# EVIDENCE FOR A CORONAL MAGNETIC BOTTLE AT 10 SOLAR RADII

KENNETH H. SCHATTEN*

*Laboratory for Space Sciences, NASA-Goddard Space Flight Center, Greenbelt, Md., 20771*

(Received 10 November, 1969)

**Abstract.** The Faraday rotation of a radio source (Pioneer 6) occulted by the solar corona has been measured by Levy *et al.* (1969).

During the course of these measurements, three large-scale transient phenomena were observed. These events were preceded by subflares and class 1 flares. These transient events are interpreted as evidence for a coronal magnetic bottle at 10 $R_\odot$. The velocity of propagation for the disturbance is set at 200 km/sec; the dimension of the region, 10 $R_\odot$; field strength at 10 $R_\odot$, 0.02 G; particle density, $2.0 \times 10^1/\text{cm}^3$; Alfvén speed, 320 km/sec. From the nature of the observations and the lack of related effects from similar flares on the interplanetary sector pattern observed at 1 AU, it is suggested that such coronal magnetic bottles expand to perhaps 10–30 $R_\odot$ and then contract to a few solar radii. Such a phenomena is evidence for an expansion of the corona with a sub-Alfvénic velocity. It is further suggested that such magnetic bottles may be important in the storage and diffusion of solar generated cosmic ray particles.

## 1. Observations

The magnetic field of the solar corona from 4 to 16 $R_\odot$ has indirectly been measured by Levy *et al.* (1969). They measure the Faraday rotation of the microwave signal transmitted by Pioneer 6 as the signal passes through the solar corona. This provides a measure of the line integral of the electron density multiplied by the component of the magnetic field along the line of sight to the spacecraft. They report three large scale transient phenomena with Faraday rotations on the order of 40° with a duration of approximately 2 h. These Faraday rotation signals were observed when the distances from the Sun to the Pioneer 6-earth line of sight were 6.2, 8.6 and 10.9 $R_\odot$.

Figure 1 from Levy *et al.* (1969) shows the polarization angle of the radio signal in degrees vs universal time on November 12, 1968. The time interval between points is 10 sec. The spacecraft was transmitting its signal at a polarization angle of 90°. The background Faraday rotation is due to the effects of the ionosphere and the corona.

Levy *et al.* identified these events with Type III solar radio bursts, however, Schatten (1970) gives evidence that a different series of flares were responsible for these events. Levy *et al.* (private communication) concur with the new identifications which are shown in Table I. Approximate velocities of transport are calculated by dividing the distance from the Sun to the Pioneer 6-earth line of sight by the time between the flare and the observed Faraday effect. Average velocities of about 200 km/sec are obtained.

* NAS-NRC Postdoctoral Resident Research Associate.

*Solar Physics* **12** (1970) 484–491. 

TABLE I

Identification of Faraday rotation events with flares

| Date (1968) | $r/R_\odot$ | Faraday rotation (U.T.) | | Flare associated with Faraday rotation event | | | | | $\Delta T$ HR:min | $\bar{V}$ km/sec | Corrected area sq. degrees | Degrees from west limb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Max. | Start | Start | Max. | McMath plage number | Location heliographic coordinates | Importance | | | | |
| Nov. 4 | 10.9 | 1700 | 1550 | 0520 | 0614 | 9740 | S15 W90 | 1B | 10:30 | 200 | 4.8 | 0 |
| | | | | 0933 | 0938 | 9740 | S18 W90 | −N | 6:17 | 330 | 2.3 | 0 |
| Nov. 8 | 8.6 | 1730 | 1640 | Nov. 7 2005 | Nov. 7 2018 | 9747 | N7 W79 | 1F | 20:35 | 80 | 1.44 | 11 |
| | | | | Nov. 7 2017 | Nov. 7 2032 | 9747 | N10 W76 | −F | 20:23 | 80 | 0.41 | 14 |
| Nov. 12 | 6.2 | 1900 | 1750 | 1421 | 1452 | 9754 | N5 W72 | 1B | 3:29 | 340 | 14 | 18 |

Using this speed and the average 2 h duration of the observed Faraday rotation effect one can find an approximate value for the dimension of the region moving past the line of sight. A value of 2 $R_{\odot}$ is thus obtained for the thickness of the region.

