EVIDENCE FOR THE REVERSAL OF MAGNETIC FIELD POLARITY IN CORONAL STREAMERS

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Abstract

Faraday rotation observations are unique amongst radio occultation measurements in that they respond to magnetic field in addition to electron density, making it possible to probe the coronal magnetic field. Transients observed by Pioneer 6 Faraday rotation measurements in 1968 in the heliocentric distance range of 6-11 $R_{\odot}$ are shown to be caused by the radially expanding coronal streamer stalks of angular size 1-2° observed in white-light measurements rather than the magnetic bottles interpreted earlier. This identification makes available the first magnetic field observations of coronal streamers. The detection of the reversal of magnetic field polarity high in the corona provides observational evidence confirming what has previously only been inferred from modeling — that streamers observed in white-light measurements are the manifestation of the heliospheric current sheet. These results reinforce the apparent connection between the coronal streamer stalks and the plasma sheets in the solar wind identified by in situ fields and particles measurements beyond 0.3 AU.

Introduction

Radio occultation measurements using natural radio sources and spacecraft radio signals have probed the solar corona for many years [Hewish 1972, Bird and Edenhofer 1990, Coles 1993, Woo 1994, 1996a]. Based on a wide variety of radio propagation and scattering phenomena, these measurements include angular broadening, intensity scintillation, ranging, and others. Decades of observation have produced considerable information on electron density and its fluctuation, as well as solar wind velocity. Faraday rotation of a linearly polarized radio wave is unique amongst radio occultation measurements because it responds to the solar magnetic field, thus making it possible to probe the coronal magnetic field [Stelzried et al, 1970] and its fluctuation [Hollweg et al, 1982, Efimov et al, 1993, Sakurai and Spangler 1994].

Variations in radio occultation measurements that appear different from the background solar wind are often identified as transients. These transients represent either spatial or temporal variations, and it is not always possible to unambiguously distinguish the two. In this regard, occultation measurements are no different from in situ plasma measurements made by a single spacecraft during a brief encounter of the Sun without the benefit of imaging, For this reason, despite years of observat ion, the spatial feature most prominent in white-light coronagraph measurements and appearing as a transient in radio occultation measurements — the coronal streamer — was not recognized in occultation measurements until recently [Woo et al. 1995].

When Faraday rotation measurements of the solar corona were first conducted in 1968 by Pioneer 6, striking transients were observed superimposed on the steady-state polarization rotation [Levy et al. 1969]. Discerning spatial from temporal variation in these measurements is even more complicated, because not only is Faraday rotation a path-integrated measurement, it also depends on two plasma parameters — electron density and magnetic field. The purpose of this paper is to demonstrate that, while some Faraday rotation transients may be associated with coronal mass ejections [Bird et al. 1985], those observed by Pioneer 6 were coronal streamers rather than the magnetic bottles interpreted e arlier [Schatten 1970a]. Coronal streamers are a subject of considerable interest [Koutchmy and Livshits 1992, Poletto 1994, Kopp 1994], and identifying the Pioneer 6 transients as coronal streamers makes available for the first time observations of magnetic field in addition to electron density. The Faraday rotation measurements provide evidence for the reversal of magnetic field polarity, thus confirming observationally what has previously only been inferred from modeling [e.g., Pneuman and Kopp 1971, Schutz

1994] --- that streamers observed in white-light measurements are the manifestation of the heliospheric current sheet.

Pioneer 6 Radio Occultation Measurements

A linearly polarized radio wave propagating through a magnetized plasma such as the solar corona will display a rotation in its plane of polarization by an angle $\Delta\Psi$:

$$\Delta\psi = \frac{e^3}{2\pi m_e^2 c^2 f^2} \int n_e \mathbf{B} \cdot ds \qquad (1)$$

where n_e is electron density, **B** the coronal magnetic field, ds the incremental path length, f radio frequency, e electronic charge, m electron mass, and c the speed of light. The angle of rotation is positive when the magnetic field has a component in the direction of radio propagation,

Reproduced from Levy et al. [1969] in Fig. 1 is polarization angle as a function of universal time in 10s intervals for the three Faraday rotation transients observed by Pioneer 6 on November 4, 8, and 12 in 1968 when the closest approach distances of the radio path were 10.9, 8.6, and 6.2 R_o, respectively. The spacecraft was transmitting its 13 cm wavelength radio signal at a polarization angle of 90°; the observed background polarization is due to the effects of the ionosphere and corona. The Faraday rotation transients are strikingly similar. Each lasts a couple of hours, has a characteristic W-shaped signature, and is accompanied by a matching spectral broadening transient [Goldstein 1969].

