JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. A11, PAGES 8893–8898, OCTOBER 1, 1981

The Coronal and Interplanetary Current Sheet in Early 1976

L. F. BURLAGA

NASA Goddard Space Flight Center, Laboratory for Extraterrestrial Physics, Greenbelt, Maryland 20771

A. J. HUNDHAUSEN

High Altitude Observatory, National Center for Atmospheric Research, Boulder Colorado

XUE-PU ZHAO

Department of Geophysics, Beijing University, Beijing, People's Republic of China

A comparison of Helios 1 and 2 observations of the interplanetary sector pattern in early 1976 with the maximum brightness curves in the K coronameter data at $1.5R_S$ shows that the latter may be identified with the footprints of the sector boundary surface to an accuracy of $\approx 10°$. The neutral line computed by Wilcox et al (1980) from a potential field model, using Mt. Wilson photospheric magnetic field measurements and a source surface at $2.6R_S$, is similar in shape to the K coronameter maximum brightness curves but extends to higher latitudes. The Helios observations give better agreement with the K coronameter curves for the one solar rotation on which a test of the latitutude extent of the neutral line was possible. The K coronameter results and the Helios data show that the sector boundary surface probably extended to $\approx 15°$ in the northern hemisphere and to $\approx 30°$ in the southern hemisphere, with little change between 1.5 R_S and 1 AU. The surface was warped appreciably from a single tilted plane (a dipole configuration) suggesting a significant magnetic quadrupole contribution.

INTRODUCTION

The sector pattern observed in the interplanetary magnetic field [*Ness and Wilcox*, 1964; *Wilcox and Ness*, 1965] was interpreted by *Schultz* [1973] as the result of an extension of the solar magnetic field which to first approximation is a dipole inclined with respect to the solar rotation axis. Schultz suggested that the observed sector boundaries correspond to crossings of a current sheet that separates north polarity fields from south polarity fields, as discussed by *Pneuman and Kopp* [1970], extending from $\approx 2R_S$ to the boundary of the heliosphere. He attributed the common four-sector pattern to a warp in the near-equatorial neutral sheet produced by a quadrupole component of the solar magnetic field. *Saito et al* [1978] and *Kaburaki and Yoshii* [1979] presented a model for the two-sector pattern that is very similar to that of *Schulz* [1973], but they attributed the four-sector pattern to inhomogeneities in the solar wind speed rather than to a solar quadupole magnetic moment. The current sheet associated with sector boundaries is often referred to as the neutral sheet, null-sheet or null surface, although *Klein and Burlaga* [1980] showed that the magnetic field strength often does not go to zero in the current sheet. It may be visualized as a mathematical surface (e.g., see *Schulz* [1973] and *Svalgaard and Wilcox*, [1976] that we shall call the sector boundary surface.

Schatten et al [1969] and *Schatten* [1971] attempted to calculate the interplanetary magnetic field from measurements of the photospheric magnetic field, assuming that the field is radial at a source surface with radius $1.6R_S$ and that it is a potential field (all currents are zero) between this surface and the photosphere. They found curves on the source surface at which $B = 0$ and across which the polarity of the field changed, and they identified these neutral lines with the footprints of the sector boundaries observed by *Wilcox and Ness* [1965]. A similar attempt to model the coronal magnetic field as a potential field was made by *Altschuler and Newkirk* [1969], and there have been many such models since then [see *Schatten*, 1971; *Altschuler et al.*, 1977; *Svalgaard and Wilcox*, 1978; *Levine*, 1977; *Levine et al*, 1977*a*, *b*; *Burlaga et al.*, 1978]. A recent application of this method is by *Wilcox et al.* [1980] who related the neutral line computed from Mt. Wilson photospheric magnetic field data to observations of the interplanetary sector boundaries made by the spacecraft Pioneer 11 [*Smith et al.*, 1978] and Helios 1, 2 [*Villante et al.*, 1979] in early 1976.

Bright coronal streamers seen above helmet-like structures in eclipse photographs have been interpreted as neutral sheets for some time [e.g., *Newkirk*, 1972; *Pneuman et al.*, 1978]. *Hansen et al.* [1974] suggested that the sector boundary surface near the sun (the neutral line) can be identified with bright features observed in the whitelight corona. *Hundhausen* [1977] used this suggestion to develop a phenomenological model of the global solar magnetic field; in particular, the simple pattern of coronal brightness observed in 1974 was likened to a 'tilted dipole', such as originally discussed by *Schulz* [1973].

