Astron. Astrophys. 331, 383–391 (1998)

ASTRONOMY AND ASTROPHYSICS

An ambiguity-free determination of J_Z in solar active regions

M. Semel and A. Skumanich★

DASOP, Section de Meudon, URA 326, Observatoire de Paris, Place Jules Janssen, F-92195 Meudon Cedex, France

Received 11 July 1996 / Accepted 24 July 1997

Abstract. We propose a way to derive a radial electric current density from vector magnetograms that is free of any particular choice of the two possible azimuths for the plane of the sky field. The method is applied to active region data obtained with the Advanced Stokes Polarimeter (ASP). A comparison of this current density with that derived for two particular sets of possible azimuth assignments allows one to evaluate the appropriateness of each set. In addition one may verify the detection of currents in general and the occurrence of current sheets, i.e. field discontinuities, in particular.

Key words: Sun: magnetic fields; plages; sunspots

1. Introduction

There is a general consensus on the importance of electric currents in the solar atmosphere. They play a role in the magnetostatic modeling of sunspots, in the dynamics of rapid evolution, as in flares, and in a variety of other solar physics problems like the heating of the upper atmosphere. However, their determination from vector magnetograph data depends on the particular azimuth assigned to the inferred transverse (plane-of-the-sky) magnetic field component at each point. We refer to such an assignment over a specific solar region as a *disambiguation*. The sign ambiguity in the *direction* of transverse field is unavoidable. It is due to the nature of the polarization of light and cannot be removed by any extant diagnostic analysis of the solar Zeeman effect [see however Landi Degl'Innocenti et al. (1993)]. Thus, there is an ambiguity inherent in the nature of the radial component of the electric current. Here, we propose to go beyond this limitation and show how some conclusion on the currents may be reached independently of any particular azimuthal disambiguation.

A disambiguation of the azimuths of the tangential field, $\boldsymbol{B}_t = (B_x, B_y)$, derived from a vector magnetogram at *disk center*, requires a choice between $\boldsymbol{B}_t$ and $-\boldsymbol{B}_t$ over the observed region. This allows one, in principle, to compute the vertical current density (hereafter called current)

$$4\pi J_z = (\nabla \times \boldsymbol{B})_z = \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \ . \qquad (1)$$

Because of a possible faulty choice of the sign of the direction vector of the transverse field at each point, i.e. of the disambiguation, the resulting currents have some degree of error. But without a disambiguation the variables B_x and B_y are not available as algebraic, i.e. properly signed, quantities and the x and y derivatives of B_x and B_y are not available. A new approach, as proposed here, is to cast Eq. (1) in a form that minimizes the role of the proper sign of $\boldsymbol{B}_t$. One needs to introduce other algebraic quantities that may be differentiated with respect to x, y.

The *first point* to note is that the resolution of the ambiguity in the azimuth of the transverse magnetic field entails a reflection operation, i.e. one does not know the sign or parity of $\boldsymbol{B}_t$. We shall use the word *parity* rather than *sign* to avoid confusion with the algebraic sign of B_x, B_y and, in particular, that of B_xB_y which by our nomenclature is parity free. The quantities B_x^2 and B_y^2 are sign free as well as parity free. The sign of B_xB_y is correctly given by the observations.

The *second point* entails the Principle of Continuity. If for instance, each of the variables B_x^2, B_y^2 and B_xB_y were regular (analytical) functions of x, y in a given domain, then the resolution of the ambiguity is reduced to just a *single* choice of the parity of $\boldsymbol{B}_t$ at a single point for the whole domain of regularity. In some cases even this choice may be removed by an additional assumption. We don't consider, for the moment: 1) errors in calibration, or 2) noise, or 3) true field discontinuities that are solely rotational, i.e. jumps in azimuth alone, or amplitudinal, i.e. jumps in magnitude alone (or a combination of both). In other words, if the parity were known or assumed at one point, a parity propagation may be applied to the domain of regularity using the principle of continuity. In any case the variables (B_x^2, B_y^2, B_xB_y) are independent of any azimuthal ambiguity, and may be examined for continuity and differentiated with respect to x, y.

Send offprint requests to: M. Semel

★ On leave from the High Altitude Observatory of the National Center for Atmospheric Research (NCAR) Boulder, Colo, USA. The NCAR is sponsored by the National Science Foundation.

2. Algebra for the calculation of $|J_z|$

2.1. The adopted expressions

If we multiply Eq. (1) by B_x, then incorporate this factor into the right hand side and rewrite it in binomial forms we obtain

$$|(\nabla \times \boldsymbol{B})_z| = \frac{1}{|B_x|}\left|\left(\frac{\partial(B_xB_y)}{\partial x} - \frac{(B_xB_y)}{B_x^2}\frac{1}{2}\frac{\partial B_x^2}{\partial x} - \frac{1}{2}\frac{\partial B_x^2}{\partial y}\right)\right| . \quad (2)$$

Since the term in the parenthesis is parity free then the absolute value of the radial current is independent of any disambiguation. A disadvantage of the above equation is the excess weight given to B_x. If B_x is small, significant errors are possible. In this case one may use the alternate expression obtained by multiplying Eq. (1) by B_y [interchange x and y and B_x and B_y in Eq. (2)] with B_y now weighted heavily. In the case of Cuperman et al. (1990), that equation was used which had the largest denominator, either that with $|B_x|$ or $|B_y|$.

Since the two observables are not completely independent it is not clear as to which expression for $|(\nabla \times \boldsymbol{B})_z|$ is best. If these variables were known with analytical precision, all the expressions would be identical. However, errors in magnetograph measurements may yield different results for different expressions.

