THE CROSS SECTIONAL MAGNETIC PROFILE OF A CORONAL TRANSIENT

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The role of the magnetic field in a coronal mass ejection event has not been unequivocally defined, and may in fact be quite variable in view of the large variety of shapes and sizes of coronal transients. Measurements of the magnetic field associated with these events have thus far been inferred from simultaneously observed radio bursts, which provide no information on the direction of the field and are limited in spatial resolution. Substantial improvement in these two areas could be achieved by continuous monitoring of the Faraday rotation of a linearly polarized spacecraft signal during solar occultation. A coronal event traversing the line-of-sight would yield a characteristic profile in cross section, which would be of value for discriminating between the various models of coronal transients.

I. Coronal Transients in White Light and Faraday Rotation

The coronal mass ejection event has been a widely studied solar phenomenon since the Skylab missions, and many important characteristics such as their plasma composition (Hildner et al., 1975), their speeds (Gosling et al., 1976), their frequency of occurrence (Hildner et al., 1976), and their associations with other solar activity (Munro et al., 1979) have been documented. Supplementary measurements of solar radio activity were made during the events of 14-15 September 1973 (Dulk et al., 1976) and 21 August 1973 (Gergely et al., 1979). If the broadband emission recorded could be interpreted as gyrosynchrotron radiation, then the magnetic field strengths associated with the enhanced density loops were of the order of a few gauss at a distance $r \simeq 2\text{-}3\ R_S$ (R_S = solar radius).

Dynamic coronal events were also observed during the 1968 solar occultation of Pioneer 6 (Levy et al., 1969) and even during solar minimum at subsequent occultations of Helios 1 and 2 (Bird et al., 1977). The Faraday rotation of the linearly polarized telemetry signal of these spacecraft was seen to abruptly deviate by tens of degrees before returning to its presumed baseline after about 2 hours. These deviations have been attributed to density enhancements (Pintér, 1973), or to moving mag-

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netic bottles (Schatten, 1970). The separation of magnetic field effects from electron density effects is impossible without additional information such as dispersion measurements or white light observations. The Faraday rotation due to the disturbance can be written

$$\Omega_t = K \int_t \left[N_t \vec{B}_t - N_o \vec{B}_o \right] \cdot d\vec{s} \quad \text{deg} \qquad (1)$$

where $K = 2.58 \times 10^{-13}$ in gaussian units
N = electron density in cm^{-3}
$\vec{B}$ = magnetic field in gauss
$d\vec{s}$ = path element in cm

The subscripts "t" and "o" refer to the transient and ambient values respectively. The second term of (1) can be safely neglected for transient magnetic fields and electron densities well above the ambient (Dulk et al., 1976). Furthermore, it will be shown below that for only a small component of B along the Earth spacecraft line-of-sight one would expect very large contributions to Ω_t from a typical coronal mass ejection event. Combined with white light data, the magnitude and signature of the time profile of the Faraday rotation could then be utilized to determine the strength and orientation of the magnetic field in the density enhancement.

Models of transient propagation have been designed to explain the most conspicuous form of coronal event, the loop transient. These models can be loosely subdivided according to the proposed driving force required to propel the observed density enhancement outwards through the corona. The numerical simulations described by Nakagawa et al. (1978) and Wu et al. (1978) in the solar equatorial plane or by Steinolfson et al. (1978) and Dryer et al. (1979) in a solar meridional plane do not require an enhanced magnetic field associated with the disturbance. A pressure pulse applied at the coronal base propagates into the outer corona provided the pulse (flare) occurs under an open magnetic field topology. The perturbation to the ambient field is only slight, particularly if the plasma β is low as expected in the regions of interest.

A different philosophy is espoused by Mouschovias and Poland (1978) and by Anzer (1978), who consider the coronal loop to be driven by the magnetic Lorentz force arising essentially from field gradients in the helical magnetic field threading the enhanced density loop. The higher magnetic and thermal pressures in the loop cause it to expand as observed as it propagates radially outward. The model of Mouschovias and Poland (1978) will be employed here as an example of the use of the Faraday rotation technique for determination of the magnetic composition of a coronal transient.

