Are the fine structures observational artefacts of the failure of disambiguation schemes on small scales?
- Or are these a result of simplified inversion schemes that do not factor for change of line formation height on small scales horizontally?

Solutions:

- Better simulations, based on fibril models of sunspots?
- Better disambiguation on small scales?
- Better inversion schemes with tau dependent parameters?
- Multi-line observations with telescopes like **NST**, **GREGOR, SST, NVST** and **MAST** ?

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