In this paper the Mauna Loa Observatory K coronameter observations of R. T. Hansen and S. F. Hansen are used to infer the location of the sector boundary surface above 1.5 R_S in early 1976. The neutral line determined in this manner is compared with both the potential field inference of Wilcox et al and the sector structure actually observed by the Helios spacecraft [*Villante et al*, 1979]. A large measure of agreement emerges from these comparisons. However, we will find a significant difference in the latitude excursion of the warped neutral sheet predicted by the two models. In our opinion, comparison with the Helios data suggests a neutral sheet with smaller latitude excursions, as given by the K coronameter, than that determined by the potential field neutral line.

OBSERVATIONS AND RESULTS

The K coronameter measures 'polarization brightness' (the difference in the white light intensity of the tangentially and

Paper number 1A0872.
0148-0227/81/001A-087?$01.00

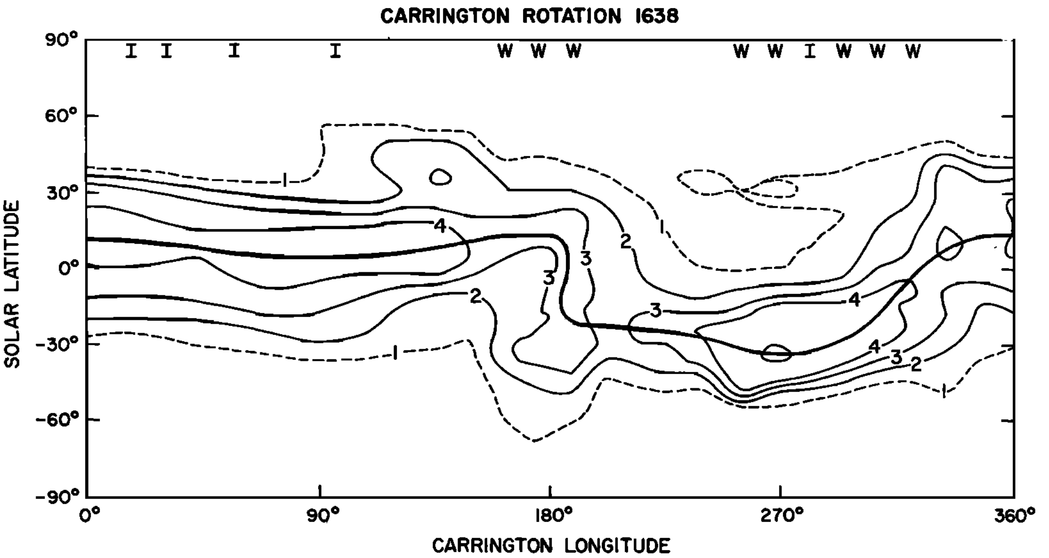

Fig. 1. This shows the brightness contours measured by the Mauna Loa K coronameters at 1.5 R_S as a function of solar latitude and longitude for CR 1638. The contour levels are in units of 10^{-8} times the brightness of the photosphere. Also shown is a curve (heavy solid line) based on an estimate of the latitude of maximum brightness as a function of longitude; we call this the maximum brightness curve, MBC.

radially polarized components) near the solar limbs as a function of latitude and time. Assuming slowly varying conditions, it is possible to construct equal brightness contours as a function of solar latitude and Carrington longitude as illustrated in Figure 1 [*Hansen et al.*, 1974]. It is then usually possible to draw a curve through the latitude of maximum brightness at a series of longitudes, encircling the sun, with an accuracy $\approx\pm 10°$ in latitude and longitude [see *Hundhausen*, 1977]; an example is the heavy curve in Figure 1. It is this curve that has been suggested as the location of the neutral sheet in the corona at ≈ 1.5 R_S. Our results are based on the curves obtained in this way for CR 1637-1640.

The relevant Helios data were published by *Villante et al.* [1979]. These are 12-hour averages of the interplanetary magnetic field polarity measured between 0.3 AU and 1 AU and projected back to the sun using the solar wind measurements of Rosenbauer with the assumption that any plasma element moves radially at constant speed between the sun and Helios.

The Helios and K coronameter results will be compared with the neutral line computed by *Wilcox et al.* [1980] from the Mt. Wilson photospheric magnetic field measurements assuming that the field is radial on a source surface at 2.6 R_S and that the field is derivable from a potential between the sun and the surface. They used an $\approx$ 6-month average of the photospheric magnetic field measurements, so the neutral line that they derive represents an average over that period. It is this average potential field (PF) neutral line that we shall compare with the Helios and K coronameter results. A basic result of the potential field calcuation is that the neutral line extends to nearly 30° latitude in the northern hemisphere and to significantly larger latitudes in the southern hemisphere; this is probably not sensitive to small time variations that may have occurred over their averaging interval.

