Coronal Magnetic Field Models

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A review of the development of coronal magnetic field models is presented. Each model's assumptions are discussed with reference to their validity within the solar corona. It is pointed out how remarkable it is that electrodynamics is applicable on a large scale as well as on the small scale from which it originated.

Observations by spacecraft and solar magnetographs over the past decade have led to a deeper understanding of coronal magnetic fields. Connections between solar and interplanetary fields represent the largest scale detailed tracing of field lines achieved by man. It is remarkable that the concept of a magnetic field line, deduced from the motion of compass needles' being deflected by coils of wire and similar experiments, on a rather small scale can apply so rigorously over an astronomical scale. The correlations observed further establish the utility of magnetic field lines and their transport in a 'frozen' state by a highly conducting plasma. Although physical theorists (see Wheeler and Feynman, 1945) have attempted to explain electromagnetic phenomena without the existence of electric and magnetic fields through the use of 'action-at-a-distance' effects, it is very difficult to see how the line splitting in a solar magnetograph could be correlated in these theories with the flux-gate magnetometer's frequency response without the superb aid of a solar, coronal, and interplanetary magnetic field.

This paper reviews the development of the coronal magnetic field models. These models stem from the suggestions by *Chapman* [1943] and *Gold* [1956] that the magnetic field in the vicinity of the sun could, in principle, be calculated. Large digital computers and routine detailed solar magnetograms now make these calculations technically feasible. Knowledge concerning the coronal field would be useful in disciplines other than coronal physics, cosmic ray physics and solar wind theory, for example.

One of the main problems concerning the coronal magnetic field is the lack of direct coronal field measurements, from which lack comes the desire to calculate the field from theory and observations.

The first calculations of the coronal magnetic field were made by *Schmidt* [1964] and *Rust* [1966]. Schmidt used the field calculations above active regions to deduce energy changes associated with flares. *Rust and Roy* [1970] showed that the forms of loop prominence material coincided with the shape of magnetic field lines computed above an active region. Figure 1 shows a comparison of the computed coronal magnetic field and the observed coronal structures in the green line of iron. It is interesting to note that they find the best agreement following flares, when the magnetic structure may have relaxed to a potential configuration.

The potential solution of Schmidt assumes that $\nabla \times \mathbf{B} = 0$ above the photosphere. *Harvey* [1969] discusses many solutions to the following more generalized equation: $\nabla \times \mathbf{B} = (4\pi j/c) = \alpha \mathbf{B}$, where it is assumed that the current flows parallel to the field. *Kotov* [1970] has made vector observations of the field and finds that substantial (inferred) currents flow along the field near active regions. Harvey's solutions appear to restrict the generality of the observed conditions to constant α, simple geometric configurations, axial symmetry, etc. Nevertheless, the class of solutions obtained provides interesting insight into the form of the magnetic field.

Newkirk et al. [1968] extended the ideas of Schmidt by allowing the potential solution to be valid over the entire sun rather than just above active regions. They utilized a Legendre expansion of the field, and by restricting the principle Legendre index to 9 the problem became tractable. This treatment is similar to the expansion employed in geomagnetic work [*Chapman and Bartels,* 1940]. They compared their calculations with the structure of the corona observed at eclipse. The results they obtained were encouraging in the inner corona at distances less than a solar radius above the photosphere.

Schatten et al. [1968] developed a model for the coronal and interplanetary magnetic fields in an attempt to understand how interplanetary sectors arose from the complex field patterns on the sun. The solution was similar to the previous work except that currents were allowed in the corona which would 'open' the solar field into the interplanetary environment.

The need for coronal electric currents in the magnetic models may be seen from the following arguments. If the magnetic field from the sun extended into interplanetary space, with the vacuum electromagnetic equations applying (a 2-G photospheric dipole field extending into interplanetary space as the inverse radius cubed), the interplanetary magnetic field near earth would be about 2×10^{-7} G, rather than the 5×10^{-5} G observed, and the field direction would be vastly different. Thus there is a need for electric currents in the corona and interplanetary space to enhance the extended photospheric magnetic field.