Possible flare associations and an interpretation of the Faraday rotation transients in terms of magnetic bottles, that are at first expanding and then contracting, have been discussed by Schatten [1970a,b]. The magnetic bottle interpretation was based solely on the Faraday rotation measurements, leaving the enhanced density fluctuations (detected by spectral broadening) and their relationship to the magnetic bottle unexplained. Doubts have also been raised by Cannon [1976] because of the seemingly coincidental nature of the magnetic bottle interpretation. In the following section, coronal streamers arc demonstrated to be the more likely explanation for the Faraday rotation transients.

Corona] Streamers

Enhanced density fluctuations associated with propagating interplanetary disturbances and coronal streamers give rise to transients in both spectral broadening and Doppler scintillation measurements [Woo and Armstrong 1981, Woo et al. 1985, Woo et al. 1995]. Propagating disturbances are closely related to coronal mass ejections, with the enhanced density fluctuations apparently representing the compressive turbulence ahead of the mass ejections. On the other hand, the enhanced density fluctuations in coronal streamers reflect both the streamer's filamentary structures and the small-scale turbulence flowing through them. Although spectral broadening observes density fluctuations of frequencies higher than those of Doppler scintillation, the enhanced density fluctuations in both propagating disturbances [Woo et al, 1985] and coronal streamers [Woo and Habbal 1996] span a wide range of frequencies, leading to similar transient signatures for both spectral broadening and Doppler scintillation. While the signature of coronal streamers is a couple of hours long and roughly symmetric [Woo et al. 1995], that of propagating disturbances tends to be longer and asymmetric, commencing with a rapid rise followed by a slower fall-off [Woo and Armstrong 1981, Woo et al. 1985].

The similarity between the signatures of the Pioneer **6** spectral broadening transients and those of Doppler scintillation transients representing the extensions or stalks of coronal streamers in white-light measurements [Woo et al. 1995] provides the first hint that the Pioneer 6 Faraday rotation transients represent the same rather than propagating disturbances. The angular size of 1.2° corresponding to the approximate 2-hr duration is consistent with the size of streamer stalks in white-light images [Koutchmy and Livshits

1992]. The streamer interpretation is further supported by the fact that the enhanced density of streamers observed in ranging measurements [Woo et al, 1995] would produce a transient in polarization rotation. Further clues for the passage of a streamer come from the magnetograms of the Sun showing that the three transients overlie bipolar magnetic regions [Schatten 1970a] over which heliospheric current sheets arc expected to form. Also consistent with the streamer interpretation is the observation that the polarization returns to or approaches the pre- and post-transient levels midway through the Faraday rotation transient, giving the impression that the intervening plasma becomes 'invisible' there. At some point during its passage across the radio path, the streamer would appear invisible in spite of its high density, because the opposing magnetic field on the two sides of the heliospheric current sheet would produce approximately nullifying contributions to the Faraday rotation. Cannon [1976] found the frequency of occurrence of the Pioneer 6 transients intriguing because it suggested a repetitive regularly occurring solar process, This behavior can be more readily understood in terms of coronal streamers. The three Pioneer 6 transients were observed four days apart, corresponding to a longitudinal separation of about 53° and consistent with the angular separation of streamers observed in ccl ipse pictures of the solar corona near solar maximum.

Let us take a closer look at the coronal streamer scenario. Fig. 2 is the view from the north as the radially expanding coronal streamer on the west limb rotates with the Sun across the Pioneer 6 radio path. It is assumed that within the streamer the density is enhanced, and that the magnetic field reverses direction abruptly across the heliospheric current sheet, as observed in interplanetary space [e.g., Gosling et al. 1981]. The heliospheric current sheet is assumed to be oriented approximately in the north-south direction, as suggested by the orientation of the bipolar magnetic fields seen in the magnetograms of the Sun [Schatten 1970a]. Rotation of the streamer across the radio path is assumed to take place near the closest approach point of the radio path (point P in Fig. 2) where path-integrated measurements are most sensitive. The conspicuous detection in radio occultation measurements of streamers [Woo et al. 1995] rotating in a direction generally parallel to the radio path may be surprising. It suggests that the streamer depicted in Fig. 2 crosses from above to below or from below to above the radio path, and this will be assumed here. Since the angular sizes of the streamers high in the corona are small and their boundaries are abrupt, any tilt in the Sun's rotation axis with respect to the ecliptic plane, or non-radial alignment of the streamers could provide the conditions for this observed result.