CR 1637. Figure 2*a* shows the three elements of our discussion for CR 1637; the projection of the Helios 1 and 2 measurements of the magnetic field polarity (the plus sign corresponds to outward directed magnetic field lines); the maximum brightness curve (MBC) obtained from a plot of the K coronameter brightness contours; and the PF neutral line. Helios 1 and 2 observed two sectors, with a projected sector boundary at $\approx 180°\pm 10°$ and $\approx 160°\pm 10°$ from Helios 1 and Helios 2, respectively. The error quoted here is the number that has been estimated for the accuracy of the constant velocity projection method [*Nolte and Roelof*, 1973*a*, *b*]. The MBC, interpreted as the footprints of the sector boundary surface, implies that Helios 1 and 2 should have observed 2 sectors with a projected sector boundary at $\approx 180°\pm 10°$, in agreement with the Helios observations. The PF neutral line shown in Figure 2*a* also implies that Helios should have observed 2 sectors, but it predicts a sector boundary at $\approx 195°$ longitude, somewhat farther away from the projected sectory boundary than the MBC. The MBC and PF neutral line also differ in latitudinal extent, but the Helios observations for this rotation permit no test of this difference in predictions.

CR 1638. Again Helios 1 and 2 observed two sectors, and the MBC and PF neutral line are both consistent with this observation. The position of one of the projected sector boundaries ($\approx 200°$) is satisfactorily described by both the MBC and PF neutral line. The position of the other projected boundary is uncertain, because Helios 1 and Helios 2 give very different results. This is perhaps due to the gaps in the Helios 1 data or to temporal variations. The Helios 2 projected sector boundary lies close to the MBC and somewhat farther from the PF neutral line.

CR 1639. This case (Figure 3*a*) shows a significant change from the preceding rotations in two respects: (1) The Helios 1 and 2 trajectories are separated by 10–15° in latitude between the longitudes of 0° and 100°, and (2) The MBC dips to $-10°$ latitude at $\approx 75°$ longitude. Helios 1 observed four sectors, which is consistent with both the MBC and the PF neutral line; however, the longitudes of the Helios 1 sector boundaries are better described by the MBC than by the PF neutral line. Helios 2, on the other hand, observed only two sectors.

The difference between the Helios 1 and Helios 2 polarity observations between Carrington longitudes 0–100° (Figure 3*a*) might be attributed to temporal variations, but it is more

