Faraday Rotation on Decametric Radio Emissions from Jupiter

Abstract. *Some decametric radio emissions from Jupiter observed recently exhibit effects which are attributable to Faraday rotation within the earth's ionosphere. We present the evidence for the presence of Faraday rotation and discuss its origin. Identification of the magnetoionic mode in which the emission is generated at Jupiter appears possible, although near the limit of accuracy of our present observations. The emission seems to be generated in the extraordinary mode.*

Since early in 1960 the decametric radio emission from Jupiter has been observed at the High Altitude Observatory by a radio spectrographic technique. The spectrograph operates from 7.6 to 41 Mcy/sec, this frequency range being displayed in a two dimensional frequency-time plot in which the relative intensity of the received radiation appears as relative darkness on the chart. The spectrograph receives the output of two antennas, which act as an interferometer. The resulting data contain interference fringes that identify the source of emission as Jupiter. During the fall of 1963 the spectrograph records of emission from Jupiter appeared to contain an unexplained amplitude modulation as a function of frequency. The modulation was evident as alternate light and dark bands lying, in most cases, nearly parallel to the time axis. The bands appeared to be unrelated to the more prominent interferometer fringes. Moreover, the bands were more closely spaced at low frequencies than at high frequencies, and were visible over the frequency range of approximately 35 Mcy/sec to 15 Mcy/sec. The spectrograph recording of a major Jupiter emission observed on 13 September 1963 is shown in Fig. 1. The bands in question, which are visible on careful inspection, appear as horizontal fringes in the 22 Mcy/sec to 35 Mcy/sec range. They are present to about 16 Mcy/sec, and they continue uninterrupted by the delay line change at 0700, which, however, altered the pattern of interferometer fringes.

The structure of the bands suggests that they may be caused by the reception (on a dipole antenna) of elliptically polarized radiation, in which the direction of the major axis of the ellipse is rotated as a function of frequency. The crowding of the bands toward lower frequencies is very nearly inversely proportional to the square of the frequency. These facts suggest that the cause of the band structure is Faraday rotation occurring in Jupiter's ionosphere, interplanetary space, the earth's ionosphere, or in all three.

Observation of the amount of Faraday rotation over a broad frequency domain, along with knowledge of its frequency dependence, may, in certain circumstances, permit determination of the absolute amount of Faraday rotation along the ray path. A necessary condition for the determination is that all frequencies must be emitted from the same region with their linear components in the same direction. If such a condition is not satisfied, the interpretation of the Faraday data would be quite complex; but, as will be shown, the condition appears to be satisfied. From a knowledge of the total Faraday rotation and by using a model for the magnetic field, one can derive the electron content along the ray path. Also, from the knowledge of the total Faraday rotation and the observed orientation of the polarization ellipse at the receiver, one can determine the orientation of the ellipse at the source.

Relation to the Earth's Ionosphere

In the case of quasi-longitudinal propagation and no magnetoionic ray-path splitting, the total amount of Faraday rotation is

$$\Omega = \frac{K}{f^2} \int_{\text{ray}} (H \cos \theta)\ N\ ds \qquad (1)$$

where $K = 2.36 \times 10^4$ (centimeter-gram-second gaussian units); f = the wave frequency (cy/sec); H = the magnetic field intensity (gauss); θ = the angle between the ray direction and magnetic field direction; N = the electron density (electrons per cubic centimeter); Ω = the total polarization rotation (radians); and the integral is along the ray path from source to receiver. The rotation within the earth's ionosphere, when refraction is negligible, when the angle χ is not too large (where χ is the zenith angle of the ray), and when a mean value of the factor $H \cos \theta \sec \chi$ can be used, follows from

$$\Omega = \frac{K}{f^2} \overline{(H \cos \theta \sec \chi)} \int N\ dh. \qquad (2)$$

The integral is taken along a vertical path through the earth's ionosphere. Conditions in the earth's ionosphere permit us to use a mean value for the angular and field parameters, as indicated by the bar in Eq. 2.

From the Faraday fringes on the dynamic spectrograph records, one can determine the orientation of the polarization ellipse at the receiver over the frequency range of approximately 20 to 35 Mcy/sec. In practice, we measure the particular frequencies in the 20 to 35 Mcy/sec range at which the major axis of the polarization ellipse is parallel to the receiving antenna (which has polarization properties similar to a vertical dipole). The difference in total Faraday rotation between one of the particular frequencies and the next is exactly one-half cycle. We assumed an inverse-square frequency dependence for the Faraday rotation. Then, on the basis of the frequencies read from the record, we used a least squares technique to determine the total Faraday rotation from the source to the receiver.

