Reports

Pioneer 6: Measurement of Transient Faraday Rotation Phenomena Observed during Solar Occultation

Abstract. *Pioneer 6, which was launched into orbit around the sun on 16 December 1965, was occulted by the sun in the last half of November 1968. During the period in which the spacecraft was occulted by the solar corona, the S-band telemetry carrier underwent Faraday rotation as a result of this anisotropic plasma. The NASA–Jet Propulsion Laboratory 210-foot (64-meter) antenna of the Deep Space Network at Barstow, California, which was equipped with an automatic polarization tracking system, was used to measure this effect. Three large-scale transient phenomena were observed. The measurement of these phenomena indicated that Faraday rotation on the order of 40 degrees occurred. The duration of each phenomenon was approximately 2 hours. These phenomena appear to be correlated with observations of solar radio bursts with wavelengths in the dekametric region.*

The Pioneer 6 spacecraft was launched into an orbital trajectory around the sun on 16 December 1965. The completion of the 210-foot (64-meter) Advanced Antenna System, the implementation of a very low noise receiver system, and the reliability of the vehicle transmitter have made it possible to track Pioneer 6 throughout its orbit around the sun (*1*). A closed-loop polarimeter (*2*) was developed so that the orientation of the polarization could be automatically tracked. The technique not only maximized the received signal strength but yielded precise data on polarization as well.

Figure 1 shows a projection of the position of Pioneer 6 on the plane perpendicular to the sun-earth line. As the line of sight between the earth and the probe approached the sun, the telemetry signal passed through increasingly denser regions of the solar corona. Since the linearly polarized high-gain antenna of the spacecraft was spin-stabilized with respect to the plane of the ecliptic, it was possible to measure rotation of the plane of polarization produced by the interaction of the microwave signal with the magnetized plasma of the propagation medium.

The polarization measurements became increasingly difficult as the sun-earth-probe angle decreased. This was due both to the increase in system temperature from solar microwave radiation and to the spectral broadening of the carrier produced by distortion in the solar corona. Measurements of polarization angle with the automatic tracking system commenced 26 October 1968 and continued during the viewing periods at Goldstone (California) until 16 November when the signal-to-noise ratio deteriorated below the useful level. From 21 November through 24 November 1968, Pioneer 6 was geometrically occulted by the photosphere. The signal was reacquired on 29 November, and the experiment was continued until 8 December when the station was assigned to the Apollo 8 mission.

A magnetoionic medium appears doubly refracting to radio waves; thus a linearly polarized signal is split into characteristic elliptically polarized components with different phase velocities. At the down-link frequency of Pioneer 6 (2.292 Ghz) these generally elliptical components can be considered circular. The relative phase shift suffered by these two components caused the plane of polarization of the resultant linear signal to be rotated with respect to the incident polarization (*3*). The Faraday rotation Ω (in rotations) is given by

$$\Omega = \frac{1}{4\pi^2}\frac{e^3 c}{m^2 f^2}\int_0^L H(s)N(s)\,ds$$

where e is the charge on an electron (1.6×10^{-20} in centimeter-gram-second units), c is the velocity of light (3×10^{10} cm/sec), $H(s)$ is the component of

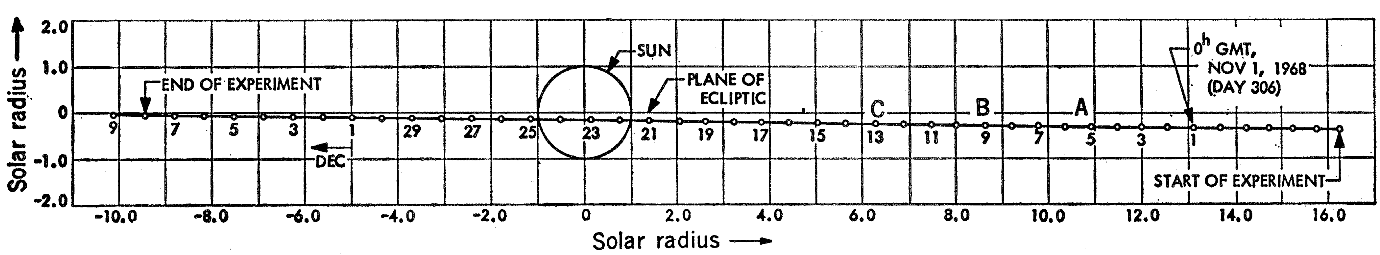


Fig. 1. Projection of Pioneer 6 orbit relative to the plane of the ecliptic.

