J. Astrophys. Astr. (2000) **21,** 185–192

Coronal Structures as Tracers of Sub-Surface Processes

Alexei A. Pevtsov & Richard C. Canfield, *Montana State University, Bozeman, MT 59717, U.S.A.*
**e-mail: pevtsov@physics.montana. edu*

Abstract. The solar corona – one of the most spectacular celestial shows and yet one of the most challenging puzzles – exhibits a spectrum of structures related to both the quiet Sun and active regions. In spite of dramatic differences in appearance and physical processes, all these structures share a common origin: they are all related to the solar magnetic field. The origin of the field is beneath the turbulent convection zone, where the magnetic field is not a master but a slave, and one can wonder how much the coronal magnetic field "remembers" its dynamo origin. Surprisingly, it does. We will describe several observational phenolmena that indicate a close relationship between coronal and sub-photospheric processes.

Key words. Sun—solar corona—magnetic field—helicity.

1. Introduction

The corona – a tenuous portion of the solar upper atmosphere – was observed as early as 1063 BC (Golub & Pasachoff 1997). The real surprise came in 1939, when Grotrian discovered that the coronal gas is a few million degrees hotter than the underlying photosphere and chromosphere. Since then, many models of the coronal heating have been proposed (e.g. Mandrini, Démoulin & Klimchuk 2000); but the question "how does the corona get so hot?" is still open. Considering the possible processes that can affect the appearance of coronal structures, one can divide them into two categories: ones that take place above the photosphere and require no connection with the sub-photospheric layers and those that, even if they occur in the corona, may have close ties with sub-photospheric processes. Below we examine several coronal phenomena and explore their sub-photospheric origin.

2. The hemispheric helicity rule in the solar corona

2.1 *Sigmzoidal loops of solar active regions*

Soft X-ray images of the solar corona (Fig. 1), routinely observed by Yohkoh, give numerous examples of bright coronal structures reminiscent of the letters S and inverse-S. Such sheared structures, discovered in earlier Yohkoh observations (e.g. Acton *et al.* 1992), were collectively named *sigmoidal* loops by Rust & Kumar