From the above demonstration it is clear that we need to multiply Eq. (1) by either B_x, B_y or by any power of them or a product of these quantities in order to obtain a convenient expression to calculate the radial current. Intuitively, we prefer to have equal weights for any of the observables: B_x^2, B_y^2 and (B_xB_y). We therefore multiply Eq. (1) successively by B_x^4, B_y^4 and by $B_x^2B_y^2$ and obtain:

$$B_x^4(\nabla \times \boldsymbol{B})_z = +B_x\left[B_x^2\frac{\partial(B_xB_y)}{\partial x} - \frac{1}{2}(B_xB_y)\frac{\partial B_x^2}{\partial x} - \frac{1}{2}B_x^2\frac{\partial B_x^2}{\partial y}\right] ,$$

$$B_y^4(\nabla \times \boldsymbol{B})_z = -B_y\left[B_y^2\frac{\partial(B_xB_y)}{\partial y} - \frac{1}{2}(B_xB_y)\frac{\partial B_y^2}{\partial y} - \frac{1}{2}B_y^2\frac{\partial B_y^2}{\partial x}\right] ,$$

$$B_x^2B_y^2(\nabla \times \boldsymbol{B})_z = +B_x\left[\frac{1}{2}(B_xB_y)\frac{\partial B_y^2}{\partial x} - \frac{1}{2}B_y^2\frac{\partial B_x^2}{\partial y}\right] ,$$

$$B_x^2B_y^2(\nabla \times \boldsymbol{B})_z = -B_y\left[\frac{1}{2}(B_xB_y)\frac{\partial B_x^2}{\partial y} - \frac{1}{2}B_x^2\frac{\partial B_y^2}{\partial x}\right] .$$

In the above equations all the terms in the square brackets are parity free. This is also true for all the introduced factors. The reflection ambiguity is left only in the coefficients B_x, B_y. Thus, any of these equations could be used but with probably different contributions to the errors from the observables and their derivatives. We prefer to use all of the four equations and with equal weights.

Adding these four equations one finds that:

$$(\nabla \times \boldsymbol{B})_z = +\frac{B_x}{B_t^4}\left[B_x^2\frac{\partial(B_xB_y)}{\partial x} - \frac{1}{2}B_xB_y\frac{\partial(B_x^2 - B_y^2)}{\partial x} - \frac{1}{2}B_t^2\frac{\partial B_x^2}{\partial y}\right] - \frac{B_y}{B_t^4}\left[B_y^2\frac{\partial(B_xB_y)}{\partial y} - \frac{1}{2}B_xB_y\frac{\partial(B_y^2 - B_x^2)}{\partial y} - \frac{1}{2}B_t^2\frac{\partial B_y^2}{\partial x}\right] , \quad (3)$$

where $B_t^2 = B_x^2 + B_y^2$. We may rewrite this equation as

$$(\nabla \times \boldsymbol{B})_z = B_xg_y - B_yg_x , \quad (4)$$

where g_x and g_y can be derived irrespective of any specific disambiguation. Thus we have that

$$((\nabla \times \boldsymbol{B})_z)^2 = B_x^2g_y^2 + B_y^2g_x^2 - 2(B_xB_y)g_xg_y . \quad (5)$$

All the terms in the last equation are parity free, i.e. independent of any specific disambiguation. It is clear that the *absolute value* of the the radial component of the electric current is well determined.

2.2. The local validity

The use of the last equation to compute $|J_z|$ requires that: 1) the vector is properly measured *locally*, and 2) the continuity principle is also valid *locally*. If for any reason these two conditions are not satisfied at any point on the sun, the computation of $|J_z|$ is erroneous only at that point and does not affect the computation at any other solar point. This is not true for various methods of disambiguation. For instance, the shear based method needs the knowledge of the normal component of the magnetic field *everywhere* on the photosphere. Also, the current-free approximation applies *everywhere* in the semi-infinite space $z \geq 0$.

At the same time, this determination of $|J_z|$ is some kind of a minimum current determination and excludes rotational current sheets, i.e. due to azimuthal discontinuities. A non-nul determination of $|J_z|$ always has a physical significance. Typically, rotational current sheets will appear as the result of a parity propagation technique and we will call attention to this below in our discussion of the observations. The interpretation of such sheets regarding their location and/or significance is not evident.

3. Lack of resolution of solar magnetic fields

With the present available instruments and observational means, solar magnetic fields often remain unresolved. In other words, within each observed pixel, the magnetic field has a significant variation, say $\boldsymbol{B}(x, y, z)$ where x, y are the lateral coordinates internal to the resolution element and z, the vertical one. First, what we really observe, and second what we then determine from our observations for the various physical quantities are various moments over this variation. Often it is impossible to know what are the real nature of these moments. By no means can one assume simply that an observable $O_i(pixel)$ is given by

$$O_i = \int_{V(pix)} \boldsymbol{W}_i(x,y,z) \cdot \boldsymbol{B}(x,y,z) dxdydz \ , \qquad (6)$$

where $\boldsymbol{B}(x,y,z)$ is the magnetic field at the point (x,y,z) within the pixel-defined volume (to be made more precise below) and $\boldsymbol{W}_i(x,y,z)$ is an hypothetical weighting function or the appropriate moment factor. Given the impossibility of solving this problem completely, the general trend is to apply a simple assumption in order to cope with the structured nature of solar magnetic fields.

The first approach is to assume that part of the volume of the pixel is free of magnetic field, so that this component does not yield any polarized light. Here the polarization is created ONLY in the magnetic component. Still, the nonmagnetic component may in some cases, canopies for instance, have an effect on the emergent polarization profile.

There are differences in the modeling of such two components features. Some authors require a distribution of values inside the magnetic component and use a variety of additional assumptions. For simplicity, here, we assume a unique field value inside the magnetic component of each resolution element. If we are lucky, this simplified assumption may fit the available observations in question and give a reasonable account of the true physical situation. We now define a volume filling factor, f_V, the ratio of the volume of the magnetic element to the total volume for each pixel. The terms "volume of the magnetic element" and "volume for each pixel" are not necessarily immediately clear. However, we assume again that appropriate ways may be found to allow a satisfactory definition of f_V. The main difficulty comes from the fact that what we observe are functions of the *optical thickness* in the z direction and not a function of the geometrical depth. For instance we could take the interval given by $\tau_c(z_{min} = 0) = 1$, and $\tau_c(z = z_{max}) = 10^{-2}$ to defines heights in a given model, say the standard solar photosphere. Any such defined f_V should at least be acceptable. For example one might want to use the line-center optical thickness or some intermediate wavelength. If we are lucky with our inversion of the Stokes profiles, we should have the true field, $\boldsymbol{B}_{true}$, and f_V. So that, in this *lucky case*, the average field becomes $\boldsymbol{B}_{average} = f_V \boldsymbol{B}_{true}$ and

$$f_V \boldsymbol{B}_{true} = \int_{V(pix)} \boldsymbol{B}(x,y,z) dxdydz/V \ , \qquad (7)$$

where $V = \int_{V(pix)} dxdydz = A_{pix}\ z_{max}$ with A_{pix} as the resolution element area.

