Faraday Rotation Observations During the 1970 Pioneer 9 Solar Occultation

A. R. Cannon
University of California, Berkeley

C. T. Stelzried
Communications Elements Research Section

J. E. Ohlson
Naval Postgraduate School

The Faraday rotation of the Pioneer 9 S-band signal was measured during the December 1970 solar occultation using the NASA/JPL 64-m Goldstone antenna. Steady-state Faraday rotation was significant over the region of 4-12 solar radii, reaching a maximum value of about 100 deg at 4 solar radii. Two transient Faraday rotation events were observed and related to solar phenomena. The Pioneer 9 steady-state Faraday rotation was similar to that observed during the November 1968 Pioneer 6 solar occultation. The first Pioneer 9 transient appears to be of the same form, magnitude, and duration as the three remarkable W-shaped Pioneer 6 transient events. The second Pioneer 9 transient was smaller in amplitude, had an S-shaped curve of longer duration, and in general was unlike the previous events. These two events occurred at approximately 6 solar radii. The Pioneer 6 observations did not extend beyond 12 solar radii, while Pioneer 9 was tracked to approximately 64 solar radii. No transient events were observed in this outer region.

The region of the solar corona from a few solar radii out to where the solar wind flow becomes super-Alfvenic at about 20–30 solar radii has been very difficult to study. An understanding of the processes occurring in this region is important because it is here that the solar wind is formed and many complex phenomena may occur. The recent advent of deep space probes and the completion in 1966 of the NASA/JPL 64-m parabolic dish at Goldstone, California, have greatly expanded our observational capabilities by enabling us to probe the corona with very narrow band continuous wave signals, of one or more distinct frequencies, and having definite polarizations. The present construction of other large antennas and the use of spacecraft like Helios, which are specifically designed to study the near-Sun region, promise to contribute significantly to our understanding of solar phenomena.

The solar occultation of Pioneer 6 in 1968 provided the first opportunity to observe the Faraday rotation of a linearly polarized S-band signal in the solar corona. Simultaneous measurements of polarization (Ref. 1) and

of spectral effects (Ref. 2) produced dramatic results and established the deep space probe as a valuable tool for studying the elusive coronal region near the Sun. The success of the Pioneer 6 experiment encouraged a major effort during the Pioneer 9 occultation in December 1970.

It has been shown (Ref. 3) that the net polarization rotation of a spacecraft signal traversing the solar corona is effectively given by the quasi-longitudinal approximation, in which the polarization rotation is proportional to the product of the electron density and the magnetic field component along the ray path, integrated along the entire line of sight from the probe to the observer:

$$\Omega_L = \frac{QL}{f^2} \int N(s) B_L(s) \, ds$$

where

Ω_L = Faraday rotation, deg

f = signal frequency, Hz

N = electron density, M^{-3}

B_L = longitudinal component of magnetic field, gauss

Q = 135.4816

L = units scaling factor for ds (L = 1 if ds in meters, $L = 6.9598 \times 10^8$ if ds in solar radii)

ds = element of length along ray path

Thus, a large Faraday rotation could result from either a high electron density or a large net longitudinal field component. On the other hand, high electron densities and strong magnetic fields could produce no net Faraday rotation if the field orientations are such as to cancel out in the integral.

The spacecraft is spin-stabilized with its antenna normal to the ecliptic plane. It transmits a linearly polarized S-band signal at 2.3 GHz, which was received on the 64-m Goldstone antenna. The polarization angle of the received signal was measured with the closed-loop tracking polarimeter developed for the Pioneer 6 occultation (Ref. 4). This polarimeter is very responsive and is capable of tracking the polarization angle to hundredths of a degree. It is uncertainties in the effect of Earth's ionosphere that really limit our ability to measure small Faraday rotation effects in the corona and prevent us from seeing the interplanetary medium far from the Sun (Ref. 5).