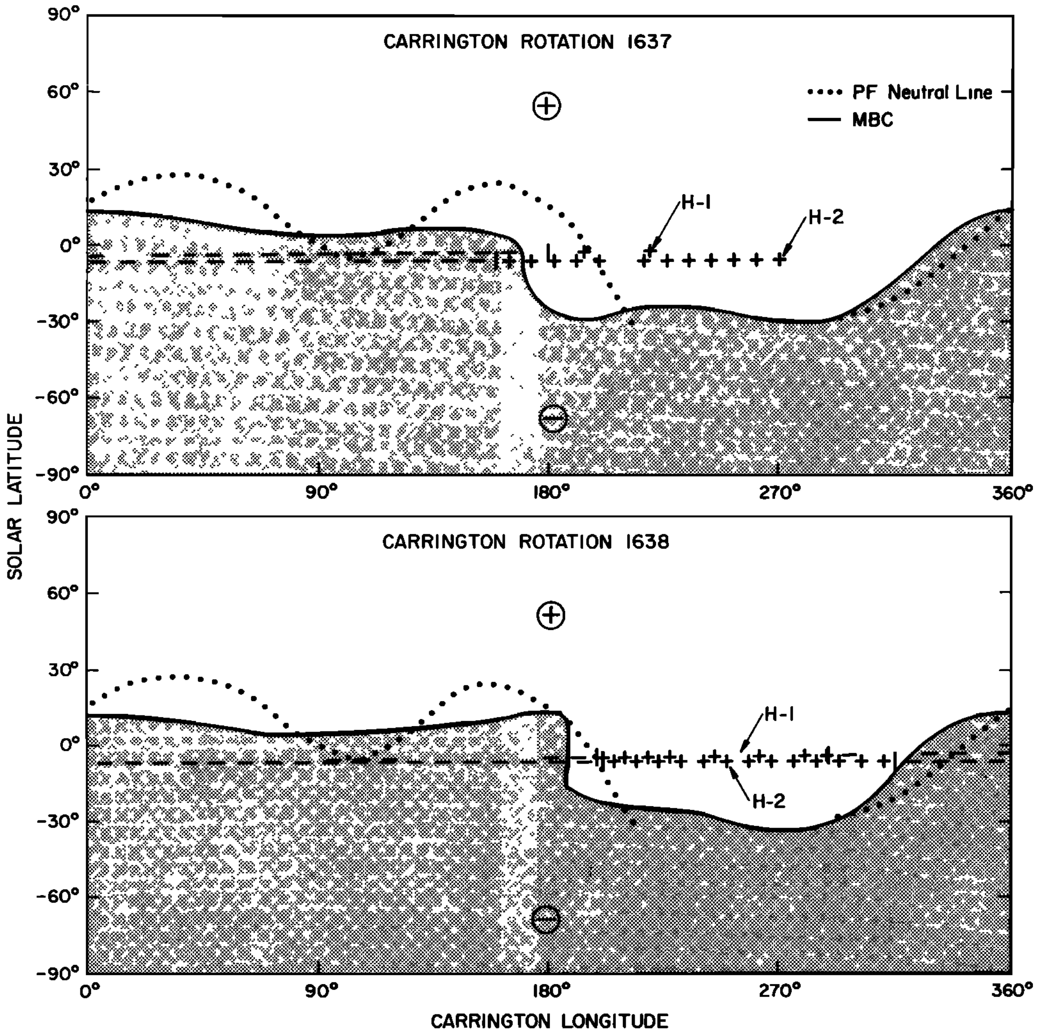

Fig. 2. The projected magnetic field polarities observed by Helios 1 and 2 (the plus sign indicates an outward directed field) and the maximum brightness curves for CR 1637 and CR 1638, together with the neutral line calculated form the photospheric magnetic field observations by *Wilcox et al.* [1981] using a potential field model (dotted curve). The shaded area indicates negative polarity fields. Projected sector boundaries observed by Helios are indicated by vertical lines separating regions of positive polarity from regions of negative polarity.

likely the result of a latitudinal variation since Helios 1 was between 4° and 7° latitude, while Helios 2 was between −3° and −7° [see *Villante et al.*, 1979]. If the difference is a spatial effect, we can evaluate a significant difference between the MBC and the PF neutral line, which is apparent on all of the solar rotations in Figures 2 and 3 and which has been discussed previously by *Pneuman et al* [1978], viz., the PF neutral line extends to higher latitudes than the MBC. Specifically, in the northern hemisphere the PF neutral line extends to nearly 30° latitude while the MBC extends no farther than ≈15°, and in the southern hemisphere the PF neutral line reached 'appreciable' latitudes (in the words of *Wilcox et al.* [1980], while the MBC extended to ≈−30°. The Helios observations between Carrington longitudes 0–100° (Figure 3*a*) imply that the neutral line lies between ≈7°and ≈−7° latitude. The MBC is consistent with this result at the longitudes where measurements are available (≈0–10° and ≈55–100°), allowing an uncertainty of ≈±10° in the position of the MBC. There are no white light data between ≈10° and ≈55°, but a linear interpolation as shown in the figure is reasonable, considering the behavior of the MBC on CR 1637, 1638, and 1640; this gives a MBC that is consistent with the Helios data. The PF neutral line, on the other hand, is not consistent with the Helios data. It extends to high latitudes, implying that both Helios 1 and Helios 2 should have observed negative polarities at longitudes between 0° and ≈80°, which is contrary to the observations. Thus, in this case where the latitude of the sector boundary surface was measured directly, the MBC provides a better description of it than the PF neutral line calculation.

CR 1640. Four sectors were observed by both Helios 1 and 2 of this rotation (Figure 3*b*). The MBC for CR 1640 is consistent with these results, the four-sector pattern again being a result of the secondary minimum near Carrington longitude 90°.