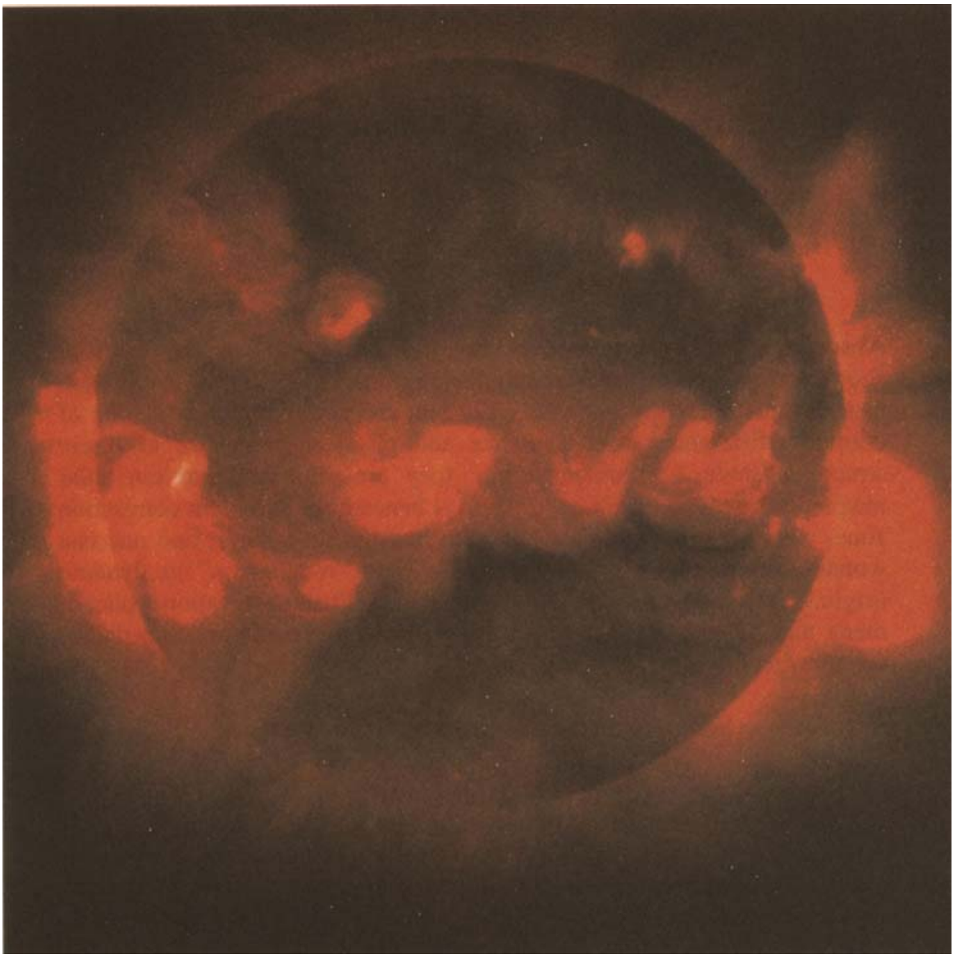

Figure 1. Yohkoh soft X-ray telescope image showing sigmoidal coronal loops.

(1996). There is a close similarity in appearance between the shape of sigmoidal loops and linear force-free field lines projected on the image plane. Pevtsov, Canfield & McClymont (1997) compared the value of α ($\nabla \times B = \alpha B$) computed independently for ~ 100 active regions using photospheric magnetograms and coronal images and found good agreement between the photospheric and coronal α values. They interpret their results as an indication of field-aligned electric currents flowing from below the photosphere through to the corona. The currents may be the result of near-surface sunspot proper motions (e.g. van Driel Gesztelyi *et al.* 1997) or may be of subphotospheric origin (Leka *et al.* 1996).

The distribution of sigmoidal loops shows a clear hemispheric dependency: S-shaped loops are typical in the southern hemisphere, and inverse-S loops prevail in the northern hemisphere. This dependency is the coronal signature of the hemispheric helicity (chirality) rule (for a review, see Pevtsov & Canfield 1999). According to the rule, magnetic fields in the northern (southern) hemisphere tend to have negative (positive) helicity. Table 1 shows the distribution of sigmoidal loops for solar cycles

Table 1. Distribution of coronal sigmoids by hemisphere.

	Cycle 22 (1991–95)		Cycle 23 (1997–98)	
	Forward S	Inverse S	Forward S	Inverse S
Northern Hemisphere	41%	59%	29%	71%
Southern Hemisphere	68%	32%	87%	13%

22 and 23. Both cycles exhibit the same hemispheric preference in chirality (sign of helicity), in agreement with the photospheric vector magnetographic data (e.g., Bao & Zhang 1998). Both strong magnetic fields of active regions (e.g. Pevtsov, Canfield & Metcalf 1995) and weak magnetic fields on large scales (Pevtsov & Latushko 2000) follow the same hemispheric asymmetry. The rule has also been observed in chromospheric filaments, sunspot penumbra filaments, superpenumbrae, and even the interplanetary magnetic field (Richardson 1941; Martin, Bilimoria & Tracadas 1994; Bieber, Evenson & Matthaeus 1987).

There are two important properties of the hemispheric helicity rule that are critical for its understanding.

- The rule is global and independent of the solar cycle. The same sign-asymmetry. was observed during cycles 20, 21, 22 and 23 (e.g. Seehafer 1990; Pevtsov, Canfield & Metcalf 1995; Bao & Zhang 1998; Hagyard & Pevtsov 1999). Solar features of different origin and size exhibit the same hemispheric preference in their helicity. Thus, it seems highly unlikely, that the small scale (local) processes such as, say, sunspot proper motions can explain this general tendency.
- The rule is not very strong, only 60–70% of all active regions follow it. Mechanisms that depend strongly on the solar hemisphere (e.g., Coriolis force, differential rotation) should result in much stronger hemispheric dependency. Hence, although such mechanisms may play a role, they are not the only ones of importance.