II. Faraday Rotation from a Transient Flux Tube

Consider a section of a coronal transient flux tube, be it a loop or a streamer of arbitrary curvature, which is probed by an Earth / spacecraft

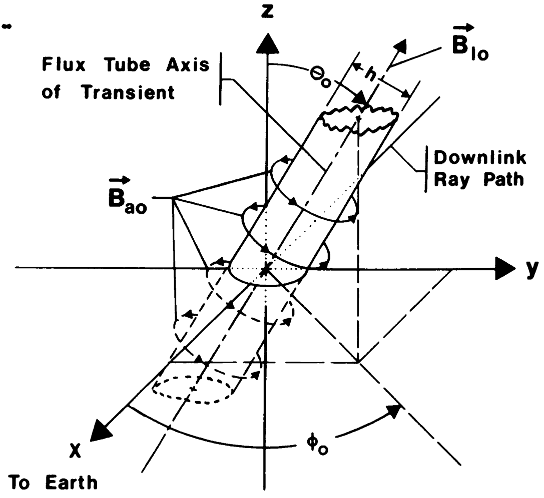

Figure 1. Geometry of the occultation of the Earth/spacecraft line-of-sight by a transient flux tube in the solar corona. The axis of the tube is defined by the angles (θ_o,ϕ_o). The helical magnetic field of the flux tube can be broken down into longitudinal and azimuthal components.

craft ray path in the z = 0 (ecliptic) plane. Figure 1 shows the orientation of the flux tube (thickness h), which is defined by the polar and azimuthal angles (θ_o,ϕ_o). For west limb observations the Sun is located at some point close to, but not necessarily right on the negative y-axis. The angles (θ_o,ϕ_o) will be assumed uniquely determined in the following from white light (with polarization) observations, although there is likely to be some uncertainty in their exact values.

The flux tube is threaded by a constant longitudinal magnetic field B_{lo} and a purely azimuthal field of constant magnitude B_{ao}. The x-component of these two fields in the z = 0 plane, which is the only component giving contributions to (1), is given by

$$B_x = B_{lo}\sin\theta_o\cos\phi_o - B_{ao}\frac{y}{r}\cos\theta_o \qquad (2)$$

If the tube is slightly curved, the azimuthal field on the concave (CC) side will exceed that on the convex (CV) side by an amount determined from the following equality (e.g. Mouschovias and Poland, 1978)

$$B_a^2(CC) - B_a^2(CV) = \left[B_a^2(CC) + B_a^2(CV)\right]\cdot\frac{h}{R_c} \qquad (3)$$

where $B_a\ (CC) = B_{ao} + b$
$B_a\ (CV) = B_{ao} - b$
R_c = Mean radius of curvature of tube

and b is a small field contribution directed along $\vec{R}_c \times \vec{B}_{lo}$

Solving (3) for b, one obtains

$$b = \frac{h}{2R_c}B_{ao} \qquad (4)$$

which for typical transients at 5 R_S ($h \approx 0.6\ R_S$; $R_c \approx 1.6\ R_S$), is a small but important contribution to (1) if the field is directed primarily along the x-axis as will be assumed here.

Using (2) and (4) in the expression for the transient Faraday rotation (1) neglecting the ambient term, one obtains

$$\Omega_t(y) = K\int_{x_-}^{x_+} N_t(x,y)\left[B_{lo}\sin\theta_o\cos\phi_o - \frac{B_{oa}}{r}\,y\cos\theta_o + \frac{h}{2R_c}B_{oa}\right]dx \qquad (5)$$

where $x_\pm$ are the solutions of the quadratic equation

$$(h/2)^2 = x^2 + y^2 - \sin^2\theta_o\left[x\cos\phi_o + y\sin\phi_o\right]^2 \qquad (6)$$

For purposes of illustration it is possible to simplify the analysis by considering only constant density fluxtubes with small θ_o(i.e. θ_o less than 30° or more than 150°), for which (5) reduces to

$$\Omega_t(Y) = K N_{to} h B_{lo}\left[T_1 + aT_2 + aT_3\right] \qquad (7)$$

with N_{to} = constant density in flux tube
a = B_{ao}/B_{lo}

and T_1 = $\theta_o\cos\phi_o\sqrt{1-Y^2}$
T_2 = $-\frac{Y}{2}\ln\left[\frac{1+\sqrt{1-Y^2}}{1-\sqrt{1-Y^2}}\right]$
T_3 = $\frac{h}{2R_c}\sqrt{1-Y^2}$
Y = $y/(h/2)$

Y, the normalized position of the ray path in the flux tube assumes the value -1 (+1) on the CC (CV) side of the curved disturbance.

Taking reasonable values for N_{to} (1.2×10^6 cm^{-3}), h (0.6 R_S) and B_{lo} (0.2 gauss) at a distance 5 R_S from the Sun, one may determine the signature of $\Omega_t(Y)$of a coronal transient flux tube as it is sampled between ± h/2 by the Earth/spacecraft ray path.

