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Chirality, Helicity, and Joy's Law

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Abstract. Connections between the morphology of filaments and the global topology of the sun's magnetic field, are an important topic that seems ready for assembly into a coherent picture. We suggest that the chirality of mid-and high-latitude filaments described by Martin et al. is most easily understood if they form in evolved "Type 1" neutral lines within active region bipoles, rather than in the "Type 2" neutral lines formed at the boundaries between bipoles, where lower-latitude filaments tend to form. This interpretation removes the disagreement between filament chirality and the well-known tilt of bipolar active regions described by Joy's law, which exists if the high-latitude filaments formed at Type 2 neutral lines. Dynamical explanation of these two observed regularities probably implies quantitative understanding of the processes that govern the sign and magnitude of the α and ω-effects in a solar dynamo.

Many interesting topics have been discussed at this meeting, and it would be difficult to do them justice in the space available here. Rather, let me focus on an area where the observations, theory, and modeling seem to be at a stage where we might make progress by knitting together a unified picture from its parts. Our former colleague Spencer Weart told me in 1971, prior to leaving us for a distinguished career in history of science, that solar physicists spend too much time building bricks and not enough time building houses. So let's try to use some of the interesting new bricks presented here to build a house. From what I have heard, the magnetic geometry of filaments and prominences, their dynamics, and the information they provide on the geometry of the global solar magnetic field, seem amenable to such a construction project.

Let me begin with a few brief comments on magnetic neutral lines. The simplest kind of neutral line (I'll call it Type 1) occurs within a bipolar active region (Figure 1a). Since it occurs within a bipole, the field lines connect across it, and often they are visible as elongated dark structures (AFS, fibrils). But filaments of significant size are rarely associated with such a neutral line, at least in its early stages of evolution. A second type of neutral line occurs when two bipolar active regions appear side by side (Figure 1b, c). Here, most of the field does not seem to connect across the neutral line, instead it runs parallel to it. This is the kind of neutral line that produces most filaments in active latitudes.

In principle, the field directions on opposite sides of such a neutral line of Type 2 could be either parallel (Figure 1(b)) or anti-parallel (Figure 1(c)). But, on the sun, only the parallel configuration seems to occur (Foukal, 1971). Some thought suggests why this is so. In the active latitudes, the bipolar axes of active regions are tilted relative to the equator by a significant (10–20°) angle, so that the preceding (p) polarity lies at systematically lower latitude. This tilt, and its

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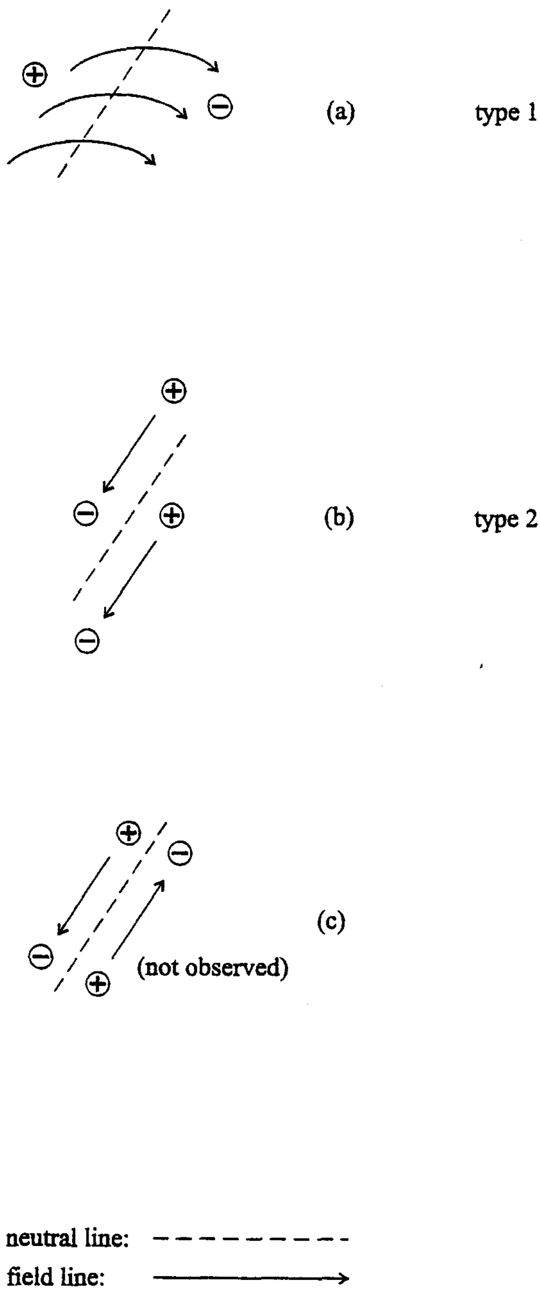