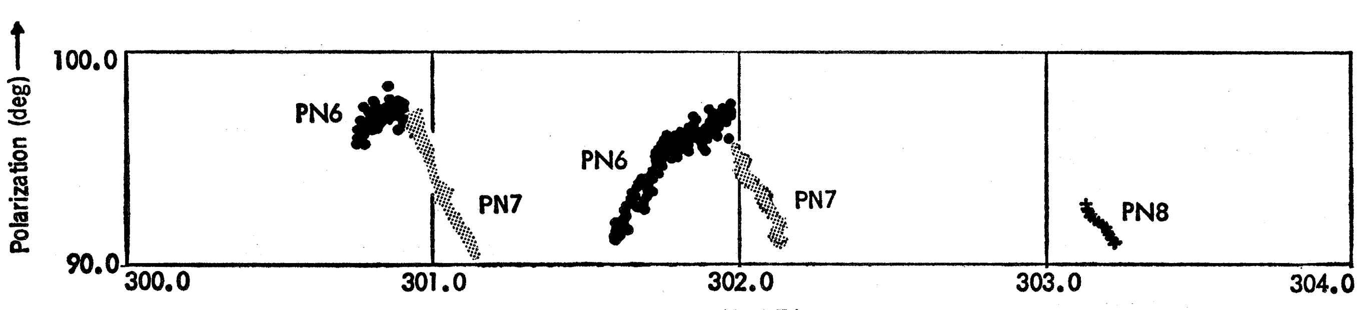


Fig. 2. Polarization as a function of time for observations of Pioneers 6, 7, and 8 in late October 1968.

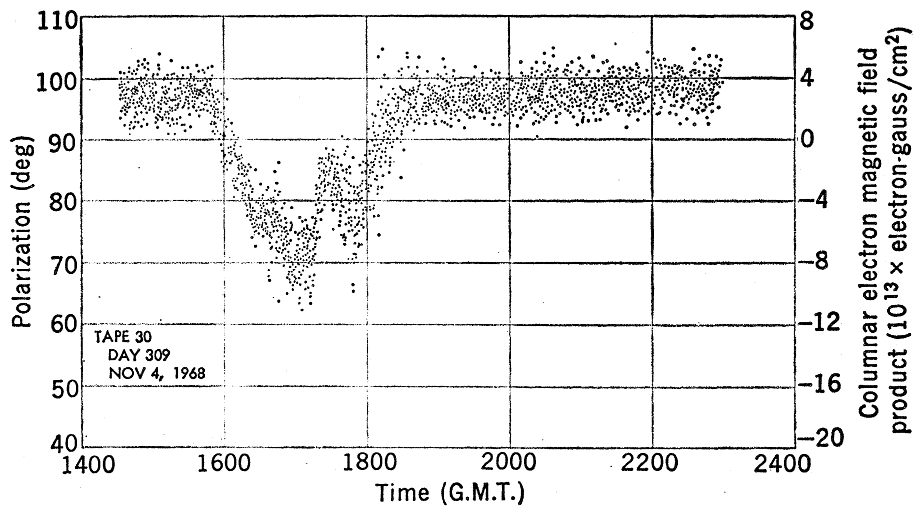
the magnetic field along the line of sight at s (in gauss), $N(s)$ is the number of electrons per cubic centimeter at point s, m is the mass of an electron (9.1×10^{-28} g), f is the frequency of the radio waves in hertz, and L is the path length of the ray in centimeters.

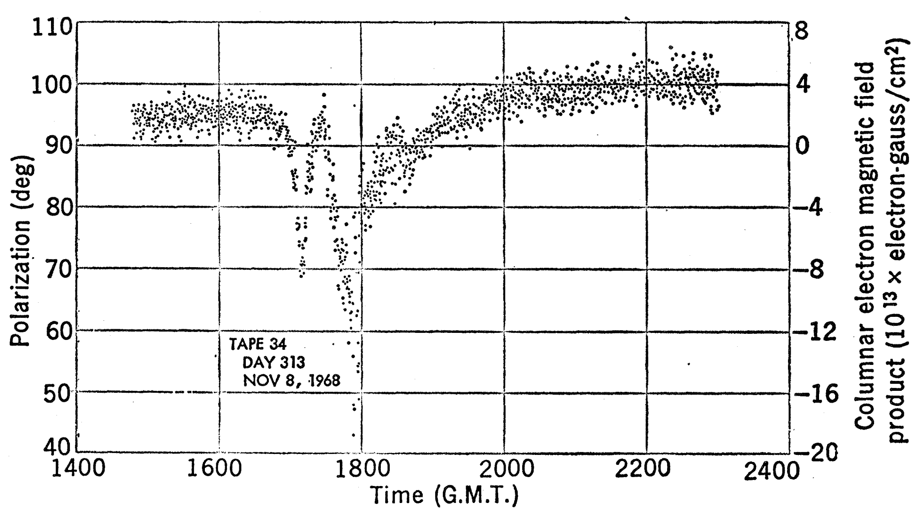
Rotation can be expressed in terms of the integrated product of the columnar electron content and the magnetic-field component. At the Pioneer 6 down-link frequency, 1° of rotation is produced by 3.9×10^{12} electron-gauss/cm^2.