We assume, first, that our hypothetical geometry applies to each pixel or resolution element, i.e. that the dependence of τ on geometrical depth is the same for each pixel. This is not true in general. However the *fluctuations* of the geometrical depth (less than 100 km) are generally small in the photosphere, certainly in comparison with the lateral extension of the resolved pixels (about 1000 km). In practice, we will consider solar elements several pixels in size and then this approximation becomes even more justified. We can then define the average current density $J_z(average)$:

$$\begin{aligned} J_{z,average} &= \int_{V(pix)} J_z(x,y,z) dxdydz/V \ , \\ &= \int_{V(pix)} (\nabla \times \boldsymbol{B}(x,y,z))_z dxdydz/V \ , \\ &= (\nabla \times \boldsymbol{B}_{average})_z \ , \end{aligned} \qquad (8)$$

where we have commuted the two operations. Their commutation may be demonstrated, for example, by Fourier transforms.

4. Application to ASP observations

The HAO inversion technique applied to the ASP observations consists of assuming that the polarization parameters Q,U,V, come only from the magnetic element and are not effected by the non-magnetic one. By using a Milne-Eddington(M-E) model, the inversion yields a unique vector $\boldsymbol{B}$. This is a sophisticated method, and we consider the ASP as the best available solar "magnetometer" today. Heuristically we will consider this determination as $\boldsymbol{B}_{true}$. The derived filling factor f_{ASP} requires some discussion. It is determined from the amount of unpolarized light needed to fit the observed intensity. As pointed out by Skumanich et al. (1992), f_{ASP} is not necessarily a horizontal filling factor as one might naïvely suspect. In some circumstances, it could be a vertical filling factor. For example, for lines of sight passing through canopies. What we need to use here is the volume filling factor, f_V. When could f_{ASP} be considered as a volume filling factor? Obviously, this happens in the case of pure vertical flux tubes. But not only in this case!

For sake of brevity, we will mention only the most instructive case as described by Skumanich et al. (1992). In this paper, the configuration studied was a realistic model for a magnetic flux channel (Knölker et al. 1991). The purpose was obviously to treat the case of both *horizontal* and *vertical* filling factors, i.e. a flux "tube" (channel) and its surrounding canopy. The use of the ASP inversion code yielded both $\boldsymbol{B}_{true}$, the true fields and f_{ASP}, an *average* filling factor. But as Skumanich et al. stated and showed in their Table 2, the filling factor f_{ASP} multiplied with the resolution size (i.e. the pixel width) resulted in the width of the flux slab at $\tau_0 = 1$, i.e. about 200 km for any simulated resolution larger than 500km. In other words, the *average* filling factor behaved as if it were a pure horizontal one! By the way, in this model, for any resolution exceeding 500 km (including the canopy situation) both $B_{z,average}$ and $J_{z,average}$ are constant with depth, $B_{z,average}$ being the constant flux and $J_z = 0$. It is interesting to note that the determined $\boldsymbol{B}_{true}$ was very near to the model value at $\tau_0 = 1$ along that particular line of sight.

Quite an older treatment of the same issue was published by Rees et al. (1979). In this precursor paper, a cylindrically-symmetric configuration was assumed and different scale heights were considered. The inversion was limited to only circular polarization and the determination of $B_{z,average}$. For any line of sight that crosses the flux tube, the field is not constant! It was effectively a canopy situation. Here, $B_{z,average}$ was given by the center of gravity method to within only a few percent with the atmosphere model taken to be the same inside and outside the flux tube.

Now, the sophisticated ASP inversion code determines the magnetic atmosphere model (i.e it is fitted) and the spectral lines used are temperature insensitive, (Wiehr 1978). Thus, the vertical thickness remains nearly invariant so its no wonder that the *volume* filling factor acts like a horizontal one. With this approach, we are ready to apply our calculations to the ASP observations. We will use the determination of f_{ASP} as if it were a volume filling factor, f_V.

4.1. The off disk-center case

Often, a solar active region is observed away from disk-center and the direct application of Eq. (5) must be reconsidered. The proposed procedure when applied to such observations will result in two possible solutions.

To simplify this problem we proceed as follows. Instead of the derivatives of B_x and B_y as required by Eq. (1) we separate the contributions to J_z due to the 1) line-of-sight field when transformed to the local solar frame, $\boldsymbol{B}_l$, which is no longer perpendicular to the solar surface, and 2) plane-of-sky field, transformed, $\boldsymbol{B}_p$ which is no longer tangent to the solar surface. This is possible because of the linearity of Eq. (1).

Let the contribution to the computed radial current due to $\boldsymbol{B}_l$ be J_{lz}. The parity of $\boldsymbol{B}_l$ is unambiguous and the resulting current can be derived in the local solar frame by application of Eq. (1). Let the projections of $\boldsymbol{B}_p$ on the solar surface be B_{px} and B_{py}. We note that B^2_{px}, B^2_{px} and $B_{px}B_{py}$ do not depend on the parity of $\boldsymbol{B}_p$ and therefore are the appropriate algebraic variables to put in Eq. (5) to substitute for B^2_x, B^2_y and (B_xB_y) respectively. Thus the parity free absolute value current derived from $\boldsymbol{B}_p$ using Eq. (5) may be labeled $|J_{pz}(free)|$.