Several different mechanisms can in principle explain the hemispheric helicity rule (Table 2), but most of them fail to explain specific details. For example, differential rotation produces the correct sense of shear in coronal loops. However, it will also introduce twist of opposite sign into the magnetic flux tubes, in disagreement with observations (e.g. Pevtsov & Canfield 1999). The Coriolis force acting on the apex of a magnetic flux tube rising through the convection zone will deflect it. This action will produce the correct hemispheric asymmetry in twist and writhe, but the resulting

Table 2. Mechanisms of the hemispheric helicity rule.

Mechanism	Hemispheric helicity rule?
Near surface proper motions	No
Differential rotation	No (wrong sign of twist)
Coriolis force	Yes
Sigma-effect	Yes
CZ mean-field dynamo	No (wrong sign)
Overshoot region dynamo	Yes

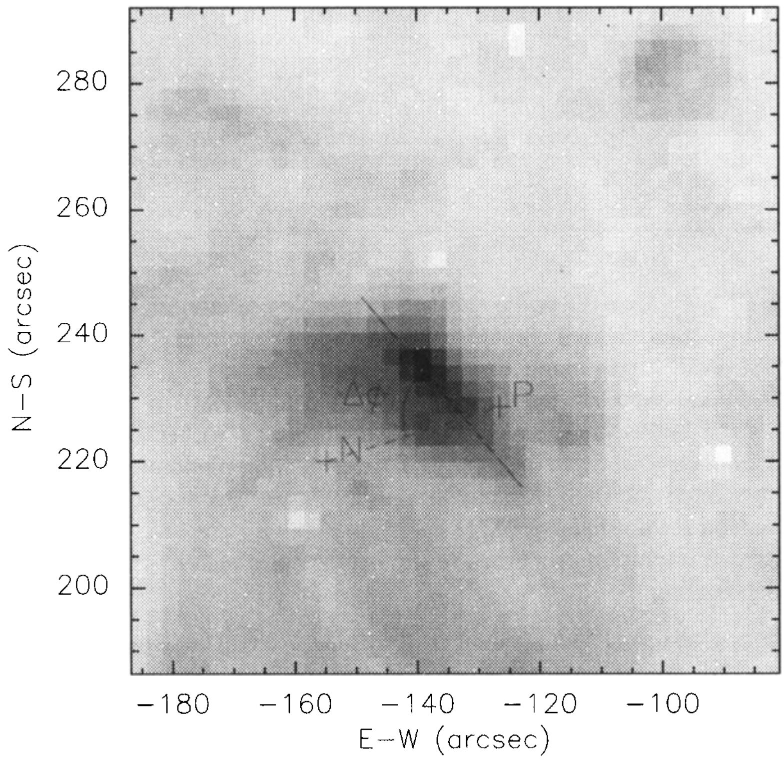

Figure 2. Example of X-ray bright point (halftone) and corresponding magnetic bipole (letters N and P connected by dashed line). Symbols N and P indicate negative and positive polarities and $\Delta\Phi$ is misalignment between magnetic bipole (dashed) and XBP orientation (solid line).

hemispheric preference should be much stronger than observed. Two mechanisms can correctly explain the hemispheric helicity rule: an interaction between magnetic flux tubes and turbulent convection (Σ-effect, Longcope, Fisher & Pevtsov 1998) and an overshoot region dynamo (Gilman & Charbonneau 1999). However, the expected contribution of the overshoot region dynamo is significantly less than that of the Σ-effect (Longcope *et al.* 1999).