Figure 1.

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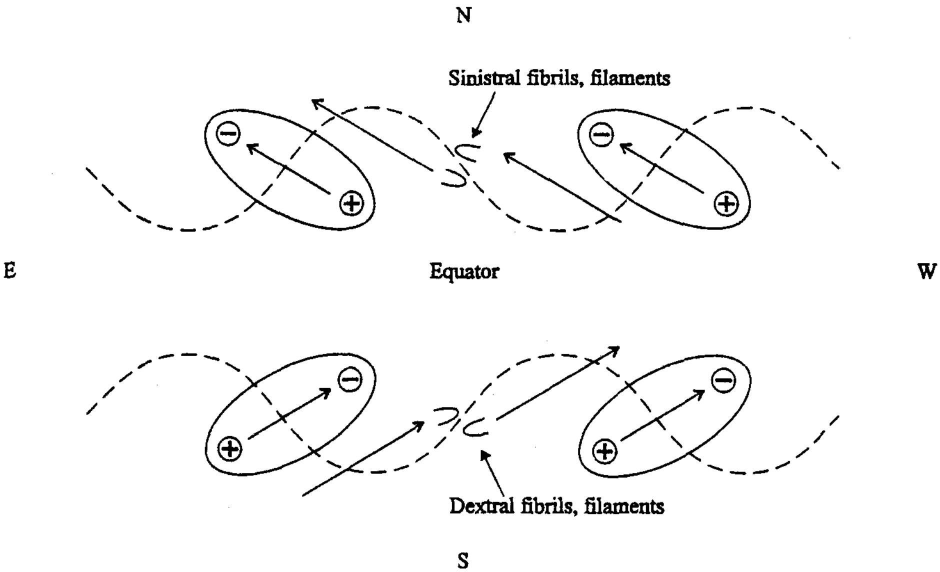
latitude dependence, is described by Joy's law, which is one of the key facts we have known about solar magnetism for almost 80 years (Hale et al. 1919).

If we draw the neutral line implied by Joy's law, including both the Type 1 neutral lines within the bipoles, and also the Type 2 lines between them, we obtain a configuration that is idealized in Figure 2. We can see from this Figure that, given the tendency to alignment of the bipolar fields, the parallel (rather than anti-parallel) configuration of the horizontal component of field on either side of the Type 2 neutral line is the only possible arrangement, provided most of the flux in such low-latitude active regions connects internally, rather than externally between active regions. The anti-parallel streaming of fibrils on opposite sides of the Type 2 neutral line indicates that is the case.

From the above, it follows that the directions of horizontal field in most filaments and filament cavities found between active regions will be the same as the field direction across the Type 1 neutral lines within the bipoles themselves. For instance, when (p) polarity is positive, filaments and channels in these latitudes will contain fields with an east-directed horizontal component in the northern hemisphere, and a west-directed component in the southern hemisphere. This polarity of the equatorial component of the prominence fields seems consistent with the Zeeman measurements on prominence magnetic fields carried out by Rust (1967) around activity minimum between cycles 19 and 20. Certainly, it would be hard to understand how the dominant direction of magnetic fields between bipolar active regions could disagree with their direction within the immediately adjacent bipoles.