The polarimeter angle was digitally recorded every 10 seconds during actual observation. These data were transformed to an angle with respect to the plane of the ecliptic. Initially, a nominal 30-second time constant was used in the servo loop. The data from 26 through 29 October 1968 are shown in Fig. 2. In this figure, polarization angle is presented as a function of time for observations of Pioneers 6, 7, and 8. Each point is an average of 20 measurements for 200-second averaging. The most conspicuous feature of this graph is the diurnal variation due to the earth's ionosphere. The ranges of Pioneers 6, 7, and 8 (in astronomical units) were approximately 1.9, 1.2, and 0.4, respectively. The relative scatter of measurements increases with increasing range from the earth, thereby reducing the signal-to-noise ratio. In the case of Pioneer 6, the line of sight of the spacecraft was approximately 15 solar radii from the center of the sun; thus, there was also a slight increase in the noise temperature of the system due to microwave thermal radiation in the side lobes of the antenna.

In Fig. 3 polarization is plotted as a function of time for 4 November 1968. One measurement point for every 10-second period is shown. A time constant for the servo loop of 30 seconds was used. This polarization transient (labeled A in Fig. 1) occurred at a distance of 10.9 solar radii from the center of the sun. The next polarization transient was observed on 8 November (Fig. 4). The servo time constant had been increased to 300 seconds. This transient (labeled B in Fig. 1) occurred 8.6 solar radii from the solar center. The last observed polarization transient (Fig. 5) occurred 12 November. Unfortunately, there was a loss of data during the first 45 minutes of this transient as a result of operational problems. This transient (labeled C in Fig. 1) occurred at a distance of 6.2 solar radii.

In the first two events, the base line is approximately 97°. The positive direction of the base line above 90° can be interpreted as due primarily to the earth's ionosphere, with interaction between electrons and the longitudinal components of the magnetic field of the earth. Any increase in the electron content of the ionosphere would cause an increase in polarization angle; a decrease in the number of electrons could not reduce the angle below 90°. In order to produce the phenomena observed, there must have occurred either





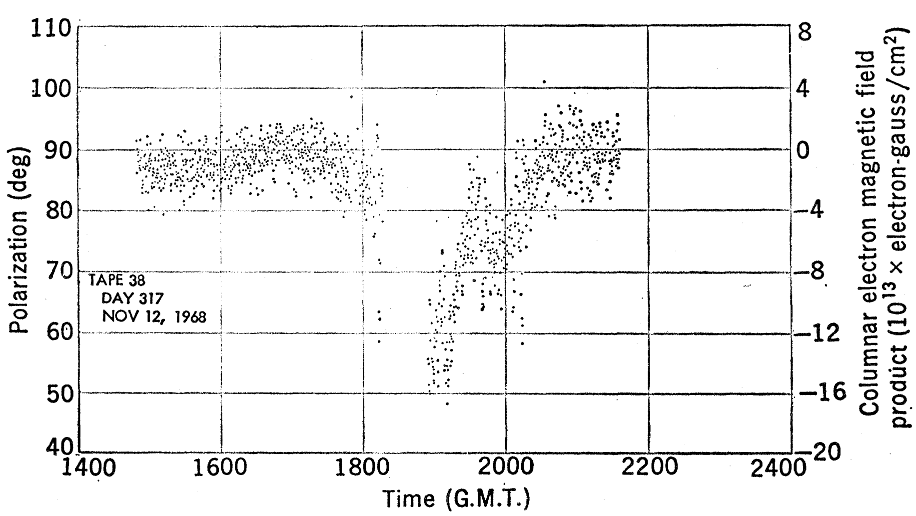


Fig. 3 (top). Polarization as a function of time, 4 November 1968. Fig. 4 (middle). Polarization as a function of time, 8 November 1968. Fig. 5 (bottom). Polarization as a function of time, 12 November 1968.

Table 1. Correlation of Faraday rotation transients and radio bursts in the dekametric range.