2.2 *X-Ray bright points*

Another coronal feature – X-ray bright points (XBP) – may also follow the hemispheric helicity rule, although their hemispheric dependency is not as clear as for the sigmoidal loops of active regions. Fig. 2 shows an example of XBP which is tilted relative to the underlying bipole. In fact, many XBPs show such misalignment of their axes (Kankelborg *et al.* 1996). Longcope (1998) developed a topological model to describe the XBP phenomena as the result of magnetic reconnection. between two independent flux systems. In his model, reconnection and energy deposit occur along a separator field line, and the separator appears as the XBP loop in the corona. The misalignment between the X-ray bright point and the magnetic

Table 3. X-ray bright point misalignment fraction by hemisphere.

Hemisphere	All data (285 XBPs)		Strongly elongated only (154 XBPs)	
	Positive	Negative	Positive	Negative
Northern	42%	58%	36%	64%
Southern	54%	46%	50%	50%

bipole depends on the mutual orientation of the large-scale ambient magnetic field and the reconnecting bipole. On the other hand, one can also consider XBP to be a single bipolar active region loop. If the loop carries electric currents it may appear to be sheared, similar to the sigmoidal loops of active regions (e.g. Fig. 1). If the electric currents (magnetic field twist) in the XBPs follow the same hemispheric helicity rule as the active regions, the orientation of the XBPs should also exhibit the hemispheric dependency. In Longcope (1998) model XBPs are formed via random encounters of two independent flux systems, and hence, should exhibit no hemispheric preference in their orientation relative to the bipole axis. Recently, Kankelborg et al. (1999) surveyed the SOHO-EIT and MDI data set and identified 764 X-ray bright points. They analyzed 285 XBPs and found that magnetic bipoles have no preference either in their polarity orientation (no Hale polarity rule, Hale & Nicholson 1938) nor in their tilt relative to the equator (no Joy's law, Zirin 1988). However, the orientation of XBPs relative to the axis of the associated bipole shows a weak hemispheric preference, which is in agreement with the hemispheric helicity rule (Table 3).

Thus, it seems that at least some XBPs do follow the hemispheric rule and hence can be explained in the framework of a flux tube model. However, a more restricted subset, including only XBPs with strongly elongated shape, shows no hemispheric preference in the southern hemisphere (Table 3). Clearly, the presence (or absence) of the hemispheric helicity rule in orientation of the X-ray bright points needs further investigation, perhaps separately for XBPs that are associated with reconnection of existing magnetic fluxes, as distinguished from those associated with emerging/submerging bipoles.

3. Large scale patterns in the corona

The topology-of the magnetic field is one of the most important factors determining the appearance of coronal structures. There is good correlation between unsigned magnetic flux and X-ray brightness of coronal loops (e.g. Fisher et al. 1998). Thus, it is not surprising that the brightest coronal areas are related to the active regions. However, some coronal features persist much longer than individual active regions. Fig. 3 shows a stackplot of Yohkoh synoptic maps for 8 solar rotations. One can clearly see several areas of enhanced coronal activity which persist for many solar rotations. Sandborgh et al. (1998) used full disk soft X-ray telescope images from Yohkoh to identify boundaries of coronal flux systems. A flux system was defined as a bright closed area (not a coronal hole, for instance) with coronal loops connecting sub-areas inside the system and no loops crossing its outer boundary. The shape of the loops (sigmoidal structure) was used to determine the chirality of each flux system.

