UBIQUITOUS OPEN MAGNETIC FIELD LINES IN THE INNER CORONA

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Abstract. If density structure reflects magnetic field lines, it is possible to deduce information on coronal magnetic fields from density measurements. The purpose of this paper is to summarize the observational evidence for ubiquitous open magnetic field lines in the inner corona from density measurements. Based on both global and filamentary structures, these density measurements explain the unexpected predominance of the radial component of coronal magnetic field discovered in polarimetric observations over three decades ago.

INTRODUCTION

It has become increasingly clear that the Sun's magnetic field is the main source of structure and variability in the solar atmosphere, yet the magnetic field measurements we have are essentially only those of the photosphere. Our knowledge and understanding of the coronal magnetic field has instead come from two indirect sources. Assuming that density reflects magnetic field, we have gleaned the Sun's magnetism from density structure observed in white-light images. Polar plumes, the small-scale, faint, thin, hair-like structures resembling the lines of force of a bar magnet, suggest that polar coronal holes are the source of open field lines (1). The abundance of photospheric magnetograms made on a routine basis has led solar astronomers to extrapolate photospheric measurements into the solar corona using the so-called source surface magnetic field models. Magnetic field modeling represents the other source of information on coronal magnetic fields. Results obtained from these models reinforce the impressions from the density structure of white-light pictures by showing that open magnetic field lines emanate from polar coronal holes, while closed fields are associated with coronal streamers (2). These models also represent the most widely used tool for tracing the distant solar wind observed by spacecraft back to its source at the Sun (3).

For nearly five decades, radio occultation measurements based on a wide variety of radio propagation and scattering phenomena have yielded a wealth of information on coronal density. The extensive but disparate results have only recently been combined to form a unified picture of coronal structure (4). For a long time, progress with these measurements was stymied by the paradigm that the observed density variations were caused solely by turbulence convected along with the solar wind; fine-scale structures which were aligned with the magnetic field and rotated with the Sun were not considered. In the meantime, improvements in spatial resolution and the processing of coronal images revealed increasingly smaller structures that filled the solar corona. Coronal density studies benefited relating of structure observed by the two major remote sensing tools, radio occultation and white-light measurements (5). Synergistic comparisons of the results from these two observing techniques has since produced significant advances in our understanding of the distribution of density structure in the corona, and by implication, coronal magnetic fields.

Knowing where open magnetic field lines prevail in the inner corona is fundamental not only for understanding the Sun's magnetism, but also for determining how the distant solar wind directly probed by interplanetary spacecraft connects to the Sun. The purpose of this paper is to summarize the evidence from density observations that ubiquitous open field lines permeate the entire inner corona rather than being restricted to coronal holes.

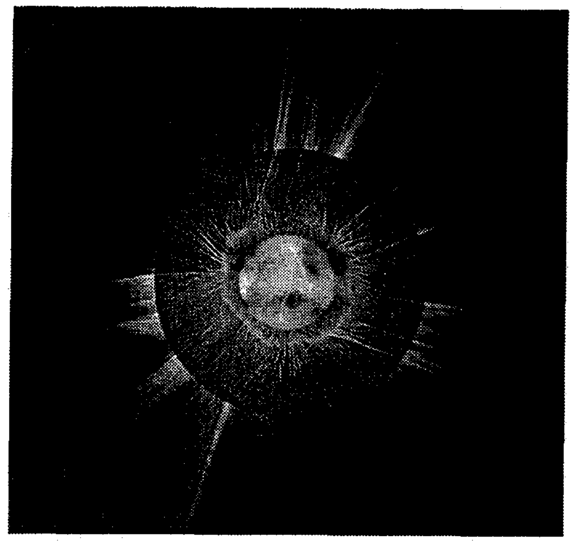
GLOBAL IMPRINT OF THE SUN

When density in the outer corona observed by ranging and white-light measurements was compared with that of white-light closest to the Sun (large-scale or global imprint of the Sun), a completely unexpected result was found. Hidden in the tenuous dark regions of the outer corona beyond the closed-field regions of the inner corona, and away from the tapered bright coronal streamers, was the global imprint of the Sun (4). How could such a major connection have escaped detection for so long?

There are two reasons. First, measurements of the outer corona may not have been sensitive enough to detect the tenuous coronal hole regions. Second, not evident in the white-light pictures because of the steep decline in density with radial distance, but brought to light in the quantitative profiles, is the fact that density changes by one to two orders of magnitude from streamer to coronal hole in the outer corona, but only by a factor of 2–3 in the inner corona (4). These differences reflect the fact that density falls off more slowly in closed-field streamers than in open-field coronal holes. The bright streamers and their conspicuous high-contrast boundaries overwhelm the tenuous and relatively low-contrast (factor of 2–3) imprint of the Sun, even when the measurements are sensitive enough. Consequently, the streamer boundaries in the outer corona are easily mistaken for the polar coronal hole boundaries, and for over two decades, impressions from white-light images have misled us into believing that polar coronal holes diverged and expanded superradially into interplanetary space (6).