Because the MBC lies close to the solar equator, the longitudes of the predicted sector boundaries are very sensitive to uncertainties in the latitude of the MBC, so it is not very meaningful to compare the predicted and observed longitudes of the sector boundaries in this case. It is true, however, that the observed positions of the sector boundaries are consistent with the MBC within the uncertainties discussed above. The

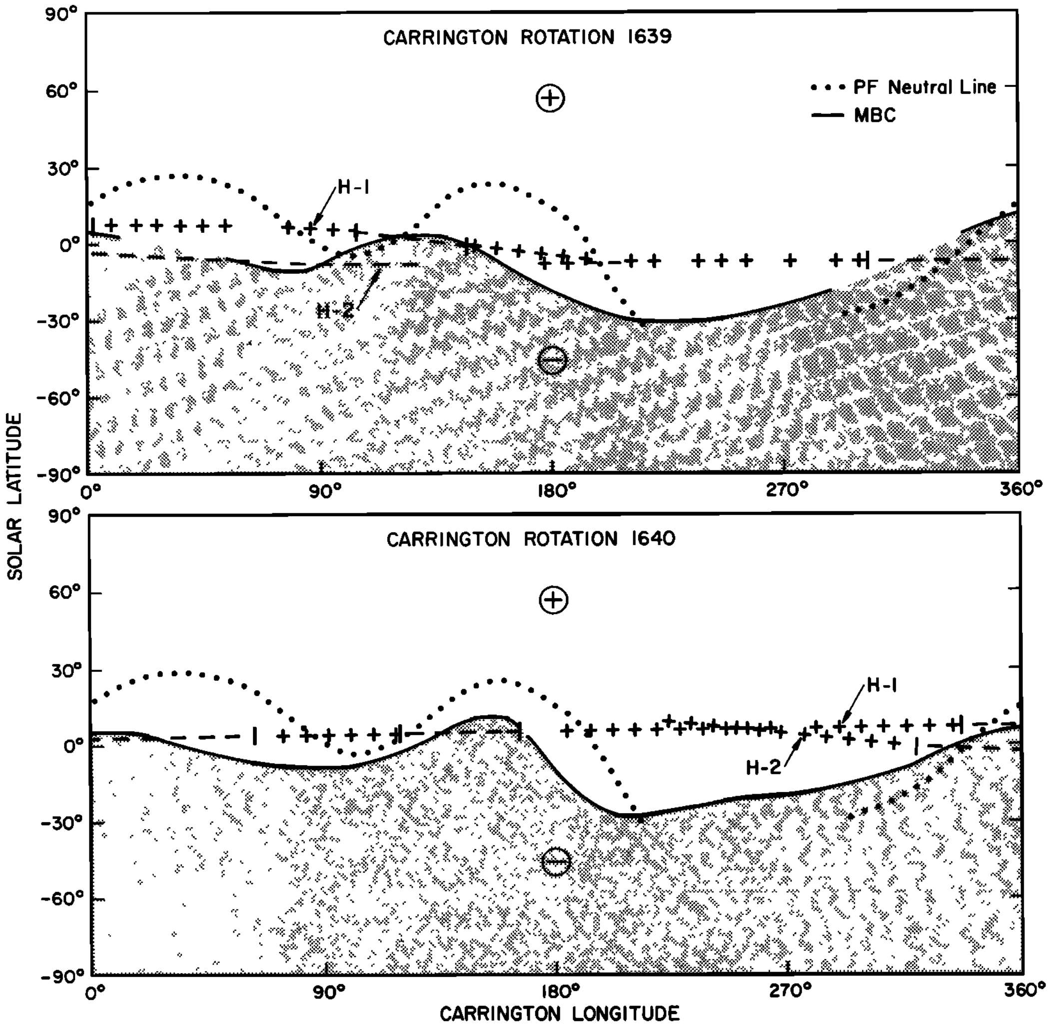

Fig. 3. The projected magnetic field polarities observed by Helios 1 and 2 and the maximum brightness curves for CR 1639 and CR 1640, together with the potential field neutral line calculated by *Wilcox et. al.* [1981]. See the caption of Figure 2 for an explanation of the symbols.

PF neutral line is also consistent with the four-sector pattern and the sector boundaries observed by Helios, allowing an uncertainty of ≈20° in the longitudes of the sectory boundaries. The Helios data do not provide a measure of the latitudinal extent of the sector boundary in this case.

