The Cassini solar Faraday rotation experiment

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Abstract
The Cassini Faraday rotation experiment improves the current understanding of the coronal magnetic field by making the first measurements of the magnetic field within two solar radii of the south pole and by allowing the separation of the changing electron density from the magnetic field using transient crossings of the line of sight. Simultaneous ranging data to Cassini also contributes to the growing body of empirical electron density models by providing electron density data at solar maximum at varying latitudes including over the poles. Faraday rotation data in the solar corona were collected in 2002 and 2003 using the Cassini spacecraft in cruise to Saturn. Although Cassini primarily transmits in right-hand polarization, enough left-hand is produced to enable polarization measurements. We show that during solar conjunction Faraday rotation is measurable with Cassini. In the X- and Ka-bands both datasets currently show an asymmetric diurnal pattern in polarization not associated with the ionosphere. The Ka-band is much more sensitive to pointing accuracy and experienced periods of power drop outs which caused the left-circularly polarized signal to drop into the noise on occasion during the 2003 conjunction. Interpretation of the data is deferred to future papers.

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1. Introduction

One of the few observational methods that is capable of obtaining magnetic field measurement of the corona is Faraday rotation, the rotation of the plane of polarization of radio waves as they traverse a magnetized medium. Faraday rotation provides the integral of the product of the electron density and the component of the magnetic field parallel to the direction of the phase velocity. The rotation occurs because the phase velocity of the left circularly polarized component of the radio wave travels faster along the magnetic field than the right circularly polarized component (Kraus, 1968). In order for the magnetic field component of the rotation to be determined, there must be an independent knowledge of the electron density.

The Cassini Faraday rotation solar conjunction experiment uses radio waves transmitted between Cassini and the Earth to measure the magnetic field of the solar corona. The multi-frequency capabilities of Cassini provides two advantages. Cassini’s high frequency radio signal (Ka-band at 32 GHz) provides measurements closer to the surface of the Sun than previous experiments (Istelzried, 1968; Bird et al., 1983), and the plasma contribution to the rotation can be removed with an order of magnitude higher resolution and accuracy. The Cassini experiment yields information on the coronal magnetic fields and the electron density that was previously unobtainable.

The amount of Faraday rotation observed depends on three variables, the frequency (f), the electron density (N), and the magnetic field (B)

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Since Faraday rotation is an integrated quantity and propor-
tional to the product of two possibly independent quan-
tities, the information obtainable about the density and the magnetic field is limited. In the regime of a well-known magnetic field such as the Earth's, Faraday rotation can be used to measure the electron density of the ionosphere. Conversely, in a known electron density situation, Faraday rotation can be used to measure characteristics of the mag-
netic field.

2. The coronal magnetic field

Measurements of the coronal magnetic field have been attempted in the past in two ways. Stokes measurements of polarized light and Faraday rotation. The Stokes mea-
surements of polarized light have been used by astrono-
mers to study celestial radio sources since 1930 (Kraus, 1986), and they can give the direction of polarization in the plane of the sky. This polarization direction can then be used to infer the magnetic field direction and magnitude from scattered light. Faraday rotation is very closely re-
lated to Stokes measurements; it gives the net polarity of the magnetic field along the line of sight and an estimate of the magnetic field magnitude. Only very recently have Stokes measurements been used to infer the solar coronal magnetic field; the two groups currently working on the problem are calibrating their instruments to begin regular studies soon (Lin et al., 2004; Keil and Avakyan, 2003).

The advantages of their instruments include 2D capability like the white light coronagraphs, and like the white light coronagraphs, their disadvantage is the quantification of the magnetic field. These magnetographs have one further disadvantage; they are limited to the base of the coronal jet above the transition region where there is sufficient density of scattered forbidden-line radiation.

The standard method of extrapolating the photosphere magnetic field into space is to use a harmonic model with inner and outer boundary conditions. The inner boundary conditions are obtained by measuring the surface magnetic field using Zeman-splitting. The outer boundary condi-
tions depend on the requirement that the magnetic field be radial at a predefined "source surface" (Schatten and Wil-
cox, 1969; Alscheuler and Newkirk, 1969). A readily avail-
able coronal magnetic field is given by the Wilcox Solar Observatory's Legendre polynomial coefficients (Hoek-
sen and Sherrin, 1986). Luhmann developed a current conserving model using these coefficients (Luhmann, 2002). The Legendre polynomials are of a special variety normalizing the values such that the magnetic field in dif-
ferent positions of the sphere can be compared (Chapman and Bartels, 1940). The source surface extrapolation model is able to predict the general characteristics of the magnetic field and solar wind at the Earth which has led to its gen-
eral acceptance in the community.