The observed interplanetary magnetic field of 5×10^{-5} G is more consistent, with the photospheric magnetic field extending into space very nearly as the inverse radius squared. This is consistent with the *Parker* [1958] Archimedian spiral model of the interplanetary magnetic field. In this model, currents in the highly conducting solar wind plasma cause the magnetic field to be nearly radially oriented near the sun and become more azimuthally oriented near earth due to the effects of solar rotation and the radially flowing solar wind. *Ness and Wilcox* [1964] observed the interplanetary magnetic field near earth and found it to be consistent on the average with Parker's spiral model. For a review of the properties of the interplanetary magnetic field see *Wilcox* [1968], *Ness* [1970], or *Schatten* [1971*a*].

Figure 2 is a schematic based upon the model illustrating the extension of the photospheric magnetic field into space (not to scale). Near the sun, magnetic loops similar to coronal arches

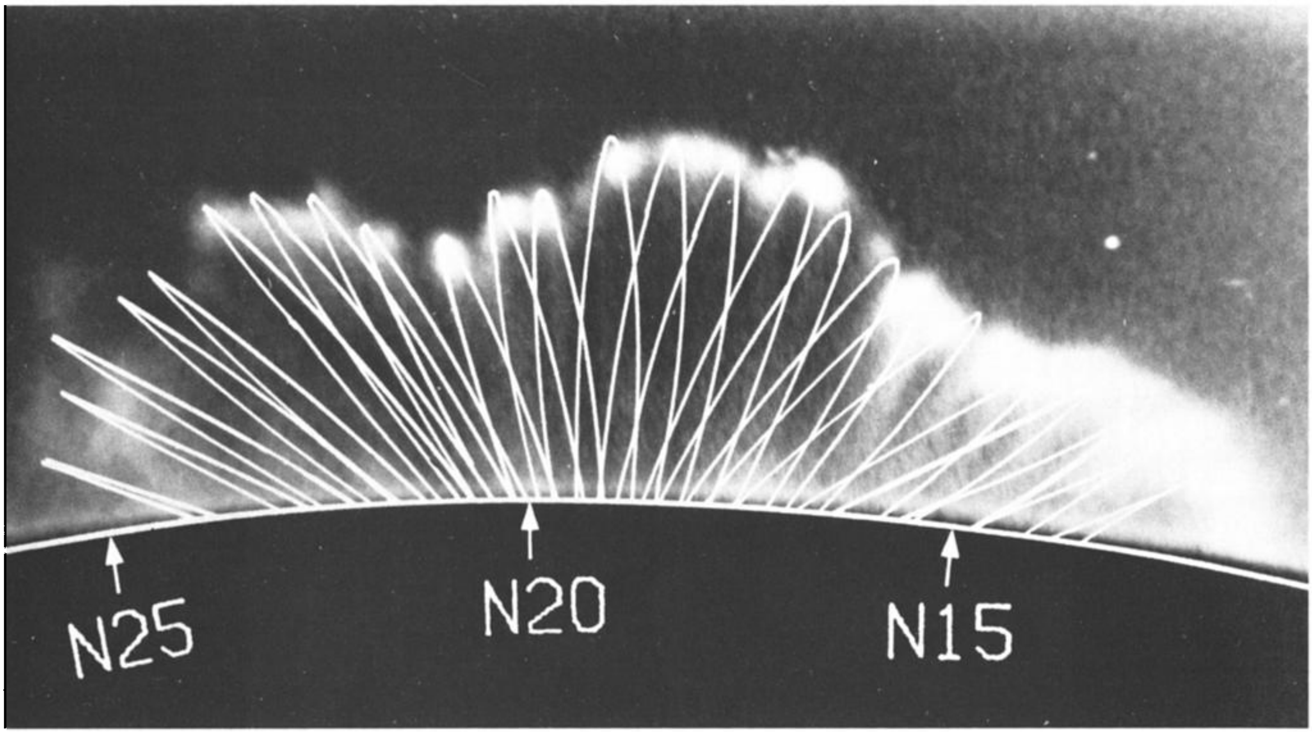

Fig. 1. A comparison of the computed magnetic field lines above the limb of the sun and observations of the coronal structure in the iron green line equal to 5303 Å. The footpoints of the field lines have been selected so as to enhance the comparison.