SUMMARY AND DISCUSSION

We have considered the configuration of the current or neutral sheet in the outer corona, as inferred by two different techniques, during early 1976 and have compared these inferences with Helios 1 and 2 observations in the interplanetary magnetic sector structure for the same epoch. The first of these techniques, the well-known potential field approximation (see the references in the introduction), has been used by *Wilcox et al.* [1980] to compute the coronal magnetic geometry from Mt. Wilson observations of the photospheric magnetic field averaged over the first six months of 1976. This computation yields directly a neutral line separating regions of outward and inward pointing magnetic field on the 'source surface,' taken by Wilcox et al. to be at a heliocentric distance of 2.6 solar radii, where the field is forced to become radial. The second technique is strictly empirical, based on the widely accepted identification of coronal streamers with current sheets in the outer corona (again, see the references in the Introduction). Synoptic maps of the polarization brightness at a heliocentric distance of 1.5 solar radii, as observed with a K coronameter at the Mauna Loa Observatory, were used to construct a 'maximum brightness curve' around the sun for four Carrington solar rotations from early 1976. The coronal neutral sheet is hypothesized to extend radially outward above this curve.

The current or neutral sheet configurations inferred by these two different techniques show considerable agreement. The neutral line computed from the potential field approximation and the four individual configurations obtained from the synoptic maps all show a major depression of the line south of the solar equator between ≈180° and 360° Carrington longitude and a smaller elevation of the line north of the equator between 0° and ≈180° Carrington longitude. The potential field gives an additional oscillation of the neutral line with a wavelength of ≈90° (longitude) in the latter range; the individual synoptic maps suggest a nearly flat neutral sheet slightly above the equator during Carrington rotations 1637 and 1638 and a small oscillation, similar to that given by the potential field approximation, during Carrington rotations 1639 and 1640. The major difference in the configurations inferred by the two techniques arises in the amplitude of the displacements of the neutral line from the solar equator. The potential field neutral line shows larger displacements from the equator than that based on the synoptic maps in every example considered here.

Comparison with the magnetic sector pattern observed by the Helios 1 and 2 space probes gives, for three of the four Carrington rotations under discussion, a test of the intersection of the warped neutral line with two orbital paths that are so close (in Carrington latitude and longitude) as to be essentially a single line. The observed sector boundaries, extrapolated back to the sun, match the crossings of this line with the warped neutral sheets inferred from either technique to within the expected accuracy of the sector boundary extrapolation and neutral sheet specification. This accuracy is $\pm 10°$ in Carrington longitude except in cases where the neutral sheet lies nearly parallel to the orbital line.

A more interesting test is possible for the single Carrington rotation, 1639, when the Helios 1 and 2 orbital paths are separated by $\approx 10°$ in lattude between Carrington Longitudes 0° and 180° (see Figure 3). The orbital paths then bracket the flatter neutral line inferred from the maximum brightness curve on the synoptic map for that Carrington rotation; the orbital path of Helios 1, at $\approx 10°$ north of the solar equator, cuts through the larger oscillations in the neutral line given by the potential field approximation. The polarity observed by the two spacecraft differed over most of this longitude range, implying that the interplanetary neutral sheet did indeed fall between their paths. The shorter wavelength structure, as predicted by the potential field approximation, was not observed by Helios at 4° to 7° north of the solar equator.

The implications of any tests such as these must be stated with several qualifications. The neutral line computed from the potential field approximation is based on a boundary condition averaged over six months and thus might not apply to a single short interval. The synoptic maps from which the maximum brightness line is deduced are valid representations of the true coronal spatial structure only if that structure changes little on the 27-day time scale over which the observations were accumulated. The interplanetary sector pattern observed at a given location during a short interval of time might be perturbed by transient solar wind disturbances and thus be not strictly comparable with the coronal structure. While both the coronal structure revealed in the synoptic maps and the interplanetary sector pattern observed by the Helios spacecraft during this epoch do change slowly and coherently, this is a necessary but not sufficient condition for the validity of our comparison. Nonetheless, to the extent with which the sector pattern observed by Helios 1 and 2 in early 1976 can be interpreted as a spatial structure, it does correspond reasonably well to the neutral line configurations inferred from either the potential field approximation or the maximum brightness line. In the single case where the major difference between the two inferences can be tested, the Helios observations favor the smaller displacement of the neutral line away from the solar equator given by the maximum brightness line on the synoptic maps of observed coronal brightness.