Faraday rotation has been used to study two character-
istics of the coronal magnetic field: the background and perturbed. The first Faraday rotation experiment was con-
ducted in 1946 during the Pioneer 6 solar conjunction in the S-band (2.2 GHz) (Stelzried, 1968). Using an adjusted Allen-Baumbach model for electron density, Stelzried com-
pared the WSO model to the Earth orbiting magnetometer data from Explorer 33 extrapolated to the sun; he found that the magnetometer data extrapolation was better than the WSO model with respect to the general trend observed in the Faraday rotation data. From 1979 to 1985, Bird con-
ducted the second spacecraft-based Faraday rotation experiment using Helios 1 and 2 in the S-band (Bird et al., 1985). Using the Solwind coronagraph at 5 times when CMES would be crossing the Helios signal path, Bird made the first measurements of the perturbed magnetic field of the corona just prior to CME transits.

During Stelzried’s experiment, the S-band was able to measure the rotation to an impact parameter (heliocentric distance of closest approach of the line of sight from Earth to the transmitter) of only 4 solar radii; at smaller impact parameters, the signal was indistinguishable from the noise. Later Bird measured to an impact parameter of 3 solar rer-
d using improved technology. The purpose of this study is to estimate the background magnetic field within ± 3 solar radii where the source surface model should be relatively accurate, and to analyze the magnetic field at disturbed times.

3. The Cassini radio system

Cassini was launched on October 15, 1997 to Saturn. At the beginning of the new millennium, January 2001, Cas-
nini passed Jupiter on its way into the outer solar system. On June 21, 2001 and July 1, 2003, Cassini was in solar conjunction with the Earth, and Faraday rotation data were collected. Cassini transmits at three radio frequencies which operate simultaneously: S-band (2 GHz), X-band (8 GHz), and Ka-band (32 GHz) (Bertotti and Giampieri, 1997). The S-band has been turned off during the cruise phase to Saturn after an initial test found that its system would heat up the Huygens probe. The X-band has been performing nominally throughout the cruise and orbit insertion phases. The Ka-band has lost some capability be-
 tween the 2002 and 2003 conjunctions; however, it is still useful for Faraday rotation studies. During the 2002 con-
junction, the spacecraft pointing was operated on reaction wheels to maintain stability. Between the 2002 and 2003 experiments, the reaction wheels were found to be gradu-
ally wearing out and their use was limited to prime mission experiments. Therefore during the 2003 experiment, the pointing was controlled by thrusters which degraded the quality of the Ka-band data somewhat. With a beam width four times larger, the X-band was relatively unaffected by the loss in pointing stability.

The Cassini radio antenna is capable of multiple modes of operation. These include S-, X-, and Ka-bands one way,
X-uplink to S-, X-, and Ka-downlink, and until 2003 Ka-
uplink to Ka-downlink, and until 2003 Ka-
uplink to Ka-downlink. The X-band coherent uplink con-
sists of the received phase being transmitted after frequency
modulation. The X-uplink and downlink frequencies are
offset, so the X-uplink frequency is modulated as well into the
X-downlink frequency. The Ka-uplink to downlink be-
came inoperable when the Ka-translator failed; it is thought to be due to charging on the translator. The disadvan-
tage of the X-uplink to Ka-downlink mode is that the
uplink noise is multiplied by 4 in the downlink. The X-up-
link to S-downlink mode is untenable at present.
The uplink polarization to Cassini is left-hand polarized (LCP) while the downlink polarization from Cassini is
right-hand polarized (RCP). All radio antennas “look” the
opposite polarization while transmitting; since this “leakage” occurs in the side lobes, the power is much
weaker in the opposite polarization. For Cassini’s antenna,
this was found to be approximately 20 dB. The 2002 and
2003 Faraday rotation experiments measured the strength,
frequency and relative phase of Cassini RCP and LCP
downlink.