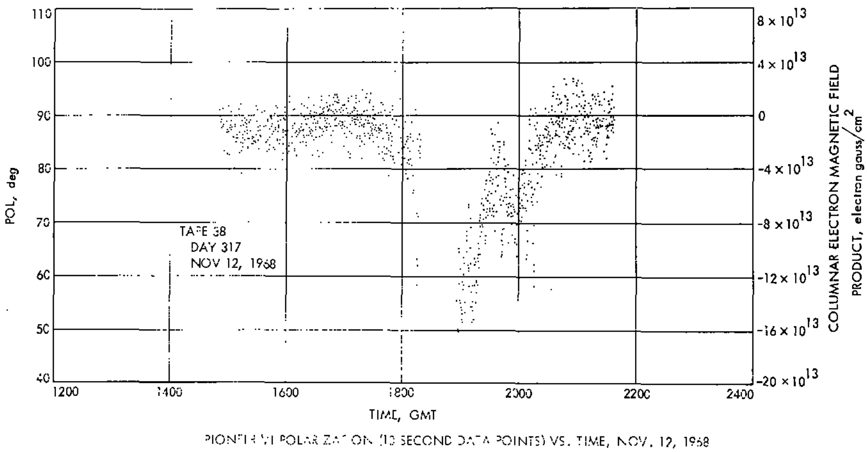


Fig. 1. Polarization of the radio signal from Pioneer 6 as a function of time, after Levy *et al.* (1969).

## 2. Coronal Magnetic Bottle-Expansion Phase

The following model is proposed to explain the Faraday rotation observed by Pioneer 6. In the top portion of Figure 2 an undisturbed magnetic field pattern above an active region is shown as suggested by the coronal models of Newkirk *et al.* (1968), Altschuler and Newkirk (1969) and Schatten *et al.* (1969). The figure shows the coronal magnetic field as viewed from the north. A flare of importance 1 or less occurs in the active region resulting in the heated coronal plasma expanding to produce the magnetic field configuration shown in the middle portion of the figure. This field configuration is similar to that proposed by Gold (1959) for a solar outburst reaching 1 AU. The tension in the magnetic field, however, may prevent the coronal plasma from escaping into interplanetary space. A sector boundary is shown above the active region associated with the event. This is not a necessary condition. There may, however, be a relationship between flare activity and the position of established sector boundaries (see Bumba and Obridko, 1969).

Another possible cause for the observed Faraday rotation would be a flare produced Parker type blast wave giving rise to a characteristic kink in the magnetic field pattern (see Parker, 1963). The field kink may be represented by a bend to a smaller heliographic longitude as radial distance increases. The three observed Faraday rotation events were of the same sense, consistent with coronal magnetic field directed from Earth to Pioneer 6. A toward-the-Sun magnetic field in the three cases would thus be consistent with a kink in the field as the cause of the observed Faraday rotation. The observed interplanetary sector pattern, five days after the central meridian passage of the active regions thought responsible for the three events, however, is away from the Sun on two days (November 6 and November 10) and not clearly defined on November 2 (Fairfield, private communication). Thus no support for this model may be obtained from field geometry.

Support for the first model may be obtained by considering the field pattern in the

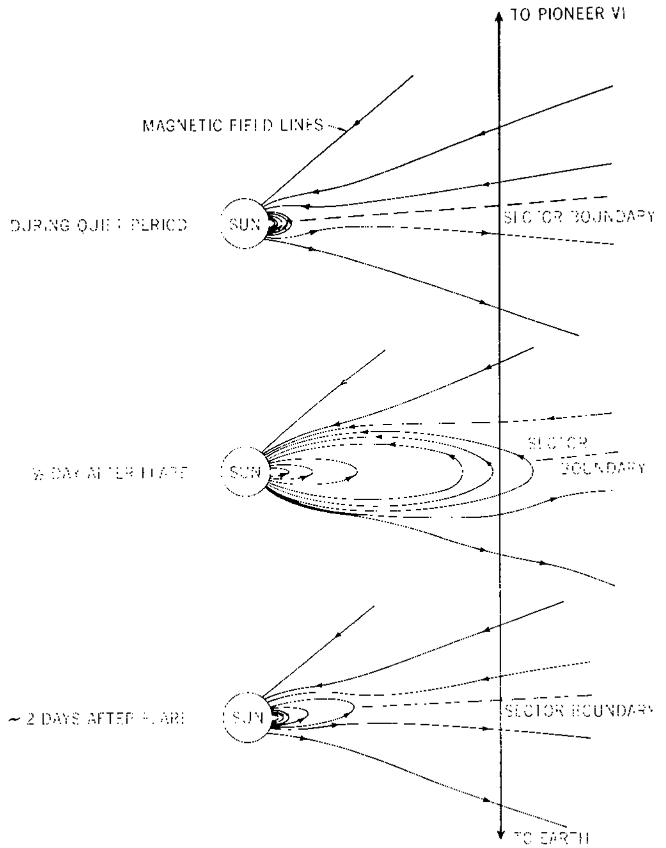


Fig. 2. View from the north of the magnetic field model proposed to explain the transient events observed by Pioneer 6. The line of sight between Pioneer 6 and Earth is shown to the right of each panel.