can form. Further from the sun the fields become radially oriented, as is the general direction of streamers and rays. Open field lines generally occur from large-scale unidirected field regions on the sun, unipolar magnetic regions. *Bumba and Howard* [1965] discuss the occurrence of these regions on the sun, and *Wilcox* [1968] discusses the relationship between them and interplanetary magnetic sectors.

Aside from improving the correlations between the photospheric magnetic field and the interplanetary magnetic field, the model has been used to predict and compare the coronal forms at the times of solar eclipses [see *Schatten,* 1970]. The model also allowed a comparison of a Faraday coronal occultation experiment [*Stelzried et al.,* 1970]. The comparisons show some degree of success and also point out some of the weaknesses in the model.

Pneuman and Kopp developed a series of models [*Pneuman,* 1968, 1969; *Pneuman and Kopp,* 1971] that utilize, in addition to the magnetic field equations, a consistent set of plasma physics equations that provide an exact MHD solution to the solar coronal expansion. The early models were very simplified in terms of the magnetic field geometry that could be handled. Their present model can handle an isothermal corona with any axisymmetric field configuration. Computer storage and time limitations prevent, at present, a full three-dimensional solution using their technique.

One model which resembles the Pneuman and Kopp models in that a realistic attempt to ascertain the electric current configuration in the corona is achieved is the current sheet model of *Schatten* [1971*b*]. A computer program which calculates the coronal magnetic fields using this model is available on request from Dr. Wende at the National Space Science Data Center, Code 601, Goddard Space Flight Center, Greenbelt, Maryland 20771.) Figure 3 shows the November 12, 1966, solar eclipse along with the magnetic field configuration computed in accordance with this model. Of interest is the relatively open configuration of the magnetic field of both poles. It has been proposed [see *Schatten,* 1973] that the sun's differential rotation results from the deceleration of the sun's polar convection zone by the solar wind through the coronal magnetic field agency. This figure illustrates this effect nicely in that the poles are clearly more 'open' to the solar wind and its decelerating