Instrumental sensitivity is not an issue with direct measurements of the polar solar wind made by Ulysses. Conditioned by three decades of in situ measurements confined to near the ecliptic plane where streamers reside, we have been accustomed to seeing large variations in the solar wind plasma. At high latitude, Ulysses found a wind exhibiting relatively small daily variations in all of its solar wind properties (7, 8). Since polar coronal holes were thought to be structureless (9), it was natural to conclude that the fast wind probed by Ulysses must have come from the diverging polar coronal holes. Comparisons with simultaneous white-light measurements of the inner corona have shown that the factor of 2 daily density variations of the fast wind observed by Ulysses beyond 2 AU were actual vestiges of the global imprint of the Sun (10, 11).

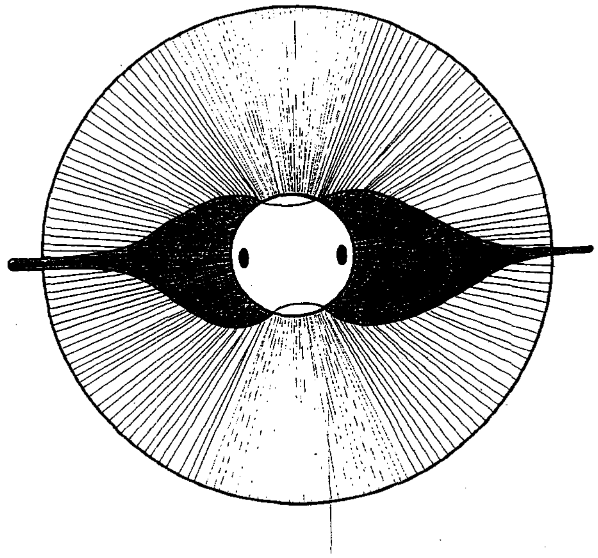
The global imprint of the Sun found in the outer corona and distant solar wind could only have been transported there by ubiquitous and approximately radial open field lines emanating from both the quiet Sun and coronal hole. Is there any observational evidence for these open fields? The answer is yes, in observations of small-scale density structures.

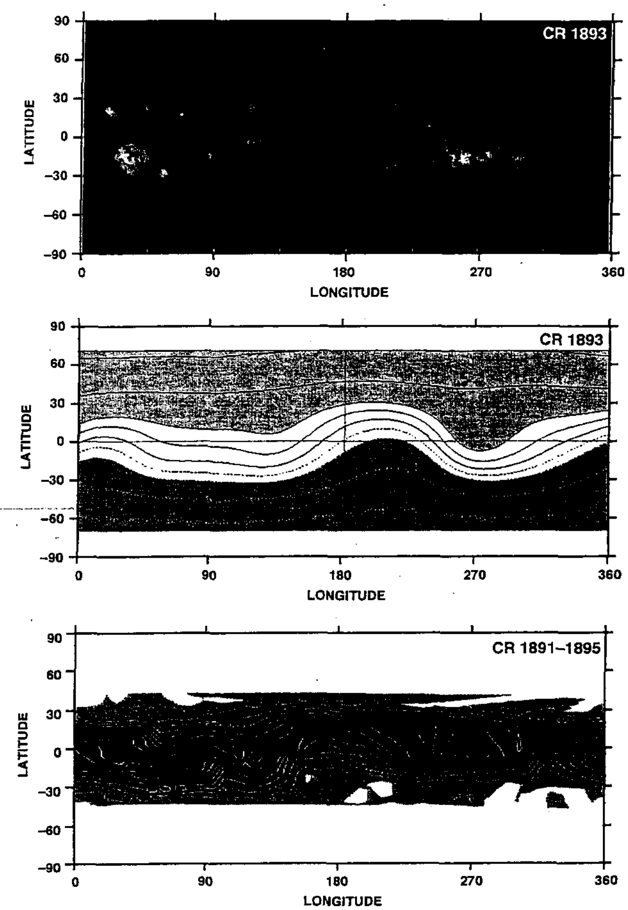


SMALL-SCALE STRUCTURES

To anyone who has observed a total solar eclipse in person, the corona looks richer than that captured by a photograph. Three decades ago, Serge Koutchmy started processing eclipse pictures by enhancing their density gradients. The result was images that not only showed the boundaries of the large-scale streamers, but many of the small-scale filamentary and raylike structures seen by the naked eye (Figure 1). Why do unprocessed and processed pictures give such different impressions? The answer lies in the fact that small-scale (filamentary or striated) structures are low-contrast features. They are difficult to see in unprocessed pictures not because they are faint, but because their density levels are not significantly different from the background level. They are revealed in the processed images because of their steep density gradients. Such structures are more readily observed by eclipse watchers because the human eye is rather adept at distinguishing low-contrast features.