4. Geometry at conjunction

The motion of the line of sight during Cassini solar con-
junctions is primarily the result of the Earth’s orbit around
the Sun as Cassini changes celestial longitude but slowly.
Cassini’s location in the outer solar system places it locally
around midnight during the northern winter and noon dur-
ing the northern summer as seen from Earth. The one way
light time to Cassini was approximately an hour in 2002 and
1.5 h in 2003. This time span is long enough that the
signal may have passed through different coronal plasma
conditions on its way to Cassini and on the return trip.
During neither conjunction was the signal between the spacecraft and the Earth occluded by the surface of the
Sun, passing beneath the south pole of the Sun instead.
The impact parameter of the signal is the length of the line
perpendicular to the signal path, intersecting the center of
the Sun. During the 2002 conjunction, the minimum im-
 pact parameter was approximately 1.5 solar radii; in 2003
it was approximately 1.25 solar radii as shown in Fig. 1.

Because the amount of Faraday rotation is proportional
to the component of the coronal magnetic field parallel to
the line of sight, there is a significant geometrical aspect to
the analysis of Faraday rotation. As shown in Fig. 2 (Pue-
tzold and Bird, 1998), the parallel component of the mag-
netic field can reverse due to the passage by closest
approach in a uniformly diverging radial IMF and upon
crossing of a sector boundary. The Faraday rotation mea-
sured at the Earth is a density-weighted measurement of
the integrated magnetic field direction. Thus, the integrated
Faraday rotation in Fig. 2 would increase to the current
sheet where it would decrease because of the parallel mag-
netic field reversal; once the signal passed closest approach,
it would begin to increase again. The net Faraday rotation
from this signal path is the final angle that is achieved. This

Fig. 1. During the 2002 and 2003 solar conjunctions, the motion of the
Earth shifted Cassini’s line of sight from the left to the right in the field of
view.

Fig. 2. The structure of the electron density and magnetic field through
which the radio wave passes is important to consider when interpreting
Faraday rotation data. This figure shows the line of sight between Pioneer
6 and the Earth during Sturdevant’s 1988 Faraday rotation experiment
(Puentzold and Bird, 1988). A current sheet with thickness δ dies at δ/3
degrees from the Sun-Pioneer vector. The radial magnetic field reverses
across this current sheet.

net rotation depends on the integral of the product of the possibly asymmetrical electron density (i.e., as shown in
Fig. 2) and the magnitude of the parallel component of
the magnetic field. Therefore, the observed Faraday rotation near a sector boundary like that shown in Fig. 3 will change with the position of the path of integration and the sector boundary. Interpreting Faraday rotation data requires the use of 3D models of both electron density and magnetic field. Fig. 3 shows the location of the sector boundary with respect to the path of the signal from Cassini on both the ingress and the egress passes, on the background of the radial component of the photospheric magnetic field.

The white and black lines in Fig. 3 are the lines of sight from Cassini to Earth as projected on the solar photosphere. The black line on the top diagram is for 2002 June 16, 1600 UT (the start of the June 16 pass shown in Fig. 6); the white line is for 2002 June 21, 0200 UT (the end of the June 20 pass shown in Fig. 6). The white line on the bottom diagram is for 2002 June 21, 1600 UT (the start of the June 21 pass); the black line is for 2002 June 16, 0200 UT (the end of the June 25 pass). On the days between the first and last lines, the projected line of sight assumes a shape intermediate between the end members. When the line of sight to Cassini moves behind the south pole, the signal increases in solar longitude as it travels from Cassini to the Earth. When Cassini emerges from behind the corona, the signal travels in a decreasing solar longitude direction. This is reasonable because the longitude coordinates are in the counter-clockwise rotation direction of the sun. Furthermore, the solar rotation is apparent in the relative changes in longitude for Cassini and the Earth shown, both Cassini and the Earth decrease in longitude during the period of the conjunction reflecting the rate of solar rotation.

As shown in Fig. 1, the approximate latitude of the closest approach at the beginning of the pass on June 19 (around 1600 UT as shown in Fig. 6) is more equatorial than at the end of the June 20 pass (around June 21 0200 UT as shown in Fig. 6). These latitudes are clearly visible in the top plot of Fig. 3 at the minimum of the curves (approximately -38 degrees and -50 degrees, respectively). The colors in Fig. 3 indicate the magnitude of the solar magnetic field at the 2.5 solar radius surface. The field is positive in red and negative in blue; therefore, the heliospheric current sheet where the IMF is weak is in the green region which we have marked more closely with the thin black line. To estimate the expected Faraday rotation, we can assume the field is mostly radial in the region around closest approach.
approach. If we look at the line of sight for the June 21 pass, the direction is primarily positive (outward) of which the parallel component is in the opposite direction of the wave vector of the signal; therefore, the cumulative contribution to Faraday rotation prior to closest approach is mostly negative. At the point of closest approach, the parallel component of the magnetic field is in the same direction as the signal’s wave vector which brings the cumulative Faraday rotation closer to zero before reaching Earth. However, due to the nature of the asymmetric magnetic field and electron density, we have to model the expected Faraday rotation to find the expected amount of Faraday rotation in this situation. Conversely on the June 20th pass, the magnetic field is negative (inward) so the parallel component is primarily in the same direction as the signal’s wave vector contributing to positive cumulative Faraday rotation until the closest approach is reached. Just after the closest approach is reached, the rest of the track is spent in and around the current sheet of which the parallel component of the magnetic field is in the opposite direction of the signal’s wave vector which would decrease the cumulative Faraday rotation. Therefore, to obtain a more accurate estimate of the expected Faraday rotation for this pass we need to model.