region causing the disturbances. Figure 3 shows magnetograms of the Sun obtained from the Mt. Wilson Observatory 7 days prior to each of the three events. Thus due to solar rotation, central meridian in these magnetograms corresponds to the west limb at the three events. The three regions thought responsible for the events are labeled by their McMath plage number. Regions 9747 and 9754 were simple bipolar magnetic regions oriented with the positive flux (solid contours) following (eastward of) the negative flux. This orientation is of the proper sense to produce the Faraday rotation observed, if the model previously outlined is correct. Region 9740 is a magnetic region with a more complex field configuration. The field arrangement does

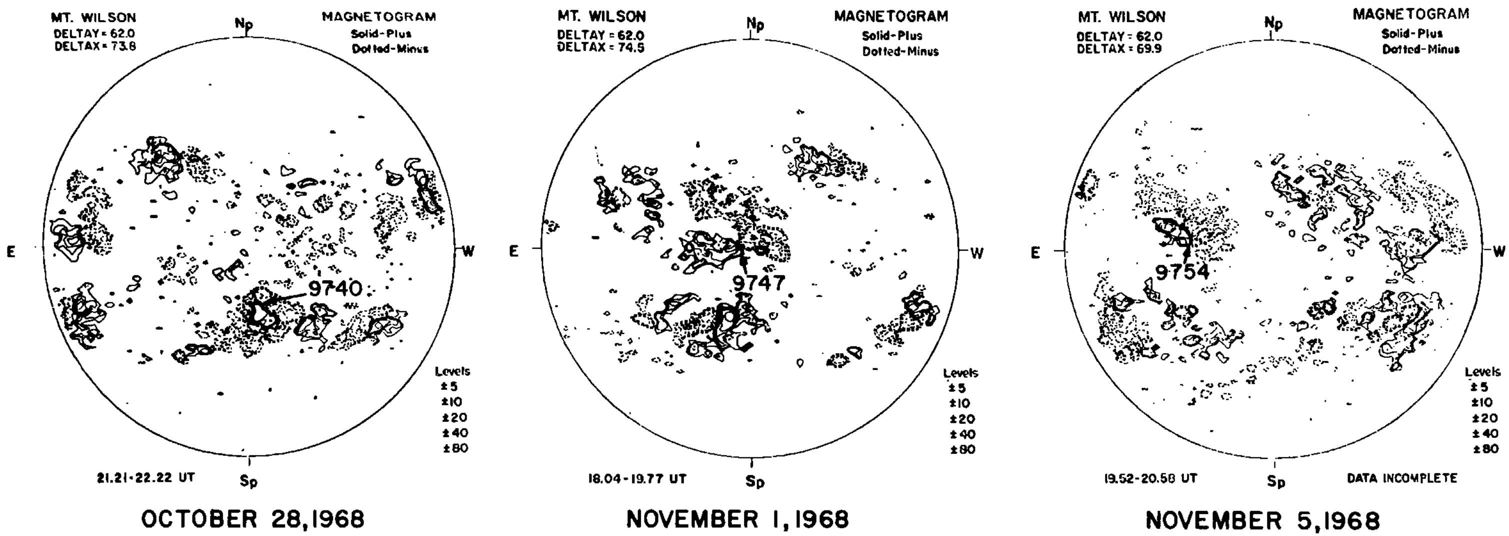


Fig. 3. Mt. Wilson daily magnetograms obtained seven days prior to each Faraday rotation event. The active center thought to be responsible for each event is labelled by its McMath plage number. Solid contours represent field out of the sun and dashed contours field into the sun. Gauss levels are shown at the lower right hand corner.

have positive flux following negative flux and hence could also produce the observed Faraday rotation in accordance with the model.

These regions contain approximately $3 \times 10^{21}$ G cm$^2$ of magnetic flux. If this flux is spread through a meridianal cross-section perpendicular to the flux loop in Figure 2, one can estimate the field strength in the region where the Faraday rotation occurs. A 20° annulus with a 10 $R_\odot$ radial dimension would have a cross-section of $1.5 \times 10^{23}$ cm$^2$. This would result in a 0.02 G field strength at 10 $R_\odot$. An estimate for the coronal density at 10 $R_\odot$ of $2.0 \times 10^4$/cm$^3$ may be obtained by using an enhanced coronal density found near solar maximum at these distances from the Sun (Newkirk, 1967).