Because the magnetograms show positive flux following negative flux in the three solar regions associated with the transients [Schatten 1970a], the magnetic field in Fig. 2 is depicted as inward pointing, As the streamer rotates across the radio path (Fig. 2a), the inward pointing magnetic field intercepts the radio path first, and the increasing density causes the polarization rotation to increase negatively (since the component of magnetic field along the radio path points from earth to spacecraft). Another reason for polarization to increase negatively is that density falls off with increasing heliocentric distance, and the contribution of the inward pointing magnetic field is greater because it is closer to the closest approach point,

When the outward pointing field following the heliospheric current sheet joins the inward pointing field in intercepting the radio path, the polarization rotation decreases negatively — the first reversal of the W-shaped signature. Near the closest approach point of the radio path, the inward and outward fields intercepting the radio path are approximately the same and the change in polarization rotation is minimum (Fig. 2b). As the streamer rotates beyond the closest approach point (Fig. 2c), the components of the magnetic field along the radio path reverse direction. As the component of magnetic field in the direction from earth to spacecraft increases, polarization rotation increases negatively — second reversal of the W-shaped signature — before decreasing (third reversal) when the streamer rotates away from the radio path.

It should be pointed out that if the magnetic field ahead of the rotating heliospheric current sheet were outward pointing rather than inward pointing as depicted in Fig. 2, then the W-shaped signature would become an M-shaped signature. In principle, quantitative information on the magnetic field can also be obtained through modeling and application of cq. [2] to the observed results. This will not be attempted here, since without the benefit of separate and independent measurements of density any estimates would necessarily have large uncertainties associated with them. The important result of the streamer explanation is that it confirms the reversal of magnetic field polarity.

Conclusions and Summary

The Pioneer 6 spectral broadening transients that were observed simultaneously — and not taken into account in the magnetic bottle interpretation — impose tighter constraints on the interpretation of the Faraday rotation transients, but at the same time have played a major role in the new interpretation by providing important clues that suggest coronal streamers. The coronal streamer identification appears to explain the major features of the Faraday rotation and spectral broadening transients, and opens up the possibilities of contrasting magnetic field fluctuations in the fast and slow solar wind. There is remarkable consistency not only amongst the diverse radio occultation measurements of coronal streamers but also in their relationship to white-light coronagraph and in situ fields and particles measurements.

Ranging measurements have confirmed the detection of the extensions or stalks of coronal streamers observed in white-light measurements [Woo et al. 1995], low time resolution Doppler scintillation has shown agreement with white-light measurements processed to enhance density gradients [Woo 1996a], multiple-station intensity scintillation measurements of solar wind velocity have suggested that the streamer stalks are the sources of the slow solar wind [Woo 1995], high time resolution Doppler scintillation measurements have uncovered strong fine scale structures inside the streamer stalks [Woo et al. 1995], high fluctuation frequency phase scintillation and spectral broadening measurements have shown that the finest structures in coronal streamers are substantially finer than those in the fast wind associated with coronal holes [Woo and Habbal 1996], and Faraday rotation measurements have now provided the first observational evidence for the reversal of magnetic field polarity in coronal streamers. The frequency of occurrence of the Pioneer 6 streamers is consistent with the angular separation of streamers in eclipse pictures taken near solar maximum. Since Faraday rotation is a path-integrated measurement and depends on both electron density and the component of magnetic field along the radio path, deducing meaningful profiles of density or magnetic field are difficult without additional information.

Superposed epoch analyses of plasma measurements at 1 AU have demonstrated that regions of high density [Gosling et al. 1981] and high density fluctuations [Huddleston et al. 1995] encompassing the heliospheric current sheet are the interplanetary manifestation of coronal streamers. Further investigation based on high time resolution fields and particles measurements has identified a smaller region of enhanced density (of angular size 1-2°) surrounding the current sheet as the heliospheric plasma sheet [Winterhalter et al. 1994]. The plasma sheet is believed to be the interplanetary counterpart of the radially expanding streamer stalk (of angular size 1-20), which is observed in white-light measurements and also as a region of enhanced fine-scale structure in Doppler scintillation measurements [Bavassano et al. 1996]. The evidence for the reversal of magnetic field polarity in the streamer stalks provided by the Faraday rotation measurements reinforces this important interplanetary connection, suggesting that plasma sheets are the source regions of the slow solar wind. The clear W-shaped signature observed in the Pioneer 6 measurements appears to imply that a single heliospheric current sheet crossing takes place, as is observed in plasma sheets [Winterhalter et al. 1994], but the resolution of the path-integrated Faraday rotation measurements could mask multiple current sheet crossings or multiple current sheets [Crooker et al. 1993, Dahlburg and Karpen 1995].