Dekametric noise burst* (U.T.)	Intensity†	Velocity ($10^3 \times$ km/sec)
4 November 1968 (1700 U.T.) (10.9 solar radii from solar center)		
1244		0.45
1305		.49
1457	2	.93
1502	2	.97
1522	2	1.17
8 November 1968 (1730 U.T.) (8.6 solar radii from solar center)		
1631	3	1.49
12 November 1968 (1900 U.T.) (6.2 solar radii from solar center)		
1643	3	0.44
1647	2	.43
1726	3	.64
1746	1	.82

* All bursts in the dekametric range were of type III. † Intensity scale: $3 > 2 > 1$.

a change in the sign of the particles in the ionosphere or a large concentration of electrons in a region where the longitudinal component of the magnetic field is in the opposite direction to the magnetic field of the earth. These considerations demonstrate that the phenomena were produced by plasma near the sun.

In the third event, the base line was approximately 87°. The reason for the change in base line appears to be an increase in the steady-state plasma density and magnetic field as the line of sight approached the sun. At the same time that these polarization measurements were being made, Goldstein (*4*) was using the same antenna to measure spectral broadening. Enhanced spectral broadening was observed during all three of the Faraday rotation transients. Enhancement of spectral broadening is consistent with an increase in the turbulence and density of the coronal portion of the line of sight.

Two possible explanations for the observed transient polarization effects are (i) a quasi-stationary structure which is probed as the line of sight is swept through, or (ii) a moving plasma concentration which is ejected by the sun. If we assume that we are seeing fairly stationary objects, then we can determine one dimension of these objects in terms of the time it took to sweep through them. Since the duration of each event was approximately 2 hours and the velocity of the line of sight relative to the plane containing the sun was approximately half a solar radius per day, the dimensions of these objects are of the order of 0.04 solar radius. If, on the other hand, we were observing a high-velocity concentration of plasma ejected from the sun, we would expect to find correlation with surface effects. On the 3 days that these transients were observed, there were active areas observed near the west limb where the observations were made. These areas were observed (*5*) by means of several mapping surveys at different radio frequencies. The events were poorly correlated with optical flares. However, in each case it appears that noise-burst events in the dekametric wavelength region preceded these transient Faraday rotation phenomena. On 8 November, the only events in the dekametric range that were reported prior to the Faraday rotation transient occurred between 1631 and 1632 and were classified, respectively, as intensity 1 and 3. On both 4 and 12 November there were many bursts. All bursts with wavelengths in the dekametric range which occurred within 11 hours before the Faraday rotation transient are listed in Table 1 along with the reported intensity (where available). Furthermore, we have calculated the velocity that the plasma clouds must have had if they were produced by the same mechanism that produced the noise bursts in the dekameteric range (Table 1).

Unfortunately, the locations of the origins of these noise bursts in the dekametric range on the photosphere were not known. Only three transients were observed in a period of high solar activity; thus the significance of the correlation with noise bursts is not known at this time. An effort is being made to see if other solar and interplanetary phenomena can be correlated with the Faraday rotation transients.

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6. We acknowledge the cooperation and support of the personnel at the Pioneer Project Office and the Deep Space Network, and particularly of D. Girdner and the operational personnel at the Jet Propulsion Laboratory Mars site. We also thank D. Bathker, F. McCrea, and R. Cormack for their work in developing the microwave portion of the system. W. Peterschmidt supplied the servo electronics, and B. Parham assisted with the digital instrumentation. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory under NASA contract NAS 7-100.

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Superior Conjunction of Pioneer 6

Abstract. *Spectrograms of the radio signals from Pioneer 6 were taken as the spacecraft was occulted by the sun. The spectral bandwidths increased slowly at first, then very rapidly at 1 degree from the sun. In addition, six solar "events" produced marked increases of bandwidth lasting for several hours. The received signal power seemed unaffected by the solar corona.*

The remarkable lifetime of the Pioneer 6 spacecraft, still operating 3.5 years after launch, has provided us with a rare opportunity to examine the solar corona. Pioneer 6 was injected into solar orbit 16 December 1965 and ever since has reliably transmitted to earth by S-band telemetry the results of its scientific experiments. Last November Pioneer 6 traveled directly behind the sun so that the telemetry signals passed through the interesting regions of the corona.

The corona is a very difficult object to study. The best data have been obtained only during the rare event of a total solar eclipse. Recently, radio astronomers have observed the scintillation of radio stars as they pass behind the sun, in order to draw conclusions about the corona. Radio stars are wide-band sources of radiation, and scintillation can be thought of as a manifestation of multipath phenomena. The Pioneer 6 signals, on the other hand, were extremely narrow-band (monochromatic) and give information of an entirely different kind about the corona.

During the superior conjunction of