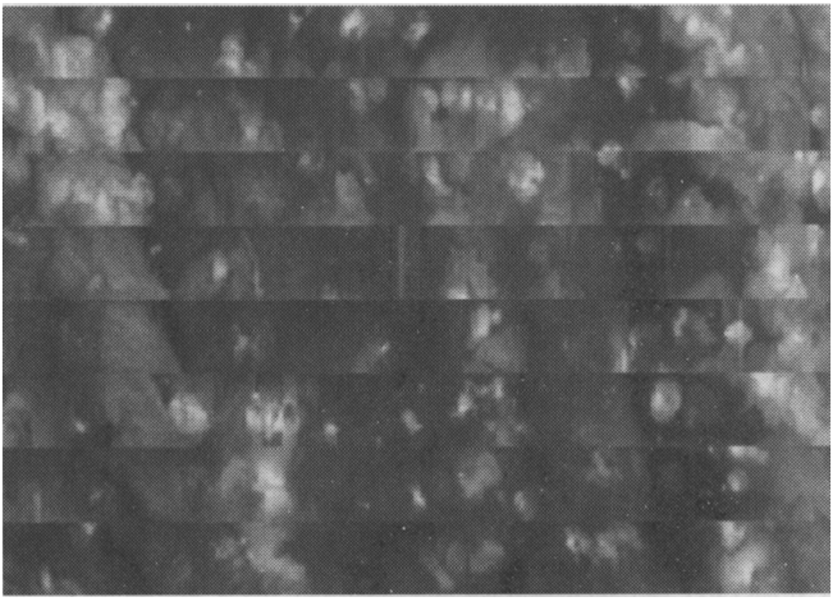

Figure 3. Stackplot of Yohkoh synoptic maps for 8 solar rotations (1851-1858). Each strip covers 360° in Carrington longitude and 0-20° in latitude in the northern hemisphere. Longitude runs from left (0°) to right (360°).

Table 4. Coronal flux systems observed in 1991–1992.

	Extension in		Lifetime		
No.	Latitude	Longitude	First CRN	(rotations)	Chirality
1	−40° to −20°	300° to 360°	1851	3	positive
2	−20° to 0°	90° to 120°	1851	3	complex
3	−40° to −5°	60° to 90°	1852	3	negative
4	−40° to −10°	140° to 180°	1852	3	negative
5	−40° to 0°	320° to 20°	1854	4	negative
6	−30° to 0°	90° to 130°	1855	3	zero
7	−10° to 40°	320° to 20°	1856	3	negative
8	0° to 30°	240° to 280°	1857	5	negative
9	−15° to 15°	20° to 40°	1858	4	positive
10	0° to 20°	300° to 340°	1858	3	positive

Table 4 lists size, a lifetime and chirality of several flux systems found by Sandborgh et al. (1998) during 11 consecutive solar rotations.

The coronal flux systems listed in Table 4 are significantly larger than a typical active region (up to 50° in latitude and 60° in longitude, flux system No. 7). They persist for up to 5 solar rotations (e.g. No. 8) maintaining the same chirality.

Large scale structures of similar size have been observed in magnetic fields (e.g. Ambroz 1992) and photospheric flows (Hathaway et al. 1998). Close similarity in size and lifetime suggests a common origin for all these different structures. However, without co-temporal comparison of the features, their relationship remains questionable.

Transequatorial loop systems (TLS) connecting independent active regions across the solar equator are another example of large-scale organization in the corona. Pevtsov (2000) studied the distribution of TLS observed during 1991–1998 and found that such loops are formed only in selected areas on the Sun. Such areas persist for several consecutive solar rotations and exhibit no significant difference in rotation rates between its northern and southern hemisphere ends. The majority of TLS exhibit sheared loops, implying the presence of electric currents. As a rule, magnetic fields in areas connected across the equator have the same chirality, which suggests continuity of electric currents flowing between connected active regions.

The coronal flux systems and TLS can be seen as coronal counterparts of complexes (nests) of activity, previously observed in the distribution of solar active regions (e.g. Brouwer & Zwaan 1990). The size and persistence of the activity nests can not be easily explained by photospheric processes alone and may, for instance, indicate an asymmetry in the solar dynamo and/or large-scale persistent pattern inside the convection zone (e.g. giant cells).

Acknowledgements

This work was supported by NASA through SR&T grant NAG5–6110. A.A.P. would like to acknowledge partial travel support by the International Astronomical Union to attend the IAU Colloquium 179 in Kodaikanal, India.

References

Acton, L. W., et al. 1992, Science, **258,** 618.

Ambroz, P., 1992, in *The Solar Cycle,* (ed.) K. Harvey (San Francisco: ASP), **27,** 35.

Bao, S., Zhang, H. 1998, *Astrophys. J.,* **496,** L43.