We are thus led to the following possible conclusions. If the potential field approximation, as applied by *Wilcox et al.* [1980], does give a valid current or neutral sheet geometry in the outer corona, then the neutral line must be 'squashed' toward the solar equator between 2.6 solar radii and the interplanetary distances (0.3 to 1.0 AU) where the Helios observations were made; this equatorward displacement would be by $\approx 20°$ for the case described above. The line of streamers surrounding the sun would have no obvious relationship to the neutral sheet. If the maximum brightness line, as derived here from K coronameter observations, does correspond to the neutral sheet configuration in the outer corona, there is no need to evoke an equatorward displacement in interplanetary space. This conclusion, clearly favored by the present authors, raises a serious question concerning the detailed validity of the potential field approximation. Given the unproven nature of the physical assumption basic to this approximation (total neglect of coronal electric currents below the source surface), the expected sensitivity of the computed amplitude of neutral line distortions to the poorly known strengths of the polar magnetic fields, (as noted by Pneuman et al but neglected by Wilcox et al), and the artificial requirement that the field become radial at an arbitrary distance from the sun, we believe there are ample physical as well as empirical reasons for raising this question.

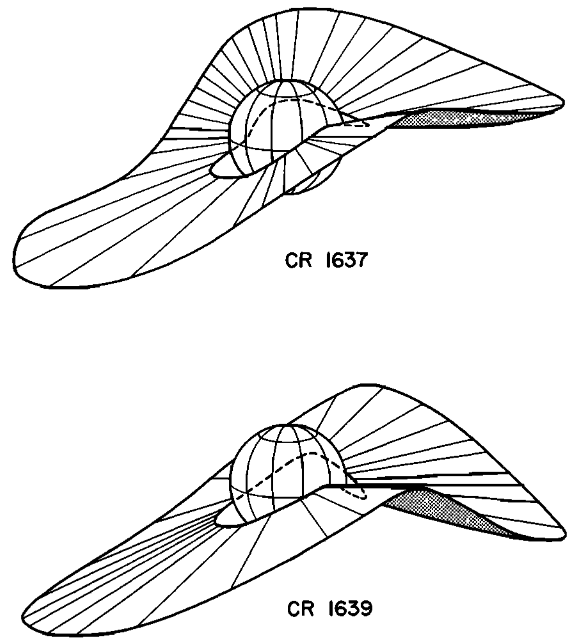

Fig. 4. The sectory boundary surface between 1.5 R_S and 5 R_S for (*a*) CR 1637 and (*b*) CR 1639 obtained by using the white light maximum brightness curves at 1.5 R_S and a radial projection out to 5 R_S.

If, following *Smith et al.* [1978], the solar magnetic field is approximated as a concentric dipole and the sector boundary surface as a plane, then the observations of Helios [*Villante et al.*, 1979] and Pioneer 11 [*Smith and Wolfe*, 1980] imply that the dipole axis was tilted $\approx 20°$ to $\approx 15°$ with respect to the solar rotation axis. However, this cannot explain the sector pattern observed by Helios on CR 1639 and CR 1640. The white light and Helios observations indicate that the surface was eccentric and appreciably warped, as shown in Figure 4. Such a configuration combines the tilted neutral sheet with a 'warping' associated with the four sector structure by *Howard and Koomen* [1974]. This is consistent with the qualitative sketch in Figure 4*b* of *Villante et al.* [1979]. A sketch shown by *Smith and Wolfe* [1980] also shows a warped surface, but the warping in our Figure 4 is more severe than they suggested. We conclude that while the sector boundary can be roughly approximated by the plane associated with a tilted dipole, the bending, such as would be produced by higher multipoles, is appreciable and cannot be neglected during the early 1976 epoch.

Acknowledgments. This work was performed while two of the authors (L. F. Burlaga and Xue-pu Zhao) were visitors at the High Altitude Observatory of the National Center for Atmospheric Research. They wish to thank R. M. MacQueen and other members of the staff for their hospitality and assistance. We thank T. Holzer and V. Pizzo for their comments on the manuscript. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

The Editor thanks J. M. Wilcox and W. C. Feldman for their assistance in evaluating this paper.

REFERENCES

Altschuler, M. D., and G. Newkirt, Jr., Magnetic fields and the structure of the solar corona, *Solary Phys.*, *9*, 131, 1969.

Altschuler, M. D., R. H. Levine, M. Stix, and J. W. Harvey, High resolution mapping of the magnetic field on the solar corona, *Solar Phys.*, *51*, 345, 1977.

Burlaga, L. F., K. W. Behannon, S. F. Hansen, G. W. Pneuman, and W. C. Feldman, Sources of magnetic fields in recurrent interplanetary streams, *J. Geophys. Res.*, *83*, 4177, 1978.

Hansen, S. F., C. Sawyer, and R. T. Hansen, K-corona and magnetic sector boundaries, *Geophys. Res. Lett.*, *1*, 13, 1974.