Radio occultation measurements show a near-Sun corona that is rich in structure and temporal variation, some of which is not yet fully understood. For instance, in the case of the 1968 Pioneer 6 spectral broadening measurements [Goldstein 1969], two other transients not accompanied by corresponding Faraday rotation transients were also observed. It is clear that the gains in knowledge and understanding of the deduced plasma variations of coronal streamers and plumes [Woo 1996b] are making it possible to further exploit the unique probing abilities of radio occultation measurements in exploring additional features and events in the solar corona.

Acknowledgments. It is a pleasure to thank J.W. Armstrong and C.T. Stelzried for many useful and stimulating discussions. 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.

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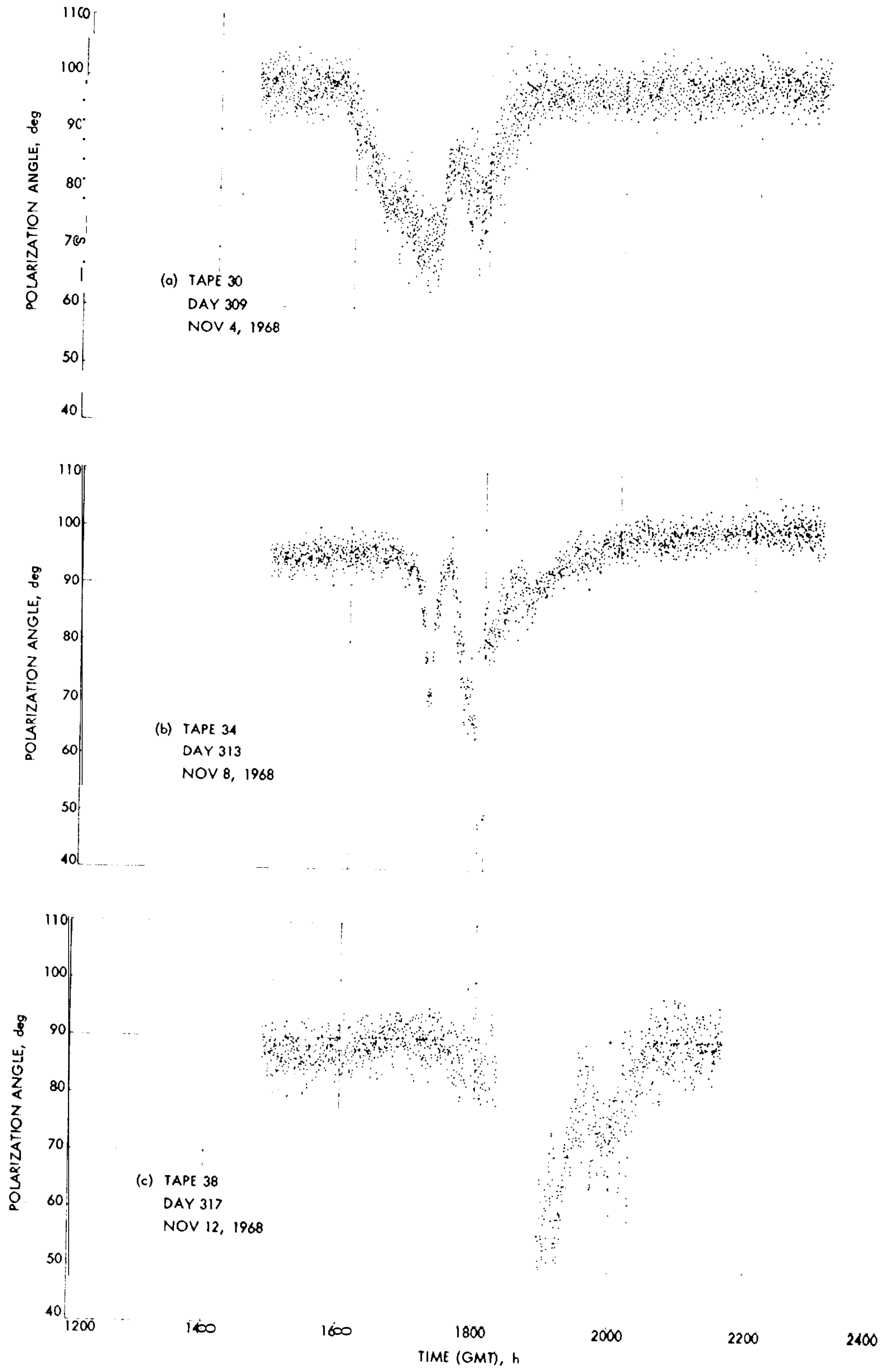