Let us now investigate the relationship of the two types of neutral lines shown in Figure 2 to the "handedness" or "chirality" of filaments described by S. Martin and her co-workers (Martin et al. 1994). Her key findings are: a) quiescent filaments and filament corridors are predominantly "dextral" in the northern hemisphere and "sinistral" in the south; b) this sense of chirality is invariant from cycle to cycle (although the magnetic field polarity switches every 11 years); and c) this N-S asymmetry of chirality is not seen in active region filaments and corridors, which exhibit both dextral and sinistral behavior in both hemispheres. Let's also note that, since the observed chirality is invariant with respect to polarity switches between cycles, its essence is that the lower-latitude polarity precedes (in the direction of solar rotation) the polarity positioned at higher latitude (see Figure 3).

Now, this observation of predominantly dextral structures in the north and sinistral in the south would not be expected from the configuration at Type 2 neutral lines. As shown in Figure 2, we expect these to be mainly sinistral in the north and dextral in the south. I propose that the observed chirality amongst quiescent filaments and corridors would be easiest to understand if we assume that they form in the later stages of evolution of Type 1 neutral lines. It is well known from studies of the random walk of solar bipolar fields (e.g., Leighton 1964, Sheeley 1992) that, as the bipolar fields mature, the f-polarity migrates toward the poles while the two opposing p-polarities move toward the equator, where they eventually merge. This process occurs over time scales that enable the sun's latitudinal differential rotation to shear the field, and its sense of shearing agrees with the observed shear of neutral lines reported by Martin et al.



N.B. In this figure, we adopt p, f polarities as +ve, -ve, respectively, in the N. hemisphere.

Figure 2.

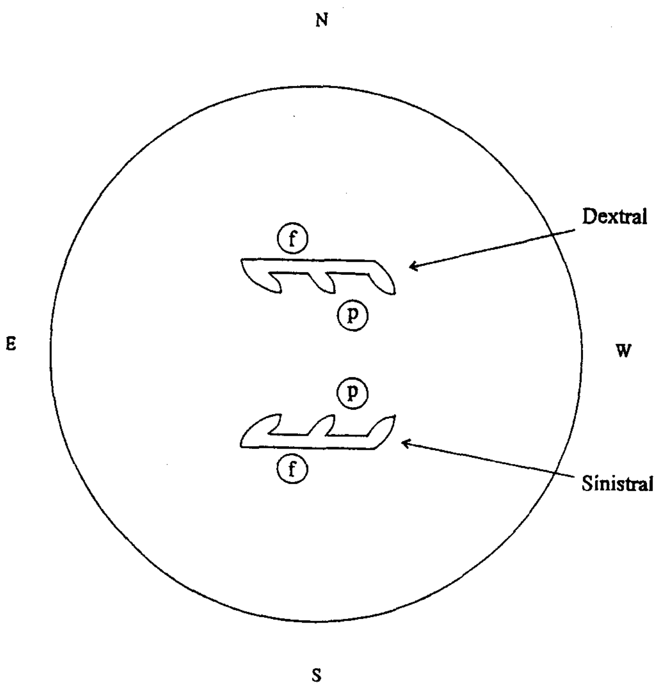


Figure 3.

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This tendency of differential rotation to produce the observed chirality in Type 1 neutral lines should act on whatever "primordial" chirality may be observed in newly emerged Type 1 neutral lines. In the simple picture illustrated in Figure 2, we would expect no primordial chirality, but emerging AFS probably exhibit non-potential character on emergence. The relative importance of the primordial and evolutionary influences, which would be related respectively to α and ω effect in dynamo language, remains to be established by observations.

In this picture, we would expect that filaments and corridors observed in active latitudes would include a mix of dextral and sinistral structures, produced at both Type 1 and 2 neutral lines. This agrees with Martin et al.'s results. By the time these neutral lines moved to the higher latitudes located at and above the upper limit of the sunspot belt, where most quiescents (and their corridors) are observed, we would expect the progressive shearing of the evolved Type 1 neutral lines to become most noticeable, leading to the observed predominance of dextral structures in the N and sinistral in the S (Figure 3). Another aspect of selection that may contribute to the predominance of one chirality in quiescents, is the progressive tendency of Type 2 neutral lines to contribute fewer filaments, in their later evolutionary stages, for reasons I return to below.