5. Ground support equipment

All the equipment necessary to conduct the Faraday rotation experiment were located in Goldstone, California at JPL’s Deep Space Network (DSN) facility. The data collected in this experiment used the DS513 antenna in Goldstone. DS513 is the experimental antenna in the facility which allows for “rapid” changes in equipment to allow radio astronomers, engineers, and scientists flexibility in conducting experiments. Located approximately 10 km away from DS525, DS513 is a 34 m diameter Beam Wave Guide (BWG) antenna as shown in Fig. 4. BWG antennas fix the radio receivers in the base of the antenna and use “mirrors” to pass the incoming signal to the receivers. The signal path from a source reflects off of the main dish which focuses the signal on the subreflector. The subreflector then reflects the signal onto a mirror just below the dish. 

![Diagram of a Beam Waveguide Antenna](image)

Fig. 4. The internal structure of the beam waveguide antenna such as DS513 used for the Cassini Faraday rotation experiment.
which directs the signal down the shaft of the antenna. At the base of the shaft, an adjustable mirror reflects the signal in the direction of the receivers. Above the receivers, another mirror would reflect the signal into the horns of the receiver. In the case of the Cassini experiment, this mirror was placed above the Ka-band receiver while a dichroic plate was placed above the X-band receiver in front of it. The dichroic plate consists of a metal plate with holes large enough to allow the ~1 cm Ka-band wavelength through while small enough to reflect the ~4 cm X-band wavelength signal into the X-band receiver.

The signal entering the radio receivers first passes into the horn which further focuses the signal, and then passes into the cryogenically cooled dewer. At the top of the dewer, the signal is passed into the receiver from the feed horn by a waveguide. The wave is then split up into “RCP” and “LCP” polarizations in the “Magic-T” to pass through separate channels for measurement. In the separate channel, the wave passes through an isolator (which acts like a diode) to make sure that only radiation passing from the horn is measured. It is then amplified and passed through another isolator to the base of the dewer. In the case of the Ka-band frequencies, the wave is then mixed with a high frequency oscillator to downconvert the frequency to X-band and passed out of the dewer. Outside of the dewer, the wave is isolated, amplified, and isolated again. Then it is mixed with the low frequency oscillator to downconvert the frequency to 300 MHz and passed into coaxial cables. In the case of the Ka-band, the signal is then pluged into the Radio Science Receiver (RSR) at DSS13. In the case of the X-band the signal is piped down a fiber optic line to the Goldstone operations center and plugged into an RSR in center. During the 2002 experiment, the fiber optic lines were found to have differing effects on the quality of the received signal. Therefore, the RCP signal was passed down the poorer line because of its better signal to noise ratio.

Inside the RSRs, the signal is amplified and split and mixed again with a tunable frequency determined by frequency predictions model by JPL. The mixing of signals this time is different; the mixing sine wave of either side of the split are 90° out of phase with each other. This allows the measurement of the in-phase (I) and quadrature-phase (Q) signals or rather the real and imaginary components to the incoming signal. The mixing frequencies were chosen to lower the signal frequency down to a few Hz. Usually, this was in the range of 1–5; however sometimes the signal frequency was larger generally when Madrid was transmitting or the signal was one-way. The signal is then sampled at 1000 samples per second. The Faraday rotation is measured from hall of the sum in phase from the LCP to the RCP.

6. Observations

In 2002, the X-band was transmitted from the Madrid DSN facility in the morning for approximately 2 h and then from the antenna DSS25 in Goldstone until Cassini set below the horizon. The switch after 2 h was due to the round trip light time that it took for the first Goldstone transmission to return to Earth for Cassini. Because Madrid does not have a Ka-band downlink, in the first 2 h of the morning the Ka-band downlink was coherent with the X-uplink only. When the Goldstone Ka-band

Fig. 5. S, T, and Ka-band minimum coronal radio of measurement.