POLARIZATION ANGLE, deg
110
100
90
80
70
60
50
40
(a) TAPE 30
DAY 309
NOV 4, 1968
POLARIZATION ANGLE, deg
(b) TAPE 34
DAY 313
NOV 8, 1968
POLARIZATION ANGLE, deg
(c) TAPE 38
DAY 317
NOV 12, 1968
1200
1400
1600
1800
2000
2200
2400
TIME (GMT), h

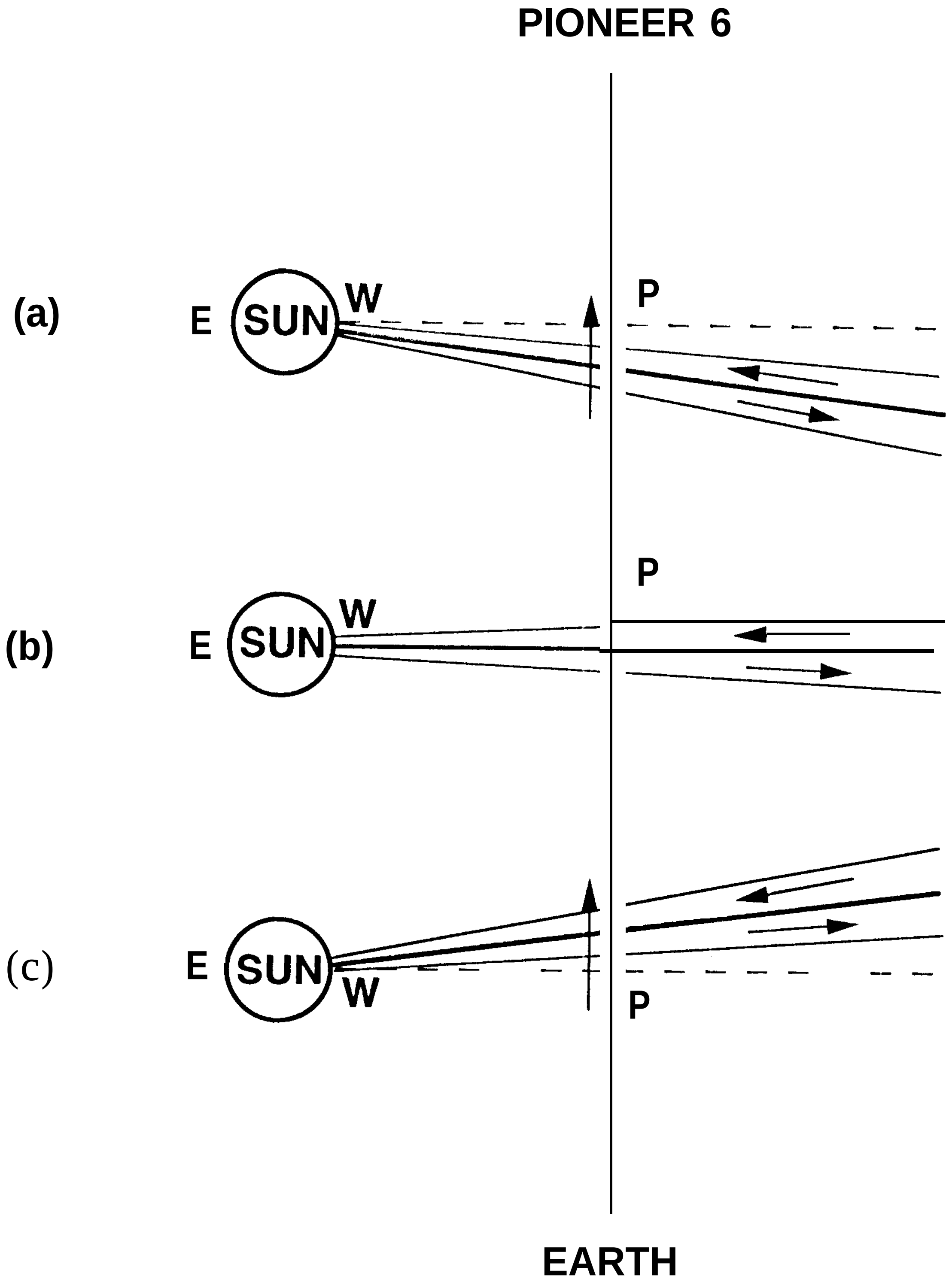

Fig. 2