The expected Faraday rotation can then be calculated by the formula:

$$\Delta\Omega = \frac{1}{4\pi^2} \frac{e^3 c}{m^2 f} \int_{\text{disturbed region}} N\mathbf{B}\cdot\mathbf{dl} \quad \text{rotations}$$

One degree of rotation results from $3.9 \times 10^{12}$ eG/cm$^2$ (see Levy *et al.*, 1969). Allowing an azimuthal extent of 30°, the line integral of N $\mathbf{B}\cdot\mathbf{dl}$ is approximately $1.4 \times 10^{14}$ G/cm$^2$. Hence approximately 35° of Faraday rotation should occur as the signal from Pioneer 6 passes through the solar corona. The observed Faraday rotation is from 30–40° in each of the three events. Thus the proposed model is consistent both in sign with the observed photospheric field and in magnitude with the observed Faraday rotation.

## 3. Coronal Magnetic Bottle – Contraction Phase

Further insight into the dynamics of the phenomena associated with these coronal disturbances may be obtained by considering their effect on the interplanetary medium. The question may be posed, 'Do these coronal disturbances reach 1 AU?' Similar events must be investigated to answer this question as these events occurred near the solar limb and thus were separated from the Earth by about 90° in heliographic longitude. Wilcox and Schatten (1969) discuss the effect of active regions on the interplanetary magnetic field sector pattern. The sector pattern, it appears, relates mostly to the background field and is usually not affected by most solar flares occurring within active regions. For example, an average of 17 flares of importance 1 or greater occurred on the Sun within 30° of central meridian per 27 day solar rotation during the last quarter of 1968. Only a few sign changes, however, in the sector pattern each 27-day period are noted for this time (Fairfield, private communication). Thus it is expected that events of the type observed with Pioneer 6 at about 10 $R_\odot$ do not usually affect the interplanetary magnetic field pattern at 1 AU. In addition, the Faraday rotation returns to background level sharply after each event suggesting no permanent influence on the field beyond 10 $R_\odot$.

If an adiabatic expansion of the heated coronal gas is allowed, one can consider the variation in gas pressure relative to magnetic pressure as expansion occurs to gain a qualitative understanding of the dynamics. The adiabatic gas pressure varies as

$P_G \propto V^{-\gamma} = V^{-5/3} \propto L^{-5}$, where $V$ represents volume and $L$ is a characteristic dimension of the system. The magnetic pressure varies as $Pm \propto B^2 \propto L^{-4}$ if the field varies as an inverse square with distance. This assumes the field is stretched by the plasma in a conical expansion geometry. Thus the gas pressure falls off more rapidly than the magnetic tension and at some distance the magnetic field will no longer expand. The field can retain the plasma if stability problems do not arise. If, however, coronal heating occurs thereby increasing the plasma pressure, or the hot coronal plasma expands past the Alfvén point which is about 20–30 $R_{\odot}$, the expansion can continue to 1 AU. This would be the case in large flares associated with terrestrial effects (Wilcox, 1968; Hirshberg and Colburn, 1969). In the current investigation it is suggested that although the coronal plasma is expanding with a supersonic velocity, the Alfvén velocity exceeds the expansion rate and the magnetic region collapses as shown in the bottom panel of Figure 2. This, it is suggested, can occur at coronal distances within 20–30 $R_{\odot}$. The coronal gas may cool by radiative losses and conduction in the lower corona with the field configuration slowly returning to its initial state. Thus, the observed Faraday rotation, it is thought, is related to the expansion and contraction of a looped field pattern in the solar corona. The November 8, 1968 event observed by Levy *et al.* (1969) shows a definite double peak in the Faraday rotation. This may in fact be related to the outward and inward passages of the looped magnetic fields past the line of sight.

The coronal plasma at 10 $R_{\odot}$ has an estimated magnetic field strength of 0.02 G and a density of $2.0 \times 10^4/\text{cm}^3$ and thus an Alfvén velocity of 320 km/sec. This is slightly greater than the speed of transport of the plasma calculated from delay times. Thus the magnetic field can transport the force necessary to retain the expanding coronal plasma. Although no definite proof exists for believing these coronal magnetic bottles are contained within the corona, the author hopes that a highly plausible case has been established.