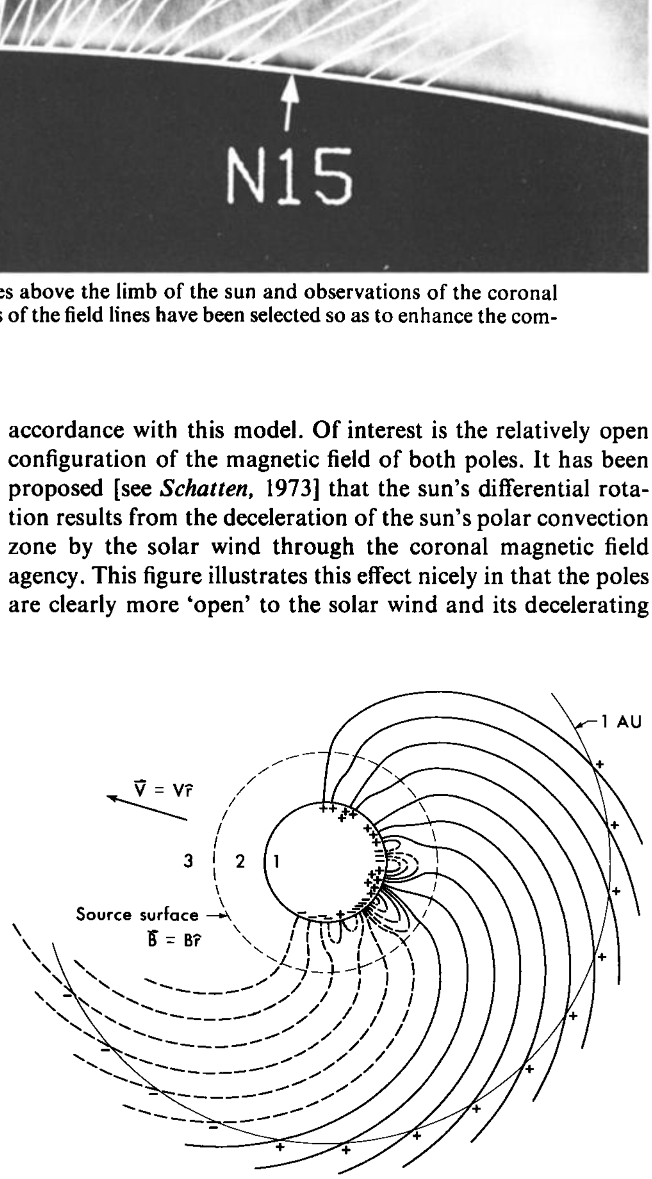

Fig. 2. Schematic representation of the source surface model. The photospheric magnetic field is measured in region 1, represented by fictitious monopoles in the sun (shown by plus and minus signs). Closed field loops exist in region 2. Currents flowing on an outside the source surface eliminate the nonradial portion of the magnetic field on the source surface. The solar wind extends the magnetic field to 1 AU, where it may be observed by spacecraft. The fields shown illustrate how an irregular solar field may be ordered into a fairly extensive 'sector' pattern at 1 AU.