Fig. 6. X-band Faraday rotation measurements for Cassini Conjunction 2002.
transmitter's signal was returned after the round trip light time, the three frequencies would be established: X-uplink to X-downlink, X-uplink to Ka-downlink, and Ka-uplink to Ka-downlink. Occasionally in 2002, the Ka-band transmitter at DSS25 would fail due to a cooling problem at the antenna reducing the total measured frequencies to 2. In 2003, fewer resources were devoted to the conjunction experiment because of Cassini's Ka-translation failure, and Madrigal was no longer used. Therefore with the longer round trip light time, the first 3 h of the morning after Cassini rose above the horizon, the measured frequencies were X- and Ka-downlinks one-way. After this time the two frequencies would be established: X-uplink to X- and Ka-downlinks. In this report, we concentrate on the 2002 observations because they occurred under the most ideal situation.

S-band, X-band, and Ka-band frequencies lie close to 2, 8, and 32 GHz respectively. The higher frequencies of X- and Ka-bands allow them to penetrate much closer to the Sun (Fig. 5). However, the Faraday rotation effect is inversely proportional to the square of the frequency. Thus, at the same distance from the sun, the Faraday rotation angle at X-band will be 1/16th that at S-band and the Ka-band 1/16th that at X-band. As a result, if one frequency rotates more than 180° (the angle ambiguity), this can be measured with the rotation observed in a higher frequency. The Faraday rotation seen at S-band by Stetson and 4 solar radii was 153° and by Bird at 4.25 solar radii was 160°. Thus, given similar coronal structure configurations at distances of 4 solar radii, using X-band we would expect to see only 10° of rotation for example. This distance was reached at 0900 UT on June 20th and then exceeded again at 1700 UT on June 22nd. In the Ka-band during this time we would expect to see only 0.3° here. Because these values are much smaller than the uncertainty in our preliminary analysis presented here we concentrate on the X-band. Suffice it to say that Faraday rotation data were taken all the way through closest approach in the Ka-band but its signal strength appeared to be sensitive to solar disturbances and there were many artifacts associated correlated variations of magnitude greater than the expected natural signal. We expect to be able to overcome some of these difficulties with further processing.

Fig. 5 shows the theoretical radii which can be measured with the available frequencies on Cassini. The S-band at 2 GHz can measure as close as 4 solar radii; while the X-band can measure through a prominence above the surface of the sun. The Ka-band can measure much closer. Fig. 6 shows a zoom in of the plot of the Faraday rotation (the measured plane of polarization) on the sun during the solar conjunction. Closest approach to the Sun occurred on June 21 near the beginning of the plot shown. In preparing this plot we have approximately removed a constant diurnal variation as measured at the beginning and end of the experiment when solar effects were minimal shown in Fig. 7. We assume that the plane of polarization measured on June 16th and 25th to be the original plane as transmitted by the spacecraft. Therefore over the period of the experiment, the transmitted plane of polarization was rotating approximately 44° per day corresponding to the slope observed in the diurnal variation in Fig. 7. The maximum variation of the diurnal pattern occurs when the spacecraft is at its highest elevation in the sky and the diurnal pattern is probably due to the combination of the parallactic angle due to Earth's rotation, an observed variation in the way the antenna at DSS13 is moved when increasing elevation versus decreasing elevation, and the rotation of the transmitted plane of polarization. The time of maximum elevation varies over the 10 days of the experiment to about half and hour earlier on June 25th from June 16th. The resultant fluctuations observed in the plane of polarization clearly are the result of coronal effects on the signal. We continue to review our technique for reducing the scatter around the signal; however, we find the non-linear structures in the June 20th and 21st plots to be particularly interesting because of their deviation from our background forward model.

7. Conclusion

While Cassini was not designed to provide the ideal signals for a Faraday rotation experiment we have demonstrated Cassini's capability to obtain such data and we expect to be able to conduct the experiment at two and later at three frequencies. The signals are behaving as expected but have some artifacts. These artifacts, especially the diurnal variation may be due to the receiving antenna. While no experiment was possible in 2004 because conjunction occurred at the time of Cassini orbit insertion, we look forward to new data over the northern pole of the sun in the summer of 2005 and 2006 including S-band measurements that will be more directly comparable with previous observations.
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