4.2. Observed currents

It is possible to construct two *independent* and *disambiguated* current states in terms of our parity free current, viz.,

$$J^{\pm}_z = J_{lz} \pm S(J_{lz})|J_{pz}(free)| \; , \tag{9}$$

where $S(J_{lz})$ is the sign of J_{lz}. The current $J^-_z \equiv J_z(\text{min})$ represents the *smallest* possible current allowed by the data. Whenever it is non-zero, we may conclude that an electric current has been detected to within the observational error. If continuity were to hold everywhere then the J^+_z current would be the largest current allowed by the data. We do not consider it further here.

We may also obtain a sign for $|J_{pz}(free)|$, for instance, by attributing a parity sign (i.e. a disambiguation) to $\boldsymbol{B}_p$, hence to the components (B_{px}, B_{py}) in Eq. (5). In this case J_z differs from that calculated by Eq. (1) for the same parity assignment with regard to rotational discontinuities and/or other possible errors in the parity assignment. As we will see below, the difference has significant interest.

Our proposed constructions have been applied to vector field maps inferred from observations of an active region obtained with the ASP of the High Altitude Observatory and the National Solar Observatory at Sacramento Peak, New Mexico. For a discussion of this region refer to Lites et al. (1995) and Skumanich et al. (1996). We have determined the noise present in our constructs by examination of their histograms. We find that some of the distributions may be fit by a Gaussian about zero with $\sigma = \pm 25$ G/Mm. We assume this is our noise.

In Fig. 1, the top left panel shows a derived parity free current $|J_{pz}(free)|$. On the left bottom we see the absolute value of J_{pz} as determined with Eq. (1) after a particular disambiguation (labeled AZ-L) based on the use of the AZAM utility [described in Lites et al. (1995)]. The upper right panel presents the absolute value of the unambiguous J_{lz} current while the lower right shows its signed value. The gray scale saturates at 0.6 kG/Mm or 24σ.

Strong linearly extended features appear on *all* maps near the *heliocentric coordinate frame* neutral line in the plage region, south of and neighboring the delta spot. They are not of uniform amplitude along their length, i.e. they are often fragmented. Their presence indicate the occurrence of amplitudinal as well as rotational discontinuities or current sheets. A careful study shows that some of these sheets that appear in $|J_{lz}|$ or $|J_{pz}$(AZ-L)$|$ are not present in $|J_{pz}(free)|$. This is not surprising since $|J_{pz}(free)|$ is not supposed to show rotational current sheets. Furthermore some sheets that are present in $|J_{pz}$(AZ-L)$|$ are not detectable in $|J_{lz}|$. The difference between J_{pz}(AZ-L) and J_{lz} is due only to a perspective effect and it is unlikely that current sheets appears only in the plane-of-sky contribution and not in the line-of-sight one. Note that some differences between these quantities will occur due to noise.

Consider the linear feature extending SW from (x, y) = $(35, 15)$ Mm to (x, y) = $(45, 10)$ Mm. It is present in all three current maps but slightly displaced in $|J_{pz}$(AZ-L)$|$ and of lower amplitude in $|J_{pz}(free)|$. The latter observation implies the occurrence of an amplitudinal discontinuity in addition to a rotational one. However the feature NE of the same SW line extending from $(29, 22)$ Mm to $(35, 18)$ Mm is seen only in $|J_{pz}$(AZ-L)$|$. This may be a pure rotational discontinuity but its absence in $|J_{lz}|$ raises doubt about its reality. A more ambiguous case is that of the semi-circular feature starting at $(28, 34)$ Mm and proceeding counter-clockwise to $(33, 28)$ Mm. It is strongly defined in $|J_{pz}$(AZ-L)$|$, somewhat weaker in $|J_{pz}(free)|$ and only partly visible in $|J_{lz}|$ (lower part). Ignoring the visibility problem in $|J_{lz}|$ one has further evidence of a mixed discontinuity. A similar visibility problem holds for the extended currents associated with the delta-spot umbrae at $(29, 45)$ Mm and $(32, 37)$ Mm. The reality of these currents is not in doubt. Other extended features may be found that are present in all three maps, e.g. at $(28, 18)$ Mm.

We examine the difference between the two $|J_{pz}|$ currents further. Here we consider in addition to our AZ-L disambiguation an alternate one, labeled AZ-S, as given by Lites et al. (1995). They differ mostly in and around the delta- spot. In Fig. 2 we present the consequent $|J_{pz}|$ in the upper panels. We