Sheeley and co-workers have developed very useful kinematical simulations of the random walk of photospheric magnetic fields, and shown that they provide sensible explanations to aspects of solar magnetic field evolution that were once considered mysterious. The extension of such models to enable tracking of the connections between magnetic flux elements has been undertaken by van Ballegoijen and his collaborators, and such models will be helpful in deciding which neutral line Type (if either) is preferred. But it is also worth placing some limits both on the new information contained in the findings on chirality (and helicity; e.g, Rust 1997), and also on what we can expect to learn about its underlying dynamics.

On the first subject, we seem to be learning that latitudinal differential rotation may be capable of impressing a systematic shear on long-lived magnetic neutral lines, and on the chromospheric and coronal structures that form along them. This is important to know, but it suggests that study of the chirality and helicity of such structures extends to higher latitudes information that is more likely to be complementary to (rather than qualitatively different from) information available in the sunspot belts from past studies of Joy's law. These studies have used much longer data bases on the motions of photospheric magnetic tracers, than are available for study of Hα structures, and they should be useful in future work on helicity also.

Regarding the second subject, we should consider that if the picture put forward above is correct then the fundamental mechanism underlying the N-S asymmetry of chirality is the same as that underlying the progressive (with time) separation in latitude of p and f polarities. It has been considered since Leighton's pioneering work that this occurs because the p polarity of a bipole tends to erupt at systematically lower latitude than its f polarity (Joy's law). Ideas have been put forward to "explain" Joy's law, (Parker 1955, Babcock 1961, Leighton 1964) based on the winding up (helicity-generation) of flux ropes by both latitudinal and radial gradients of solar rotation. But no good consensus has been reached on a quantitative model. Further study through helioseismology of sub-photospheric velocity fields, together with increasingly sophisticated models of discrete flux-tube interactions with plasma motions (e.g., d'Silva 1992), will eventually show us the way toward an explanation of Joy's law. But let's be aware that the underlying dynamical question is the same as the classical problem of defining the sign and magnitude of α-effect in dynamos, and its relative importance to ω-effect.

A determination of whether quiescent filaments form at evolved neutral lines of Type 1 rather than of Type 2 would have important implications for their dynamics, since Type 1 neutral lines favor a Kippenhahn-Schluter support mechanism, rather than the neutral sheet configuration of the Kuperus-Raadu scenario. This does not seem consistent with the Hanle observations of Leroy (1978) and Leroy et al. (1983) which indicate that quiescent prominences exhibit an "inverse" rather than "direct" magnetic geometry. However, careful interpretation of this Hanle result is necessary, and different analyses are yielding qualitatively different results (Anzer and Heinzel, 1998). An interesting explanation of how "inverse" polarity might arise at a neutral line that seems of "direct" polarity has been put forward by Martin et al. (1994). But the explanation seems to apply only to Type 2 neutral lines, not to the Type 1 variety at issue here. So there is a need to reconcile the Hanle results with the picture of Type 1 neutral lines producing quiescents.

As a final point, let me return to considering why evolved Type 2 neutral lines may produce progressively fewer filaments than in their early stage of evolution, a point I suggested earlier. The anti-parallel streaming of fibrils on either side of Type 2 neutral lines, along with the reversal of the longitudinal polarity along these neutral lines, indicates a parallel, rather than anti-parallel, direction of the horizontal field component on either side. But let's not overlook the equally interesting fact that the large vertical component of the field is oppositely directed in plagettes located in close proximity across this neutral line. This abrupt sign switch seems well suited to formation of a neutral sheet. As the Type 2 neutral line evolves the field gradients and neutral sheets will decay, making it less likely that a filament will form. This needs to be checked observationally. Clearly, we need more brick building, but let's keep working on the house at the same time.

Acknowledgments. I thank D. Rust and B. Schmieder for inviting me to present a summary at this enjoyable meeting; I apologize for missing the first two days for medical reasons. It has been a great pleasure to hear of the progress in our understanding of solar (and also stellar) prominences and to meet many old friends in the lovely surroundings of the French Alps. I also thank A. van Ballegoijen for stimulating discussions.

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