Heliospheric Current Sheet and Its Solar Cycle Variations

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The three-dimensional structure of the heliospheric current sheet is constructed for Carrington rotations 1647, 1654, 1661, 1667, 1693, 1699, and 1719. These rotations are chosen from different epochs during the sunspot cycle 21, so that one can infer geometrical changes of the current sheet during a sunspot cycle. Only for relatively simple neutral lines on the source surface do the structures of the current sheet approximate to those envisaged by Svalgaard and Wilcox [1976] and Thomas and Smith [1981].

1. INTRODUCTION

It has been known that the sun has an extensive current sheet, namely the heliospheric current sheet [Schulz, 1973; Saito, 1975; Svalgaard and Wilcox, 1976; Alfvén, 1977; Smith et al., 1978]. It is generally assumed that the current sheet is rooted at the "magnetic neutral line" on an imaginary spherical (or ellipsoidal) surface of 2.0-3.0 solar radii, which is called the "source surface" [Schatten, 1969; Schatten et al., 1969; Altschuler and Newkirk, 1969; Burlaga et al., 1981; Bruno et al., 1982; Hoeksema et al., 1982, 1983]. Thus, the heliospheric current sheet separates the heliosphere into two regions: at a given time, one region is occupied by the interplanetary magnetic field (IMF) which has the component away from (or toward) the sun and the other region is occupied by the IMF which has the component toward (or away from) the sun. The first region is thus occupied by the solar wind which blows out from the area located north of the neutral line on the source surface, and the other region is occupied by the solar wind which blows out from the area located south of the neutral line. Note that the four-sector structure envisaged originally by Wilcox and Ness [1965] is now understood to result from a double-sinusoidal wave neutral line, so that the earth (or an earth-bound satellite) crosses the current sheet four times during a single solar rotation as the wave current sheet rotates with the sun once in about 25 days (27 days as seen from the earth). At times, however, the magnetic field distribution on the source surface becomes complicated, resulting in more than one neutral line.

It is not difficult to infer that the current sheet is constituted by solar wind particles which emanate from the neutral line. It is for this reason that the current sheet provides a natural frame of reference in relating solar wind and IMF observations at single points with structures on the source surface. The three-dimensional structure of the current sheet is warped in a complicated way by the facts: (1) its "root" does not coincide with the heliographic equator, and (2) effects of this nonconformity are propagated outward with a finite speed by the solar wind for many solar rotation periods. Since the current sheet is constituted by solar wind particles which emanate from the neutral line, the geometry of the current sheet can be determined in principle by knowing the geometry of the neutral line on the source surface and the distances traversed by solar wind particles emanated from the neutral line as a function of time. The basic assumption is consistent with the concept of the source surface. Since there is now an extensive current sheet up to 5 AU, solar wind particles have only a radial motion when they leave the source surface with a given initial speed, say 300 km/s.

The distance traversed by a solar wind particle can be determined by integrating the velocity-distance relationship which is either a solution of the MHD equations or could be inferred from spacecraft observations. Hakamada and Akasofu [1982] devised a method to compute the stream pattern by introducing Lagrangian coordinates which move with the fluid flow. Recently, Olmsied and Akasofu [1985] showed how to convert a Lagrangian description of the paths of individual particles of the solar wind into the Eulerian velocity distribution as a function of space and time and vice versa. Therefore, it is now possible to apply their method to the basis of MHD solutions, namely the solar wind velocity as a function of radial distances at different times. Based on this principle, Fry et al. [1985] constructed the three-dimensional structure of the current sheet for two hypothetical cases. They assumed that the neutral line has single and double sinusoidal curves in heliographic latitude-longitude coordinates. Different amplitudes, X (the maximum excursion of the neutral line in latitude), are also considered (such as X = 20°, 40°, 60°, etc.). For large values of X, the geometry becomes decidedly complex. They showed also that the distortion becomes more serious as the radial distance from the sun increases.
Fry et al. [1985] tested successfully their method for one realistic case, namely the neutral line for Carrington rotation 1647. A similar attempt has recently been made by Suess and Hildner [1985]. In this paper, the method developed by Fry et al. [1985] is extended to show the current sheet geometry for several Carrington rotations. They are chosen from different epochs in the sunspot cycle 21, so that one can infer geometrical changes of the current sheet during a sunspot cycle. The neutral line in each Carrington rotation is taken from the work by Hockema et al. [1982, 1983]. For simplicity, it is assumed that the initial speed of the solar wind particles from the neutral line is 300 km/s and that the initial speed increases toward higher latitudes (as given by Hakamada and Akasofu [1982]).