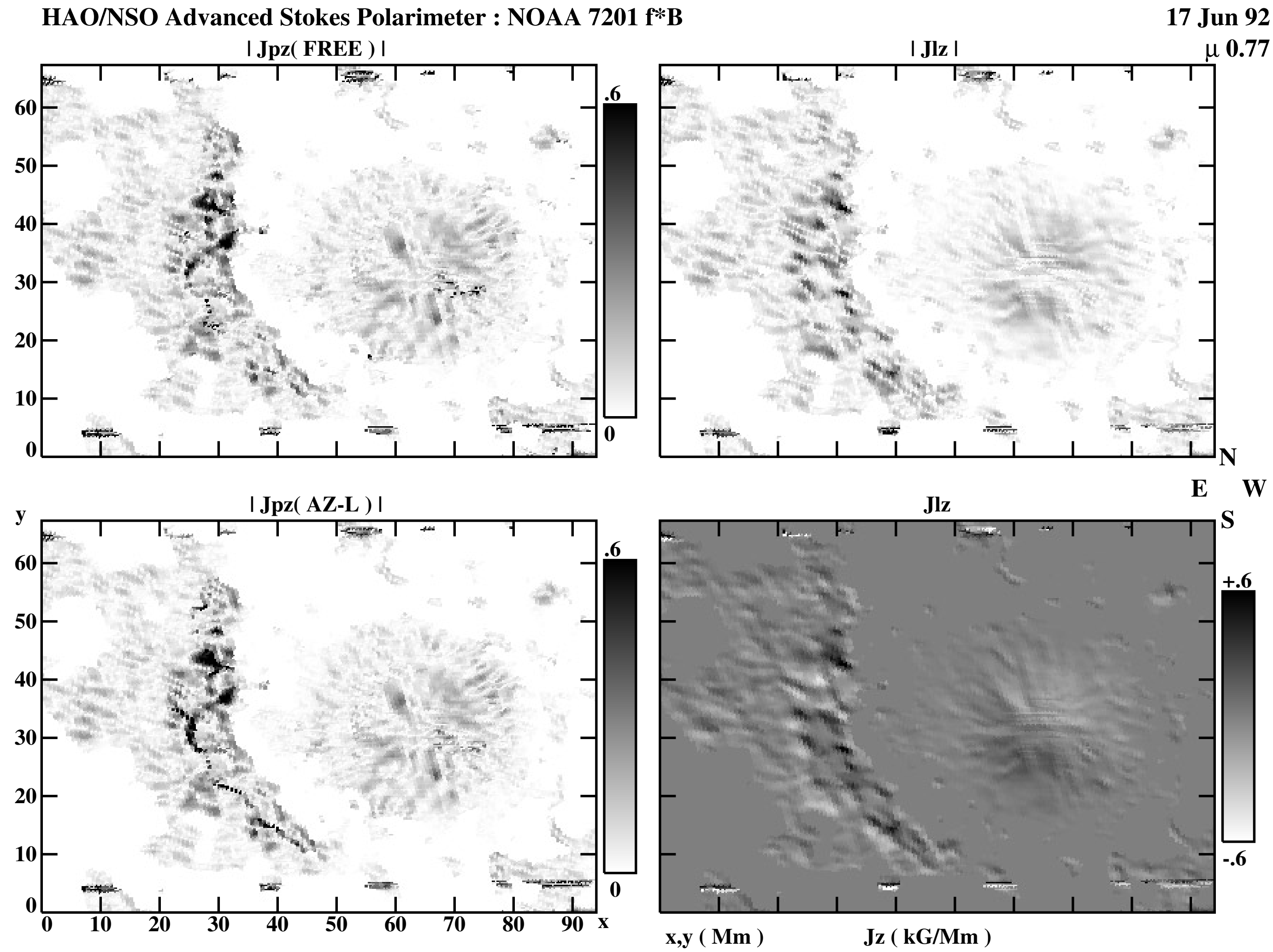

Fig. 1. Comparison of absolute values of the plane-of-sky contribution to the vertical current in the solar tangent plane (upper left: disambiguation-FREE, lower left: disambiguation AZ-L) with line-of-sight contribution (upper right: absolute value, lower right: signed). Solar West is to the right, North is upward. Direction to disk center is SW. Note that white regions in the absolutes value images indicates that such regions were not inverted due to low net-polarization and have been assumed to have zero current.

assign to $|J_{pz}(free)|$ the sign selection, S, associated with a particular disambiguation, X, and form the difference $|J_{pz}(X)| - \mathrm{S}(X)|J_{pz}(free)|$ where X is either of the two disambiguations discussed here. This yields the regions where rotational sheets occur. This difference is presented in the lower panels. In addition we have marked in black the (local solar frame) magnetic neutral line, viz. $(B_{lz} + B_{pz}) = 0$. Note that the plage region to the East of the North-South neutral line is of opposite sign to that of the major (Western) spot. The disambiguations differ in those regions where the neutral lines differ. It is evident that different rotational currents sheets are introduced by the different disambiguations.

Are these rotational sheets real or ambiguity artifacts? Certainly whenever such currents are *seen in both* J_{lz} and $|J_{pz}(free)|$ they must be real. On the contrary when they are *not seen in either* then their existence must be in doubt. When *seen in* J_{lz} and *weakly or not at all in* $|J_{pz}(free)|$ but *appear* at the same place in $J_{pz}(X)$ then they have a rotational nature and are real and confirm the disambiguation. If they *appear near* each other their location is changeable by a change in the disambiguation. When they are *weakly visible* in J_{lz} (or not at all) but are clearly *present* in $|J_{pz}(free)|$ and $J_{pz}(X)$ the currents are ambiguous but probably real. In any respect concurrence with J_{lz} should be considered as an additional factor in any disambiguation.

The total current associated with each of the two disambiguations,

$$J_z(X) = J_{lz} + J_{pz}(X) \;, \qquad (10)$$

is illustrated in Fig. 3. The upper row gives the (signed) total current while the lower one, the absolute value for comparison with previous plots. Current features in J_{lz} appear to be positive, for the most part, compared to the same features in $J_{pz}(X)$, however complete cancellation of the two current contributions