The small-scale structures revealed in white-light pictures represent those individual structures that have the largest density gradients. The corona is actually filled with





many more structures that are not seen in the images, either because they are smaller than the spatial resolution or because their density gradients are weak. Highly sensitive and highly sampled Doppler measurements detect *all* of the structures (5). They show that there is a continuum of filamentary structures whose scale sizes are described by an inverse power-law spectrum with the smallest filamentary structures being about 1 km at the Sun, more than two orders of magnitude smaller than those observed in white-light images (10). It is these unseen filamentary structures in white-light images that collectively carry the imprint of the Sun into interplanetary space. Do we have any evidence from these ubiquitous but hidden filamentary structures themselves that they, like the imprint they transport, extend radially from the Sun? The answer is yes, if we look at their density gradient

DENSITY GRADIENTS

Doppler measurements show that density gradients across the fine-scale filamentary structures are lowest in the radial extension of coronal holes, slightly higher in the radial extension of the quiet Sun, and highest over active regions of the Sun. Solar eclipse measurements reveal that the density gradients of the filamentary structures are also highest in the brightest regions of the inner corona. Density gradients, therefore, characterize the small-scale filamentary structures by their source region at the Sun, and demonstrate that the structures extend roughly radially outwards from the Sun, carrying with them the imprint of the Sun (Figure 2) (13).

Some of the individual open structures that emanate from the active regions are evident in images processed to enhance density gradients (Figures 1), and are a surprise since active regions are usually thought of as being closed field regions. These open field lines can be expected to carry some imprint of the active regions and hence their underlying sunspots into the solar wind.

It is not possible to image the distant solar. wind, but shown in Figure 3 is a synoptic map of solar wind velocity constructed based on Ulysses measurements over a period /of 5 solar rotations (3). Solar wind flow would be expected to be slowest over the active regions where the closed fields are strongest. The interaction between fast and slow wind changes the distribution of velocity as the solar wind flows away from the Sun, but the islands of slowest velocity observed by Ulysses are unmistakably the imprint of the active regions in the distant solar wind.

CORONAL MAGNETIC FIELD

Although there are no measurements of magnetic field strength, magnetic field direction was inferred from polarization measurements of the corona nearly thirty years ago (14). Such measurements showed a coronal magnetic field that was unexpectedly predominantly radial. Unexplained by magnetic field models that extrapolated photospheric fields into the corona, these results were largely forgotten until now (15). It is clear that the radial extension of the density imprint of the Sun, the ubiquitous filamentary structures that are radially oriented, and the predominance of radial magnetic fields are all manifestations of the same phenomenon (15), reinforcing the notion that coronal density reflects coronal fields.

Because density associated with closed structures is significantly higher than that of open structures, white-light images over-emphasize streamers and their evolution at the expense of the radial extension of open structures. Closed and open structures are treated more equally by polarization measurements, as well as by white-light images processed to enhance density gradients. These latter images portray the truer picture of magnetic field topology. Although streamers are mixed regions of open and closed fields, open fields far outnumber closed fields.

Streamers are shaped by the non-radial component of coronal magnetic field that appears to be associated with the strong photospheric fields that vary significantly with solar cycle. On the other hand, the radial field originating from all over the Sun seems to be the coronal counterpart of the weak photospheric fields that have a weak solar cycle dependence (16). The strong photospheric field is thought to be produced by the classical dynamo, while the weak field by the fast dynamo (17). Ironically, streamers taper to the heliospheric current sheet which occupies only a small volume of interplanetary space. In the distant solar wind encompassing the heliospheric current sheet there is evidence for both the non-radial streamer field and the radially evolved imprint of the Sun (Figure 3).

CONCLUSIONS

The new results on coronal magnetic fields are a consequence of unifying extensive density measurements made over three decades by white-light, radio occultation and in situ measurements. The density measurements measurements that ubiquitous open fields permeate the solar corona, there is a need to take a closer look at the assumptions of these magnetic field models to better understand why they seem to be missing a major component of the coronal magnetic field.

ACKNOWLEDGMENTS

This paper describes research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Support for S.R. Habbal was provided by NASA grant NAG5-6215.

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