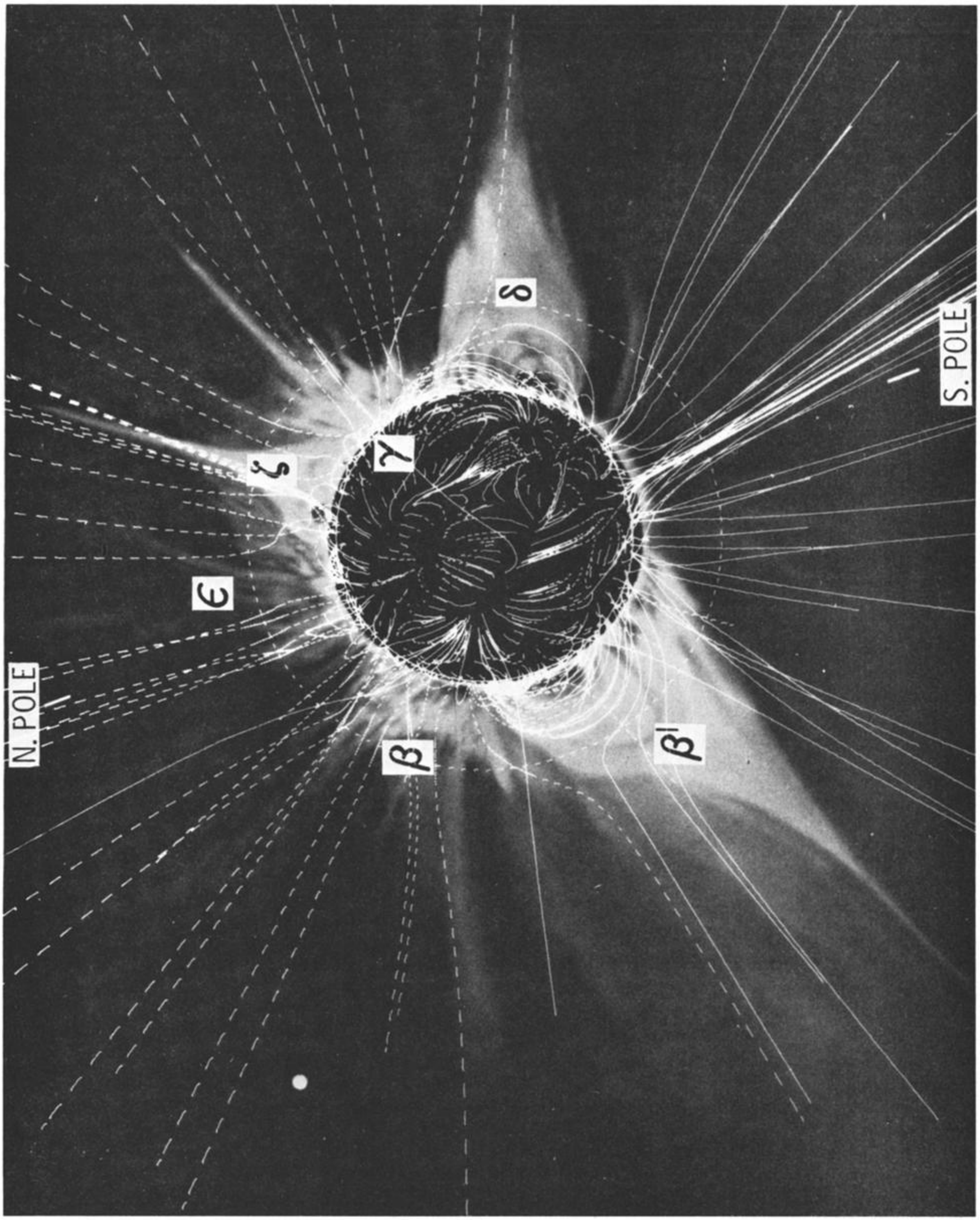

Fig. 3. A comparison of the magnetic field calculated using the current sheet model with a drawing by *Newkirk et al.* [1970] of the features observed at the November 12, 1966, solar eclipse. The comparison shows general agreement.

effects. Computations show that enough torque is present to offset viscous effects in the convection zone.

The proper handling of electric currents within the corona is one of the major problems facing coronal models. On the matter of small-scale field patterns in the vicinity of active regions, research may concentrate on force-free fields. Concerning the large-scale coronal field, the MHD solutions may be expanded to include three-dimensional problems, or force-free fields may be extended to large-scale problems.

Perhaps the most surprising aspect of the coronal models is their ability to calculate observed coronal structures moderately well, despite the lack of information fed into the models concerning the state of the coronal plasma. This is even more surprising when one considers the high conductivity of the plasma and the subsequent ease with which currents can be carried.

Wild [1970] has reviewed many of the radio observations that suggest that particle motions are related to field line orientations. Wild, Smerd, Riddle, Stewart, Sheridan, and others at CSIRO in Australia have observed a number of interesting and unusual events with the Culgoora radio heliograph that relate to the magnetic field structure in the solar corona. They have found strong evidence that MHD waves responsible for type II bursts propagate along curved paths in the corona. Many of their observations can only be understood by assuming that a large-scale magnetic arch structure exists in the corona. Their observations suggest that magnetic arches can expand, at times, to 2 R_S. Numerous cases of successive brightenings at two distant locations on the sun were observed with time separations on the order of 10 s. This is suggestive of magnetic arches connecting these points. Their observations represent a new and exciting way to probe coronal field structure and, of course, to observe dynamic solar flare phenomena.

Fainberg and Stone [1971] have also observed the coronal radio emission and deduced information concerning the coronal magnetic field. Their observations of the 0.2- to 5-MHz range provide information on the coronal magnetic field from 10 to 40 R_S. From the progressive delay of the central meridian passage of the lower-frequency emissions, a streamer curvature is deduced that is consistent with a Parker type spiral angle, the implication being that outward coronal velocities are near 380 km/s at these distances.

Coronal magnetic models have been utilized up to the present time mostly to test their own validity. They may have reached a state of development where it should be possible to use the coronal magnetic models to improve models in other fields. For example, solar wind theories may be affected by the nonradial expansion of plasma at the sun. Solar cosmic ray propagation also would be influenced strongly by the magnetic field patterns in the corona.

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