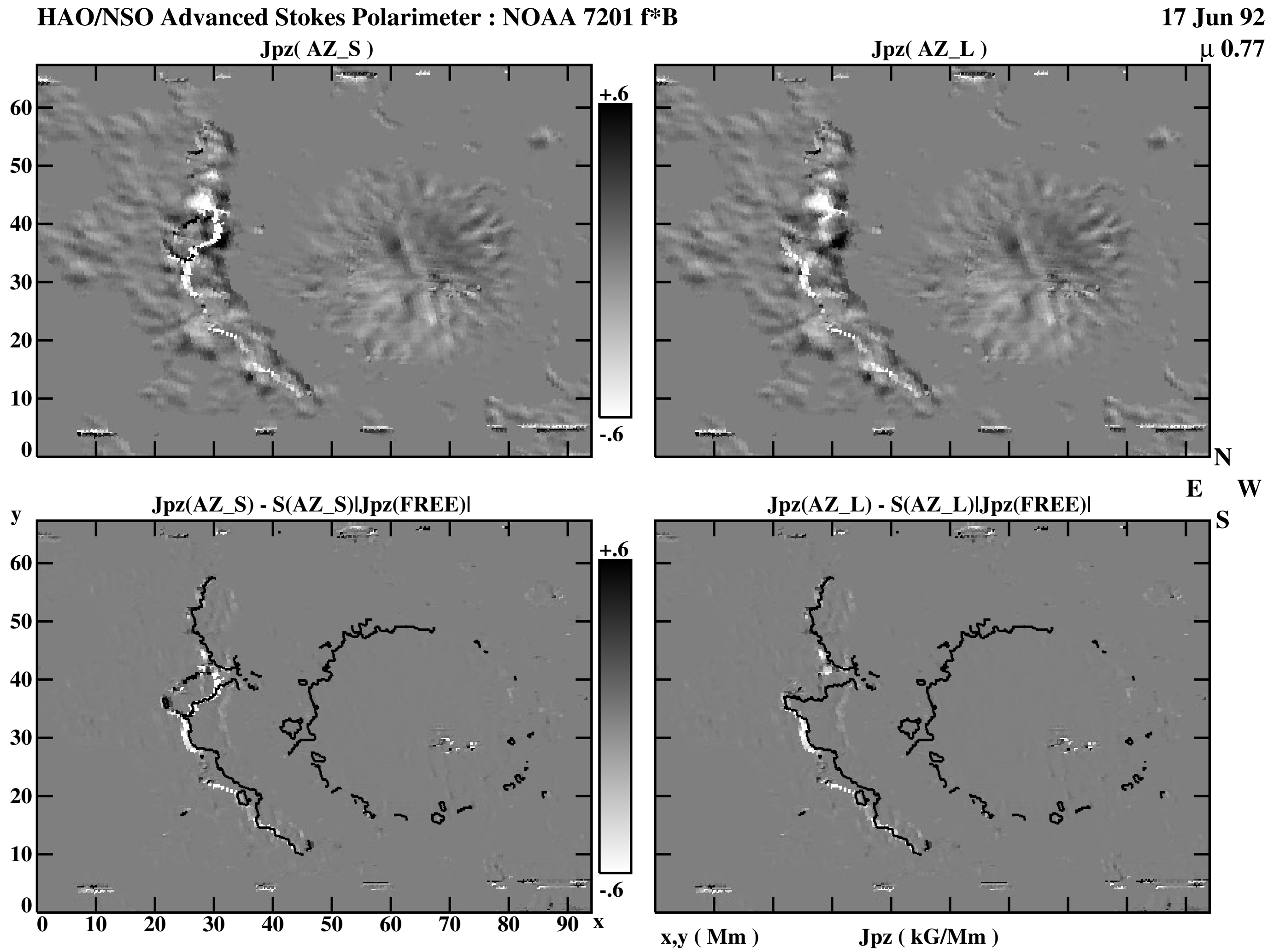

Fig. 2. Comparison of plane-of-the-sky current contributions for two alternative disambiguations. The lower row gives the difference current over the identically signed disambiguation-free current. The black contour line represents the neutral line in the solar tangent plane.

does not occur. Thus one may affirm the detection of currents when the signal is above the noise level.

For completeness, we present in Fig. 4 the "smallest" current attainable J_z(min) (upper panels) for two successive days, 17 and 18 June '92 (upper left, μ = 0.77, and upper right, μ = 0.88, respectively). A disambiguation based on such a parity assignment, i.e. $S(-J_{lz}(x, y))$, was studied by Skumanich et al. (1996) for the 17 June case but with $\boldsymbol{B}_{true}$ rather than $\boldsymbol{B}_{average}$ as suggested here. They found that the presence of noise proved to be problematic as far as continuity was concerned, so that such an disambiguation procedure is only useful as a first guess. However a disambiguation based on the use of $\boldsymbol{B}_{average}$ may be more favorable. In the lower panels in Fig. 4 we present the excess current over the "smallest" for the AZ-L disambiguation for 17 June (lower left) and the Lites et al. (1995) disambiguation for 18 June (lower right). Linear features are found in both maps. No new current structures are to be seen in this difference for 17 June when one compares the left column with Fig. 3. In regard to 18 June one finds that the linear features below the delta-spot ($NE-(30,12)$Mm to $SW-(25,22)$ Mm) and between the delta-spot umbrae are once again near and along the local solar frame neutral line, refer to images in Lites et al. (1995). The currents in the major spot are at their "smallest" value only in the umbra.

We note that the histogram of J_z compared to $J_z(min)$ for different features will differ in that $J_z(min)$ may tend to show a greater degree of cancellation of the component currents, i.e. $J_z(min)$ may show a Gaussian core with a dispersion of 25 G/Mm. Indeed in the plage East of the delta spot both currents are wellfit by the same Gaussian with σ = 25 G/Mm. We believe that complete cancellation occurs. We thus take the residual to represent the noise in our constructs. For completeness we note that the (total) horizontal field magnitude, B_h(AZ-L), for this region has a (2-D) Maxwellian "core" with a 30 G dispersion.