The expected variations are shown in the three panels of Fig. 2, which give examples when the longitudinal field of the transient is directed toward (top), perpendicular to (middle) and away from (bottom) the observer. The profiles are very sensitive to the parameter a, which is a measure of the pitch angle of the helical transient field. Mouschovias and Poland (1978) argued that a should not be less than one nor greater than 1.41. The upper bound is required by stability to the pinch effect, and the lower bound is necessary to impart a positive magnetic driving force to the loop from gradients in the azimuthal field. Values of a over the range $|a| \leq 1.41$ were selected for this study. As a goes to zero (vanishing azimuthal field), the Faraday profile loses its internal zero since the disturbance field is then unipolar. The maximum excursions of Ω_t are a measure of the magnitude of B_{lo} provided θ_o is not exactly zero. Higher values of the ratio h/R_c will shift the node

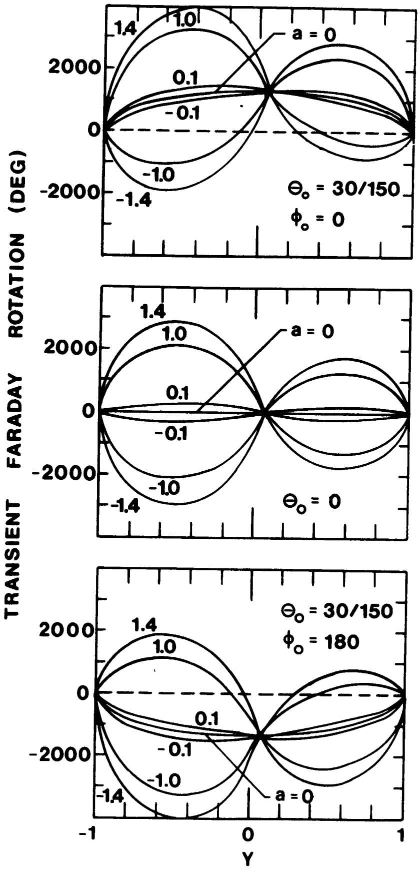

Figure 2. Faraday rotation profiles for Earth spacecraft line-of-sight passing through a transient flux tube of enhanced magnetic field and electron density. The bottom (concave) edge of the coronal loop is at Y = -1, and the top (convex) edge is at Y = +1. Curves are drawn for various values of "a", the ratio of azimuthal field to longitudinal field in the loop. The three panels correspond to three possible orientations of the flux tube as defined by (θ_0, ϕ_0).

of the family of curves even farther to the right of Y = 0. The more intense azimuthal magnetic field on the concave side of the flux tube is responsible for the higher maxima of Ω_t at negative Y than at positive Y positions.

This model of Faraday rotation expected from a transient flux tube passing through an Earth/spacecraft ray path could easily be extended to the more complicated cases of arbitrary Θ_0 and a variable electron density N(x,y) as estimated from white light data. In particular, the same basic procedure could be developed for coronal streamers or any flux tube containing greatly enhanced electron densities. Since the azimuthal field of approximately radial flux tubes is presumably small, one would expect to see only one sign of anomalous Faraday rotation during passage of the transient through the line-of-sight.

It should also be noted that a transient flux tube of width $h \simeq 0.6$ solar radii and velocity $v \simeq 400$ km s^{-1} needs only about 15 minutes to traverse the ray path. The long duration and small excursions in Ω_t seen at previous solar occultations indicate that these "Faraday rotation transients" were probably not isolated flux tubes as modelled here. The Faraday profiles recorded then would be associated with much larger and/or slowly moving coronal disturbances with much more modest field and density enhancements than those estimated for a typical coronal loop transient.

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DISCUSSION

Anzer: What holds your loop together, if both the magnetic field and the density are much larger inside the loop than outside it?

Bird: The loops are seen to expand as they propagate radially outward indicating that $P + B^2/8\pi$ is higher inside than outside. I would therefore not expect a rigorous pressure balance across the loop boundary. It should be reiterated that radio observations indicate that the regions of high electron density and magnetic field are cospatial.

Stewart: The Faraday Rotation Transients last for 1 hr or so. Consequently, I do not think you are observing an isolated thin loop transient such as the model you described.

Bird: I agree. A coronal loop of thickness 0.5 R_S moving at a velocity 400 km s^{-1} would traverse the line-of-sight in 15 min. The coronal disturbances seen with previous Faraday rotation experiments lasted much longer and would therefore be attributed to larger and/or slower moving phenomena. There is no doubt, however, that the inferred enhancements in electron density and magnetic field in the isolated loops described here would produce an easily recognizable signal in Faraday rotation.