Figure 1 shows the orbits of both Pioneers 6 and 9 relative to a fixed Sun–Earth line. Tracking of Pioneer

9 was begun on October 2, 1970, when the spacecraft line of sight was 64 solar radii west of the Sun, and continued through January 28, 1971, when the line of sight was 24 solar radii east of the Sun. The Pioneer 9 observations were extended much farther from the Sun than Pioneer 6, but no coronal effects could be distinguished from the ionosphere in this outer region.

Daily averages of the observations referred to the plane of the ecliptic (Ref. 6) made within 12 solar radii of the Sun are shown in Fig. 2. These observations are uncorrected for the Earth's ionosphere. As the Pioneer 9 line of sight moved within 12 solar radii, the polarization measurements appeared to increase slightly above the maximum ionospheric effect. At 7.5 solar radii, the signal polarization angle dropped below 90 deg for the first time, and decreased steadily to about 100 deg below predicts when the spacecraft was lost at 4.3 solar radii. The last data points could be regarded as having ambiguities of multiples of 180 deg, since the polarization angle could have rotated by such amounts during the intervals between spacecraft set and spacecraft rise. The Pioneer 9 signal was reacquired 12 days later at 5.3 solar radii on exit with a polarization angle of 120 deg— again ambiguous by multiples of 180 deg. The polarization decreased steadily to 87 deg and then increased to the normal ionospheric level at about 12 solar radii.

The steady-state rotation observed during the Pioneer 9 occultation was remarkably similar in both sense and magnitude to that seen by Pioneer 6 two years earlier. The Pioneer 6 observations were analyzed in conjunction with coronal magnetic field constructions based on both solar magnetograph data and interplanetary spacecraft data. These efforts resulted in an electron density model for the corona at the time of the observations and provided a test of K. H. Schatten's coronal model (Ref. 7). A similar analysis is now being carried out on the Pioneer 9 data. This should provide a further comparison of coronal models and also provide some idea of the changes that occur during the solar cycle.

Two large transient events were also observed, one on Day 345 at 5.9 solar radii west of the Sun, and the other on Day 360 at 6.2 solar radii east of the Sun. Figure 3a shows the Pioneer 9 data for Day 345. Two periods of high system temperature caused by the antenna side lobe structure rotating across the Sun are apparent in the periods of high scatter at the beginning and end of the track. The system temperature rose to about 400 K during these periods and the receiver lock was very weak. Near the end of the track the polarization angle

decreased rapidly by about 45 deg, returned to its original level in about 30 min, and then was decreasing rapidly again as the spacecraft set. Due to the poor receiver lock, our classification of this as an event caused by the solar corona is based largely on operator confidence. The very large amplitude and negative direction eliminate the ionosphere as a possible source.

This event, insofar as it was observed, appears to be very similar to the three remarkable W-shaped impulsive events seen during the Pioneer 6 solar occultation in 1968. These are shown in Fig. 4. Each has an amplitude of about 40 deg and a duration of about 2 h. In view of the fact that these events occurred at such different distances from the Sun, and over a period of eight days, during which the Sun rotated by about 110 deg, thus changing the coronal regions probed by the ray path, it seems remarkable indeed that all three events should have the same sense of rotation, signature, amplitude, and period. The Pioneer 6 events also produced considerable broadening of the signal spectrum, observed simultaneously by R. M. Goldstein of JPL. Unfortunately no spectral measurements were made during the entry phase of the Pioneer 9 occultation.

The Pioneer 6 events have been associated with solar flares on or near the limb of the Sun nearest the signal ray path (Refs. 8 and 9). The average propagation speeds of the disturbances resulting from these identifications range from 80–340 km/s. The Pioneer 9 event is not so readily identified with possible flare sources due to the virtual absence of flares in western longitudes. The only flare occurring near the limb was a subflare which would require a disturbance speed of 22 km/s. There was a larger flare near the central meridian that would require a disturbance propagating across some 90 deg of solar longitude with an average speed of 1100 km/s. Of course, the event could have been caused by a flare which occurred beyond the limb, or might be due to sources not directly associated with optical flares. It is worth noting that several active regions which had previously produced a number of subflares were located just beyond the west limb, and there was very bright coronal green line emission on both the northwest and southwest limbs several hours before the Pioneer 9 transient.