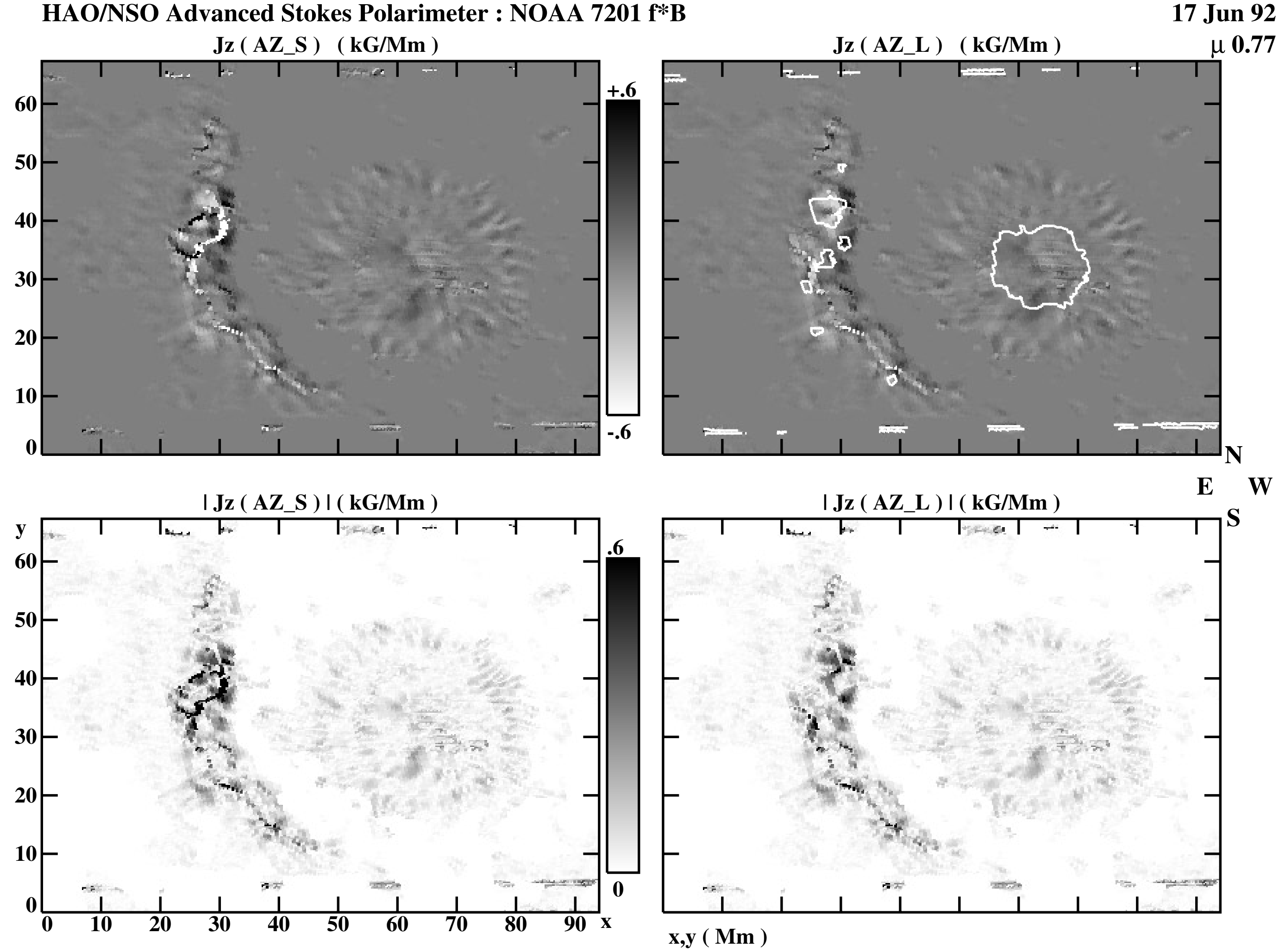

Fig. 3. Comparison of total vertical current for two alternative disambiguations. The lower row gives the absolute values. The white contour lines give umbra-penumbra transition boundaries.

5. The observational detection of currents and Parker's objection

5.1. Evidence from observations: Noteworthy features in $|J_{pz}(free)|$ and $|J_{lz}|$

On inspecting the East side plage in Fig. 1, ($x < 22$ Mm), one finds well defined structures that are repeated in both $|J_{pz}(free)|$ and $|J_{lz}|$, i.e. the patterns are the exactly same! We note that these quantities are obtained from different components and by different partial derivatives. We believe that such a concurrence is not due to an error in the analysis of the data. We do not have the freedom to discuss in detail here the determination of $|J_{pz}(free)|$ and $|J_{lz}|$ from the observables, i.e., the Stokes vector, but we can assert that errors in the observables can hardly result in similar errors in the two quantities. How is it that they show such a high resemblance? It is striking, and easy to verify by superposition of the images. Consider our $J_z(min)$ which is composed from these two quantities. If there are no vertical currents, then $J_{pz}(free)$ must compensate J_{lz}, and that is exactly what happens. The magnetic vector field is essentially vertical here. We note that this is also a demonstration on the usefulness of the assumption of minimum vertical currents to resolve the azimuthal ambiguity.

Fortunately, the West side story, i.e. $x \gtrsim 22$ Mm, is different and excludes the possibility that there was a trivial error in constructing these currents. Here the two currents are quite different! We must have a genuine non-zero solar current. It is worthwhile to note that the clearly detected electric currents in the penumbra of the big Western most spot must be of a different nature.

In short, we observe a remarkable *coherence in independent observables* in the plage area on the East side. This adds confidence to the observational procedure and data analysis on the one hand, and supports our detection and interpretation of solar magnetic fields and electric currents on the other hand.