## 4. Discussion

In the case where a flare is sufficiently strong to overcome the magnetic restoring forces, terrestrial effects can be observed as a result of the expanding coronal plasma reaching 1 AU. Ogilvie *et al.* (1969), for example, report an interplanetary disturbance associated with a class 3 solar flare. A mean speed for the shock to travel to Earth was found to be 735 km/sec. A helium rich plasma was found to lag the shock slightly, suggesting this may be associated with the flare plasma. Hirshberg and Colburn (1969) report that geomagnetic effects are often caused by limb flares and possibly even flares beyond the limb (see Cline and McDonald, 1968). Magnetic forces may play a role in directing the flare energy.

Hundhausen and Gentry (1968) discuss how flare induced shocks travel through the interplanetary medium. They find that the time lag to reach 1 AU is 80 h for a flare energy of $8 \times 10^{30}$ ergs, with smaller time lags for higher energy coronal plasma disturbances. The energy of the plasma contained in the magnetic bottle in the present model would be about $10^{30}$ ergs. Future exploration along these lines may provide a test to this model and direction in studies concerning the terrestrial effects of flares. A study comparing flare energy and field configuration above the associated active region with terrestrial effects may provide insight along these lines.

Anderson and Lin (1966) suggest that the source for high energy electrons observed in interplanetary space several days after a solar flare is a radio noise region high in the solar atmosphere. Further evidence suggesting the possibility of storage of energetic particles close to the Sun has been found by Lin *et al.* (1968) and Simnett *et al.* (1969). The time between the candidate for the parent flare and the observed energetic electrons suggested to Simnett *et al.*, a distance travelled of about 1000 AU for these particles to reach Earth. A large scale storage region close to the Sun could be provided by the magnetic bottle discussed in this paper as the field strength and size are sufficient to trap the energetic particles observed. Such large scale magnetic bottles may also provide a path for the longitudinal diffusion of solar generated cosmic rays.

## Acknowledgements

The author would like to acknowledge Gerry Levy and Charles Stelzried of the Jet Propulsion Laboratory who kindly provided use of their Faraday rotation observations. In addition, the author wishes to thank John Wilcox, Gordon Newkirk, Jr., Leonard Burlaga and Donald Fairfield for critical discussion of the ideas in this paper.

## References

Altschuler, Martin D., and Newkirk, Gordon, Jr.: 1969,
Anderson, K. A. and Lin, R. P.: 1966, *Phys. Rev. Letters* **16**, 1121.
Bumba, V. and Obridko, V. N.: 1969, *Solar Phys.* **6**, 104.
Cline, T. L. and McDonald, F. B.: 1968, *Solar Phys.* **5**, 507.
Gold, Thomas: 1959, *J. Geophys. Res.* **64**, 1665.
Hirshberg, J. and Colburn, D. S.: 1968, *Planetary Space Sci.* **17**, 1183–1206.
Hundhausen, A. J. and Gentry, R. A.: 1968, *Trans. Amer. Geophys. Union* **49**, 255.
Levy, G. S., Sato, T., Seidel, B. L., Stelzried, C. T., Ohlson, J. E., and Rusch, W. V. T.: 1969, *Science* **166**, 596.
Lin, R. P., Kahler, S. W., and Roelof, E. C.: 1968, *Solar Phys.* **4**, 338–360.
Newkirk, Gordon A.: 1967, *Ann. Rev. Astron. Astrophys.* **5**, 213.
Newkirk, G. A., Altschuler, M. D., and Harvey, J. W.: 1968, in *Structure of Solar Active Regions* (ed. by K. O. Kiepenheuer), IAU Symposium No. 35, D. Reidel Publ. Co., Dordrecht, p. 134.
Ogilvie, K. W., Burlaga, L. F., and Wilkerson, T. D.: 1968, NASA-GSFC Preprint X-612-68-127.
Parker, E. N.: 1963, *Interplanetary Dynamical Processes*, Interscience Publishers, New York.
Schatten, K. H.: 1970, *Science* **168**, 395.
Schatten, K. H., Wilcox, J. M., and Ness, N. F.: 1969, *Solar Phys.* **6**, 442–455.
Simnett, G. M., Cline, T. L., Holt, S. S., and McDonald, F. B.: 1969, *Trans. Amer. Geophys. Union* **50**, 305.
Wilcox, J. M.: 1968, *Space Sci. Rev.* **8**, 258.
Wilcox, J. M. and Schatten, K. H.: 1969, *J. Geophys. Res.* **74**, 2449.