There are a number of possible interpretations of these events. They could, for example, be caused by pairs of flares or by flares having two or more maxima. They could also be due to high-density clouds of electrons, kinks in magnetic field lines, or magnetic reconnection. One particularly interesting suggestion has been made

by K. H. Schatten (Ref. 10), who pointed out that the events could be explained by a coronal magnetic bottle. A flare, occurring in a bipolar region, might carry field loops across the line of sight, until the tension in the field lines is finally able to contain the expansion and then contract back across the line of sight again. Such a bottle might explain many coronal phenomena, including the storage of cosmic ray particles.

The fact that the same type of event has been observed in four of the five Faraday rotation transients seen so far suggests that this may represent some fundamental characteristic of solar activity—as opposed to mere coincidence—and may provide a new insight into the mechanisms of such phenomena as flares.

A fundamentally different transient event was observed on Day 360. This is illustrated in Fig. 3b. The receiver lock was good during this event, but the event was still in progress when the spacecraft set. Even so, the observed duration (about 5 h) is much longer than any of the previous events. The amplitude is much less and the signature is quite different. The polarization angle decreased by about 7 deg and then increased to about 7 deg above the original level and appeared to be leveling off as the track ended.

There were several subflares and a flare near the west limb which might be considered as possible sources. The most likely candidate was a flare of importance 1N which occurred within 18 deg of the east limb and would require a disturbance velocity of 120 km/s, which is consistent with the Pioneer 6 identifications. There were two active regions beyond the limb which became visible on Day 361 and produced several subflares on succeeding days. There was very little green line emission during this period.

Again, there are several possible explanations, including a large kink in the field lines, a compression followed by a rarefaction as might occur in a shock wave, and an X-type configuration or closed magnetic loop that might result from magnetic reconnection. Fortunately, we also have measurements of the signal spectrum during this event. These measurements have yet to be analyzed, but it is hoped that the behavior of the spectrum will shed additional light on the mechanisms responsible for the event.

One of the intriguing questions still to be answered is "How far from the Sun can these transient events be

observed?" One of the reasons the Pioneer 9 observations were extended to such large distances from the Sun was to search for impulsive events in this outer region. The fact that no events were observed does not preclude the possibility of their existence since none may have occurred, or they may have been so diffuse as to be obscured by ionospheric effects. There were three flares and a number of subflares which occurred near the east limb during the exit phase without producing noticeable polarization effects. The disturbances may not have crossed the line of sight during our view periods or they may have passed unobserved due to the magnetic field geometry involved. At any rate, not every eligible flare produces an observable effect on the signal, particularly at distances beyond 10 solar radii. This suggests that perhaps some flare disturbances do not escape from the Sun. The physical interpretation of the transient events, or lack of events, as the case may be, is still in progress. It is hoped that these unique observations will provide some new insights into coronal processes and their effects on deep space (probe) tracking at small Sun–Earth–probe angles.