Howard R. A., and M. J. Koomen, Observations of sectored structure in the outer solar corona: Correlations with interplanetary magnetic field, *Solar Phys.*, *37*, 469, 1974.

Hundhausen, A. J., An interplanetary view of coronal holes, in *Coronal Holes and High Speed Streams*, edited by J. B. Zirker, p 225, Colorado Associated University Press, Boulder, 1977.

Kaburaki, O., and Y. Yoshii, On the three-dimensional structure of the solar magnetic field in interplanetary space, *Solar Phys.*, *64*, 187, 1979.

Klein, L., and L. F. Burlaga, Interplanetary sector boundaries, 1971–1973, *J. Geophys. Res.*, *85*, 2269, 1980.

Levine, R. H., Evolution of open magnetic structure on the sun: The Skylab period, *Astrophys. J.*, *218*, 1977.

Levine, R. H., M. D. Altschuler, and J. W. Harvey, Solar sources of the interplanetary magnetic field and solar wind, *J. Geophys. Res.*, *82*, 1061, 1977*a*.

Levine, R. H., M. D. Altschuler, and B. V. Jackson, Open magnetic structures on the sun, *Astrophys. J.*, *215*, 636, 1977*b*.

Ness, N. F., and J. M. Wilcox, Solar origin of the interplanetary magnetic field, *Phys. Rev. Lett.*, *13*, 461, 1964.

Newkirk, G., Coronal magnetic fields and the solar wind, in *Solar Wind*, edited by C. P Sonnett, P. J. Coleman, and J. Wilcox, p. 11, *NASA pubSP-308*, 1972.

Nolte, J. T., and E. C. Roelof, Large-scale structure of the interplanetary medium, high coronal source longitude of the quiet time solar wind, *Solar Phys.*, *33*, 241, 1973*a*.

Notle, J. T., and E. C. Roelof, Large scale structure of the interplanetary medium-2: Evolving magnetic configurations deduced from multi-spacecraft observations, *Solar Phys.*, *33*, 483, 1973*b*.

Pneuman, G. W., and R. A. Kopp, Coronal streamers III; Energy transport in streamers and interstreamer regions, *Solar Phys.*, *13*, 176, 1970.

Pneuman, G. W., S. F. Hansen, and R. T Hansen, On the reality of potential magnetic fields in the solar corona, *Solar Phys.*, *59*, 313, 1978.

Saito, T., T. Sakurai, and K. Yumoto, The earth's paleomagnetic sphere as the third type of planetary magnetosphere, *Planet. Space Sci.*, *26*, 431, 1978.

Schatten, K. H., Current sheet model for the solar corona, *Cosmic Electrodyn.*, *2*, 232, 1971.

Schatten, K. H., J. M. Wilcox, and N. F. Ness, A model of interplanetary and coronal magnetic fields, *Solar Phys.*, *9*, 442, 1969.

Schulz, M., Interplanetary sector structure and the heliomagnetic equator, *Astrophys. Space Sci.*, *24*, 371, 1973.

Smith E. J., and J. H. Wolfe, Fields and plasmas in the outer solar system, *Space Sci., Rev.*, *23*, 217, 1980.

Smith, E. J., B. T. Tsurutani, and R. L. Rosenberg, Observations of the interplanetary sectors structure up to heliographic latitudes of 16°: Pioneer II, *J. Geophys. Res.*, *83*, 717, 1978.

Svalgaard, L., and J. M. Wilcox, Structure of the extended solar magnetic field and the sunspot cycle variation in cosmic ray intensity, *Nature*, *262*, 766, 1976.

Svalgaard, L., and J. M. Wilcox, A view of solar magnetic fields, the solar corona, and the solar wind in three dimensions, *Ann. Rev. Astron. Astrophys.*, *16*, 429, 1978.

Villante, V., R. Bruno, F. Mariani, L. F. Burlaga, and N. F. Ness, The shape and location of the sector boundary surface in the inner solar system, *J. Geophys. Res.*, *84*, 6641, 1979.

Wilcox, J. M., and N. F. Ness, Quasi-stationary corotating structure in the interplanetary medium, *J. Geophys. Res.*, *70*, 1965.

Wilcox, J. M., H. R. Hoeksema, and R. H. Sherrer, The origin of the warped heliospheric current sheet, *Science*, *209*, 603, 1980.

(Received January 30, 1981;
revised April 13, 1981;
accepted May 15, 1981.)