Bieber, J. W., Evenson, P., Matthaeus, W. 1987, *Astrophys. J.,* **315,** 700.

Brouwer, M. P., Zwaan, C. 1990, *Solar Phys.,* **129,** 221.

Fisher, G. H.; Longcope, D. W., Metcalf, T. R., Pevtsov, A. A. 1998, *Astrophys. J.,* **508,** 885.

Gilman, P. A., Charbonneau, P. 1999, in *Magnetic Helicity in Space and Laboratory Plasmas,* (eds.) M. Brown, R. Canfield & A. Pevtsov, vol. **111** of Geophysical Monographs Series (Washington, D.C.: American Geophysical Union).

Golub, L., Pasachoff, J. M. 1997, *The Solar Corona* (Cambridge: Cambridge Univ. Press).

Hagyard, M., Pevtsov, A. 1999, *Solar Phys.,* **189,** 25.

Hale, G. E., Nicholson, S. B. 1938, *Magnetic observations of sunspots, 1917–1924...* (Washington, D.C.: Carnegie institution of Washington)

Hathaway, D. H., Bogart, R. S., Beck, J. G. 1998, *Eos Trans. AGU,* **79**(17), S281.

Kankelborg, C. C., Walker, II, A. B. C., Hoover; R. B., Barbee, T. W. J. 1996, *Astrophys. J.,* **466,** 529.

Kankelborg, C. C., Nelson, J., Longcope, D. W., Pevtsov, A. A. 1999, *BAAS,* **194,** 1601.

Leka, K. D., Canfield, R. C., McClymont, A. N., van Driel-Gesztelyi, L. 1996, *Astrophys. J.,* **462,** 547

Longcope, D. W. 1998, *Astrophys. J.,* **507,** 433.

Longcope, D. W., Fisher, G. H., Pevtsov, A. A. 1998, *Astrophys. J.,* **507,** 417.

Longcope, D. W., Linton, M. G., Pevtsov, A. A., Fisher, G. H., Klapper, I. 1999, in *Magnetic Helicity in Space and Laboratory Plasmas,* (eds.) M. Brown, R. Canfield & A. Pevtsov, vol. **111** of Geophysical Monographs Series (Washington, D.C.: American Geophysical Union), 93.

Mandrini, C. H., Demoulin, P., Klimchuk, J. A. 2000, *Astrophys. J.,* **530,** 999.

Martin, S. F., Bilimoria, R., Tracadas, P. W. 1994, in *Solar Surface Magnetism,* (ed.) C. J. Rutten & C. J. Schrjiver (Dordrecht: Kluwer Academic Publishers).

Pevtsov, A. A. 2000, *Astrophys. J.,* **531,** 553.

Pevtsov, A. A., Canfield, R. C., McClymont, A. N. 1997, *Astrophys. J.,* **481,** 973.

Pevtsov, A. A., Canfield, R. C., Metcalf, T. R. 1995, *Astrophys. J.,* **440,** L109.

Pevtsov, A. A., Canfield, R. C. 1999, *Magnetic Helicity in Space and Laboratory Plasmas,* (ed.) M. Brown, R. Canfield & A. Pevtsov, vol. **111** of Geophysical Monographs Series (Washington, D.C.: American Geophysical Union) 103.

Pevtsov, A. A., Latushko, S. M. 2000, *Astrophys. J.,* **528,** 999.

Richardson, R. S. 1941, *Astrophys. J.,* **93,** 24.

Rust, D. M., Kumar, A. 1996, *Astrophys. J.,* **464,** L199.

Sandborgh, S. C., Canfield, R. C., Pevtsov, A. A. 1998, *Eos Trans. AGU,* **79**(17), S285.

Seehafer, N. 1990, *Solar Phys.,* **125,** 219.

van Driel-Gesztelyi, L., Csepura, G., Schmieder, B., Malherbe, J. M., Metcalf, T. 1997, *Solar Phys.,* **172,** 151.

Zirin, H., 1988, *Astrophysics of the Sun* (Cambridge: Cambridge University Press).