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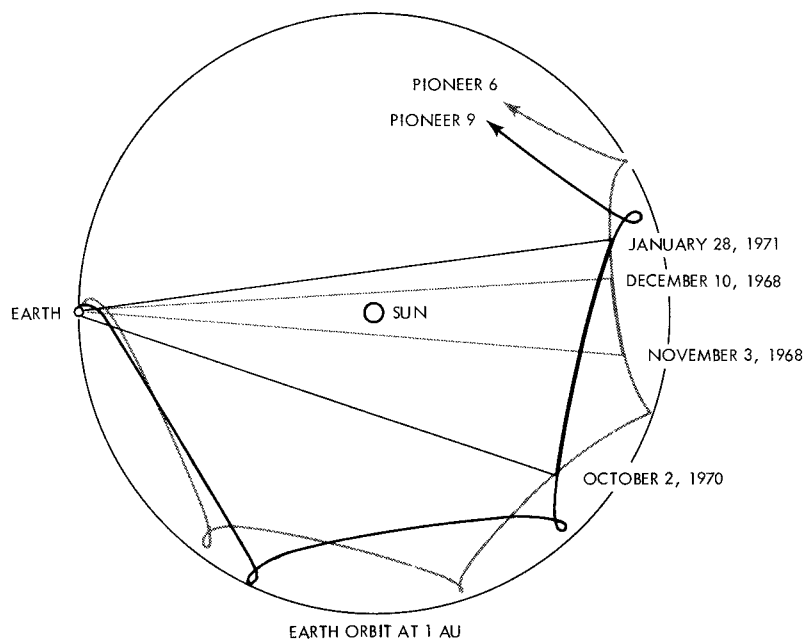
Fig. 1. Projection of fixed Sun–Earth line trajectories on plane of ecliptic
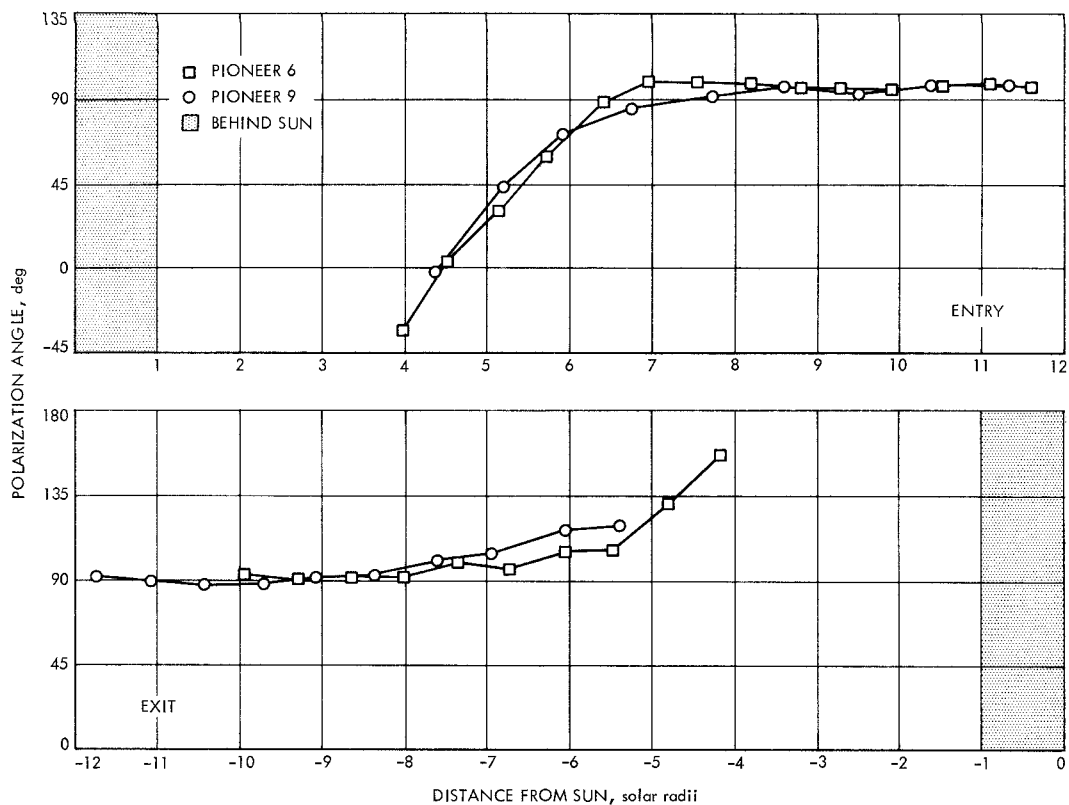