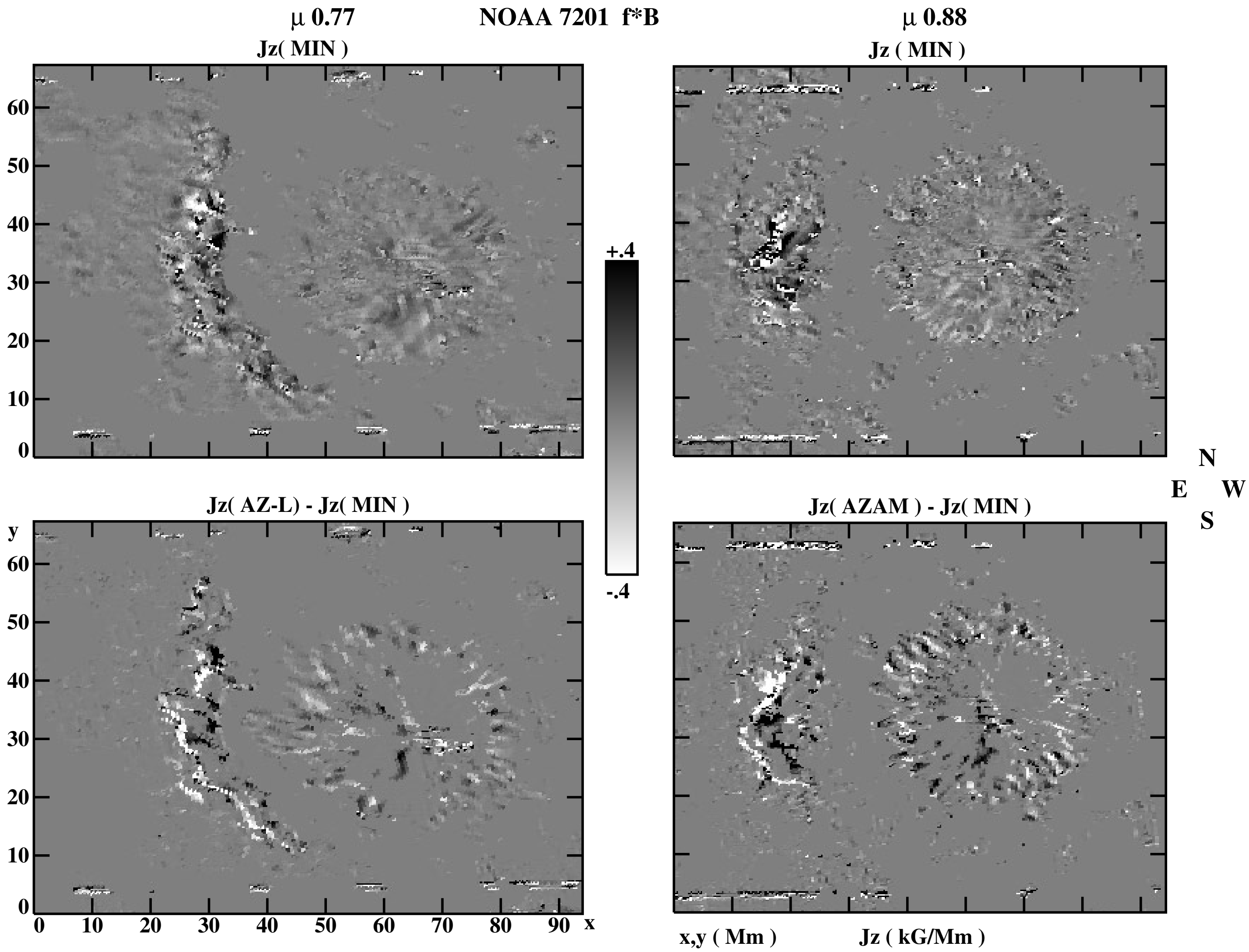

Fig. 4. Upper row: Total vertical current in the "smallest" possible current state for 17 and 18 June '92. Lower row: The difference current for the particular assigned disambiguation.

5.2. Parker and $J_z = 0$

In a recent paper Parker raises the argument that for a typical flux tube, $J_z = 0$. Here, we consider the argument further. We assume first, that a flux tube is imbedded in a zero field environment. We next apply Stokes theorem, namely that

$$\int_l \boldsymbol{B} \cdot \boldsymbol{dl} = \int_S \nabla \times \boldsymbol{B} \cdot \boldsymbol{dS} \; , \qquad (11)$$

where the line integral on the left side is along the contour l outside the flux tube, i.e. the surface element S includes the tube. Since in the surroundings of the fluxtube $\boldsymbol{B} = 0$, the line integral is zero and the mean current density for the flux tube, $J_z = 0$.

Parker refers to a very particular configuration where the field is concentrated in small elements in which each element is surrounded by an area with no field. Thus, in virtue of Stokes theorem the total current for each of these elements is zero as the line integral does not encounter any field. In such a case, we could tile the whole area, arbitrarily, into small pixels, each with zero field on its borders, so that J_z equals zero identically everywhere. In a real tiling with pixels this is not the exactly the case. The J_z of a pixel depends on the exact geometry! If the borders of the pixel cut one flux tube or more, than by virtue of Stokes theorem J_z is not zero. In this game, with these particular types of flux tubes, J_z will be non zero and fluctuate from pixel to pixel about zero according to the statistical probability for the contour defining the pixel to cut flux tubes, i.e., the probability to find *fractions* of flux tubes inside the specified geometry.

Consider the case when a fluxtube falls on the border of two adjacent pixels then J_z is non zero but of opposite sign in these neighbors and *continuity* fails to hold! The case where one falls on the corner of four pixels is left for the reader. In other words, in the case of Parker's distribution, J_z will be small, will exhibit statistical fluctuations about zero, look like noise and also be *non continuous*!

But this is not what we observe in general, we do observe significant and continuous signals. And we do observe, as well, remarkable cases of Parker's "gardens," areas with vanishing J_z, as we discussed above in some detail.

This may support the argument that the unresolved magnetic field is not always in the shape of individual flux tubes!

6. Conclusions

We have constructed a vertical current, in the local solar tangent plane, whose absolute value is independent of any particular azimuth disambiguation of the associated vector magnetic field. Our construction yields a smoother current than that derived for a particular disambiguation and allows one to examine the nature and correctness of the disambiguation. Thus our construction is useful in deriving meaningful disambiguations. We find that current sheets occur whose location can be dependent on the disambiguation but which we demonstrate are real.

Acknowledgements. We wish to thank K. D. Leka and an anonymous referee for a careful reading of our paper and for suggesting improvements.

References

Cuperman, S., Ofman, L., Semel, M., 1990, A&A 227, 227
Knölker, M., Grossman-Doerth, U., Schuessler, M., Weisshaar, E., 1991, Adv. Space Res. 11, 285
Landi Degl'Innocenti, E., Bommier, V., 1993, ApJ 413, L49
Lites, B. W., Low, B. C., Martínez Pillet, V., Seagraves, P., Skumanich, A., Frank, Z. A., Shine, R. A., Tsuneta, S., 1995, ApJ 446, 877
Parker, E. N., 1996, ApJ 471, 485
Rees D., Semel M., 1979, A&A 74, 1
Skumanich, A., Grossmann-Doerth, U., Lites, B. W., 1992, in: Methodes de Determination des Champs Magnetiques Solaires et Stellaires, eds. M. Faurobert-Scholl, H. Frisch, N. Mein, Observatoire de Paris, Meudon, p. 57
Skumanich, A., Semel, M., 1996, Solar Phys. 164, 291
Wiehr E., 1978, A&A 69, 279

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.