2. RESULTS
2.1. Carrington Rotation 1647 (October 11 to November 6, 1976)
This rotation took place during the very beginning of the sunspot cycle 21: cycle 21 began in March 1976. The neutral line lay near the heliographic equator and can be represented by a small-amplitude ($X \sim 15^\circ$) double sinusoidal curve (Figure 1): it is the line designated by $B = 0.0$. 
Fig. 2. Same as those in Figure 1, for the Carrington rotation 1654 (March-April 1977) views from (i) longitude 30°, latitude 20° at a distance of 5 AU, (ii) longitude 210°, latitude 20° at a distance of 5 AU, and (iii) longitude 210°, latitude 20° at a distance of 2 AU.

Let us examine first the 2-AU configuration viewed from the direction of longitude 30° and latitude 20°. Because of this particular view, the zero longitude (indicated by the gap) is seen 30° away in the clockwise direction. The particles from the neutral line have the minimum speed (initially 300 km/s) and those from north and south of the line have higher initial speeds. Although the stream-stream interaction will accelerate the minimum speed particles slightly, it will take more than 5 days for the particles from the neutral line to reach a distance of 1 AU. Thus, at a distance of 1 AU, we observe the particles which left the sun more than 5 days ago or the heliographic longitude of more than +70° on the sun's surface.
source surface, namely $30^\circ + 70^\circ \approx 100^\circ$ in this particular case. Since the neutral line is located slightly southward of the heliographic equator, the earth's orbit is a little above the current sheet. Similarly, the 2-AU configuration viewed from the direction of longitude $210^\circ$ at a distance of 1 AU shows the source surface feature centered about $280^\circ$ in longitude. The 5-AU configuration viewed from the direction of longitude $30^\circ$ reproduces the 2-AU configuration viewed from the same longitude and shows the geometry obviously at greater distances.

**2.2. Carrington Rotation 1654 (April 19 to May 17, 1977)**

This rotation took place during an early epoch of the sunspot cycle 21. The neutral line could be approximated to a double sinusoidal curve, but the second wave had a smaller amplitude than the first one (Figure 2). Both the 2-AU (i, ii) and 5-AU (iii) configurations were similar to those in Figure 1. The 2-AU configuration indicates a view seen from the direction of longitude $210^\circ$, so that the source surface feature of about $280^\circ$ (= $210^\circ +$
70°) is seen at 1 AU. The large dip of the current sheet resulted from a large southward excursion of the neutral line near the longitude 360° (0°). In this particular case, the latitudes of the neutral line at longitude 0° and 360° did not coincide, resulting in a distinct gap in the current sheet. Note that at 0° longitude the source surface feature at ~70° longitude on the surface is seen at the earth’s distance: a large northward excursion of the neutral line placed the earth well below the current sheet. The 5-AU configuration viewed from the direction of 210° longitude reproduces the 2-AU configuration viewed from the direction of the same longitude.

2.3. Carrington Rotation 1661 (October 27 to November 23, 1977)

This rotation took place when the sunspot number reached about one third of the way to the peak. During Carrington rotation 1661, the neutral line had a one-and-a-half cycle curve. The configuration for such a situation has not been illustrated even schematically in the past. Figure 3 shows the configuration to a distance of 2 AU (i) viewed from the direction of longitude 30°, latitude 20°, (ii) viewed from the direction of longitude 210°, latitude 20°, and (iii) to a distance of 5 AU, viewed from the direction of longitude 210°.
latitude 20°. The 2-AU configuration viewed from the direction of 30° longitude indicates the source surface feature of about 100° longitude at a distance of 1 AU. Indeed, the earth is located very near the current sheet (as the earth’s orbit intersects the current sheet near there). The large southward excursion of the neutral line about 180° in longitude (on the source surface) produced a large dip, placing the earth well above the current sheet. The 2-AU configuration viewed from the direction of 210° longitude indicates the source surface feature of about 280° at a distance of 1 AU. Note that the earth is located several degrees above the heliographic equator in October, so that the earth was slightly above the current sheet several days earlier (in spite of the fact that the neutral line was located a little north of the heliographic equator at ~280° longitude). One can see a very large slope of the current sheet at about a distance of 4 AU in the 5-AU configuration, indicating the effect of the large southward excursion of the neutral line around 180° in longitude of the source surface being propagated out to a distance of 4 AU.
2.4. Carrington Rotation 1664 (January 17 to February 13, 1978)

After Carrington rotation 1661, the amplitude of the waves became large ($\chi \sim 50^\circ$). As a result, it is practically impossible to envisage the three-dimensional configuration of the current sheet for such a large amplitude without some quantitative effort. In Figure 4, both the 2-AU (i, ii) and the 5-AU (iii) patterns are shown. In this case, the configuration was greatly complicated by the fact that the latitudes of the neutral line at longitudes $0^\circ$ and $360^\circ$ disagreed seriously (perhaps, as a result of a rapid change of the photospheric magnetic fields during one solar rotation).