DISTANCE FROM SUN, solar radii

Fig. 2. Pioneer 6 and 7 polarization angles (referred to plane of ecliptic, uncorrected for ionosphere) vs distance from Sun
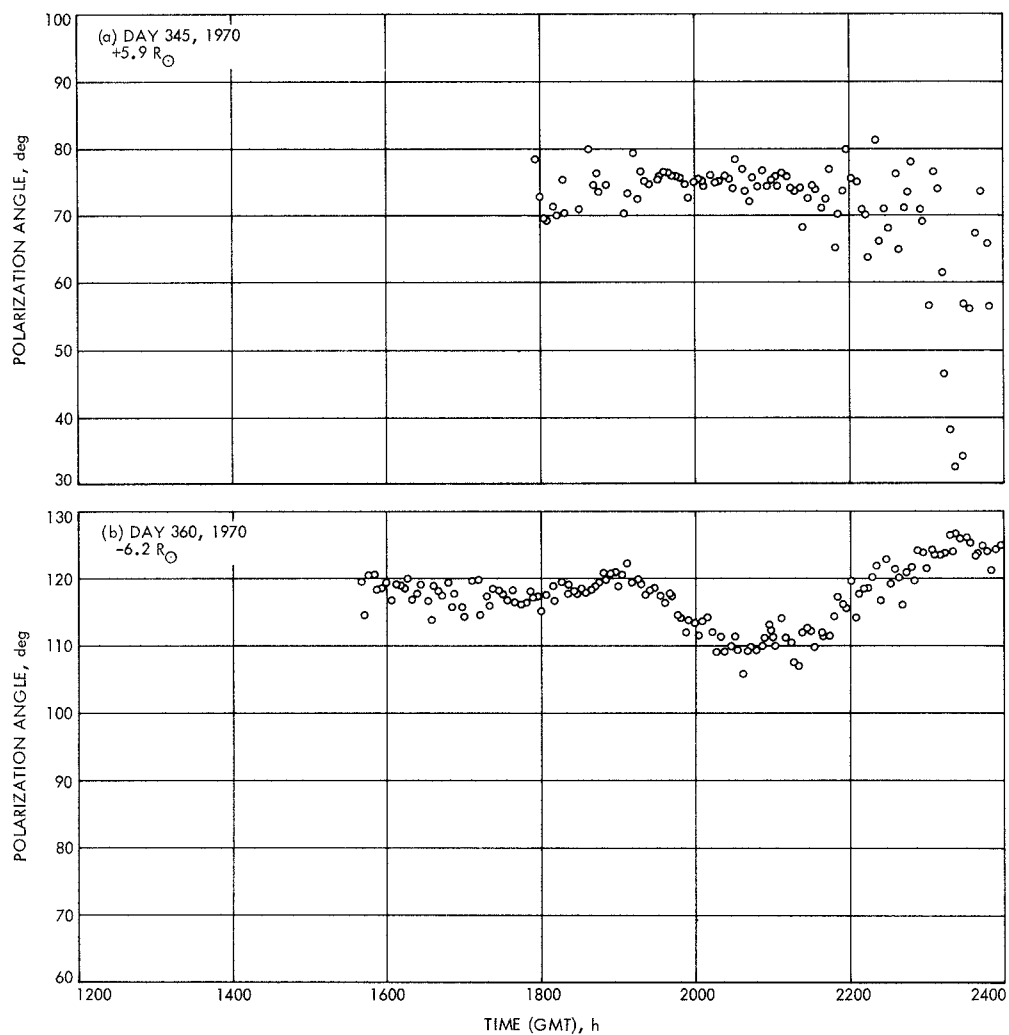
Fig. 3. Pioneer 9 signal polarization (200-s data points, referred to ecliptic, and uncorrected for ionosphere) vs time
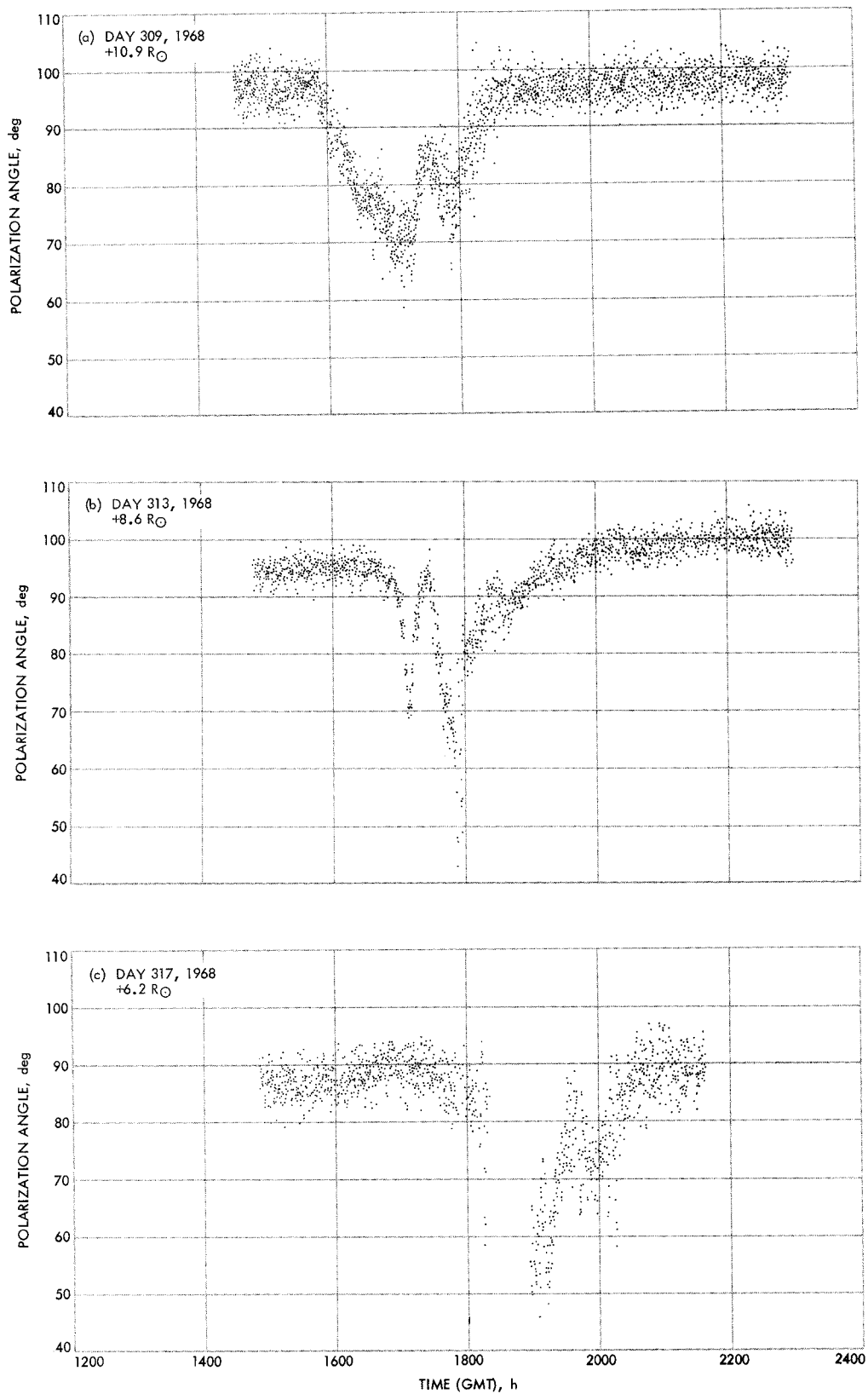
Fig. 4. Pioneer 6 signal polarization (10-s data points, referred to ecliptic, and uncorrected for ionosphere) vs time