2.5. Carrington Rotation 1667 (April 9 to May 6, 1978)

This rotation took place during the period when the sunspot number was approximately one-half maximum. The neutral line geometry is characterized by a large-amplitude double-wave geometry. Figure 5 shows the current sheet at a distance of 2 AU, viewed from the direction of (i) longitude $30^\circ$, latitude $20^\circ$, (ii) longitude $300^\circ$, latitude $20^\circ$, and (iii) longitude $210^\circ$, latitude $20^\circ$. The configuration to a distance of 5 AU was extremely difficult to determine and is at present beyond our programming capability. The view from the direction of $30^\circ$ in longitude placed the earth well above the

Fig. 6. Same as those in Figure 1, for the Carrington rotation 1693 (March-April 1980) views from longitudes $120^\circ$, $210^\circ$, and $300^\circ$ at a distance of 2 AU.
Source Surface Rotation #1699

Fig 7(a) The solar magnetic map in heliographic latitude-longitude coordinates for the Carrington rotation 1699 (August-September 1980).

current sheet as a result of the large southward excursion of the neutral line about 60°-120° in longitude on the source surface, although that part of the orbit is behind the current sheet in the 2-AU view. In the direction of about 90° to the right, one can see an archlike structure of the lower surface of the current sheet which resulted from the large northward excursion of the neutral line at about 180° in longitude on the source surface. In the direction of about 90° to the left, one can see also the archlike structure of the upper surface of the current sheet which resulted from the northward excursion at about 0° longitude. The other two views can be understood in a similar way.

2.6. Carrington Rotation 1693 (March 19 to April 14, 1980)

During Carrington rotations 1679 and 1693, two neutral lines were present and were nearly perpendicular to the heliographic equator. One can expect a vertical fanlike structure extending from each neutral line. Three views of such structures are shown in Figure 6 (the view longitudes, 120°, 210°, and 300°). Since the neutral lines were not a straight line, the fanlike structures are actually very complicated. It is important to note that the two fanlike structures divided the interplanetary space into two: one is the away sector and the other is the toward sector. As a result, we observed a well-defined two-sector structure during this sunspot maximum period.

2.7. Carrington Rotation 1699 (August 29 to September 25, 1980)

This rotation took place during the peak period of the cycle 20. There were two neutral lines, one along the equator, and the other a semicircular one, centered in the northern hemisphere (Figure 7a). The heliospheric current sheet from the former is similar to those we examined earlier (Figure 7b). The current sheet from the latter has a trumpetlike shape, as suggested first by Saito [1975], viewed from the direction of longitude 120° and latitude 20°. Examining both Figures 6a and 6b, it is not difficult to see that the source surface feature of longitude 190° (= 120° + 70°) is seen at 1 AU. The current sheet from the semicircular neutral line fans out like a trumpet and hides a significant part of the other current sheet.

Our program computes automatically the cross-section of the current sheet with a spherical surface of radii 1 AU, 2 AU and 5 AU [Fry et al., 1985]. It is our finding that on the 1-AU spherical surface the geometry of the neutral line is very similar to that on the source surface: on the 5-AU spherical surface, however, there occurs a significant difference between them. In this particular rotation the interplanetary magnetic field phi (φ) angle or the B3 component was available for most of the period. In agreement with Wilcox and Hundhausen [1983], the polarity of the IMF is in fair agreement with what can be predicted from the geometry of the neutral line (on the source surface) and from the cross-section of the two surfaces.

2.8. Carrington Rotation 1719 (February 26 to March 24, 1982)

This rotation took place well after the peak of the sunspot cycle (September 1979). In Figure 8, one can see the 2-AU configuration viewed from the direction of longitude 120° (iii) brings out the source surface features at ~190° in longitude. There, the earth was slightly below the current sheet. The neutral line had a relatively simple sinusoidal curve, but its large amplitude (X ~ 40°) produced a serious warping of the current sheet. As a result, it is difficult to envisage the

Rotation #1699  R= 2 AU

Fig 7b) The heliospheric current sheets viewed from longitude 120° and latitude 20° at a distance of 2 AU
configuration without an effort of the type made here. Obviously, the corresponding 5-AU configurations (i, ii) are even more difficult to construct without considerable effort.

3. SUMMARY

The method developed by Hakamada and Akasofu [1982] is found particularly powerful in constructing the three-dimensional structure of the current sheet for “amplitudes” of less than 50°, which can be consistent with MHD solutions. Particularly, the success of constructing the trumpetlike structure may be noteworthy. The accuracy of the geometry of the current sheet can be improved without difficulty, if distribution of the solar wind speed on the source surface could be determined accurately. In this paper, the initial speed of the solar wind particles from the neutral line is assumed to be 300 km/s throughout the sunspot cycle. This speed and its gradient with respect to the latitude (more correctly a distance from the neutral line on the source surface) are likely to change during a sunspot cycle.

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