With the total Faraday rotation now known, one can attribute the rotation to effects in the earth's ionosphere, compute the electron content from Eq. 2, and compare the result with estimates of electron content by other means. We have analyzed data obtained on three dates. For two of these dates, 12 August 1963 and 13 September 1963, we compared our results with the electron content determined from Boulder ionosonde data (*1*). An extrapolation of electron content was necessary to include the contribution above the F2 peak. In both cases the

Table 1. Electron content along the ray path from Jupiter's decametric radio source. The numbers are based on the assumption that all Faraday rotation occurred within the earth's ionosphere.

Date	Local time	Electron content (electron/cm²)
12 Aug. 1963	0300 to 0400	3.4×10^{12} (constant in time)
	0400 to 0540	Undetermined (increasing in time)
13 Sept. 1963	2300 to 0020	2.8×10^{12} (constant in time)
15 Oct. 1963	1915 to 2000	5.0×10^{12} decreasing to 4.4×10^{12}

electron content derived from Faraday rotation fell within the uncertainty of the extrapolation. The third date was 15 October 1963 at a time when the Alouette topside sounder was operating 500 km east of the region where the ray path from Jupiter to Boulder penetrated the ionosphere. From the Alouette data, from concurrent ground based ionosonde data, and from an estimate of the electron content above 1017 km (the height of Alouette), we found that the total electron content of the earth's ionosphere was $4.5 \pm .5 \times 10^{12}$ electrons per square centimeter. The corresponding electron content derived from our measurements of the Faraday rotation was $5.0 \pm .3 \times 10^{12}$ electrons per square centimeter. Thus the total Faraday rotation from Jupiter in all three of the cases examined could have occurred within the earth's ionosphere.

Further support for this hypothesis is provided by the time changes in electron content and the corresponding changes in the Faraday rotation along the ray path from Jupiter. Table 1 gives the values of the electron content along the ray path from Jupiter determined from Faraday rotation under the assumption that all rotation occurred within the earth's ionosphere. It is evident that the electron content was small and constant during night-time hours. The event of 12 August 1963 clearly indicates increasing electron content after about 0400 hours local time, the time of sunrise in the F2 region. Similarly, the event of 15 October 1963 indicates a definite decrease of electron content during the period 1915–2000 hours local time, the time of sunset in the F2 region. The magnitude of the decrease during the period of observation is consistent with the decrease indicated by ground based ionosondes.

Therefore, we conclude that the Faraday rotation and its time changes are likely to have occurred only within the earth's ionosphere. Extraterrestrial Faraday effect can account for no more than 10 percent of the total amount. The 10-percent figure results from our estimate of the precision inherent in the techniques for deducing the total content from ionosonde and Alouette data.

Polarization at the Source

From the measured position of the major axis of the polarization ellipse at the receiver and a sufficiently accurate determination of the total Faraday rotation, one can extrapolate backward to find the position of the major axis of the polarization ellipse at the source. In our calculations, the determination of the total Faraday rotation must be accurate to about 2 percent in order to determine the polarization axis at the source to within 45 degrees. In the three events analyzed so far, we believe the best accuracy attained was somewhat better than 4 percent. The indication from the event of 12 August 1963 is that the major axis of the polarization ellipse at Jupiter was parallel to the equator of the planet. We hope that further data and a refined method of analysis will enable a conclusive determination of the polarization axis.

The apparent axial ratio of the polarization ellipse of the received signal follows from measures of the modulation caused by the Faraday rotation. Microdensitometer measurements of the intensity modulation during the Jupiter event of 20 September 1963 showed an average apparent axial ratio of 0.59, with individual measurements varying from about 0.40 to 0.75. The measurements were made in the frequency range of 24 to 35 Mcy/sec. Concurrent and independent measurements of apparent axial ratio were made at the Southwest Research Institute by Sherrill (*2*) over the frequency range 15.2 to 24.2 Mcy/sec. He used a polarimeter which, at the time, was capable of determining only the apparent axial ratio and not of distinguishing the random from the polarized components. Sherrill's data gave an average apparent axial ratio of 0.452 with a range from about 0.30 to 0.65.

The qualitative agreement of the two determinations of the axial ratio provides further evidence that the observed modulations on the Boulder spectrograph are caused by Faraday rotation.

We find from earlier records that the presence of Faraday rotation was indicated as far back as 1961. Cursory examination suggests that it is more

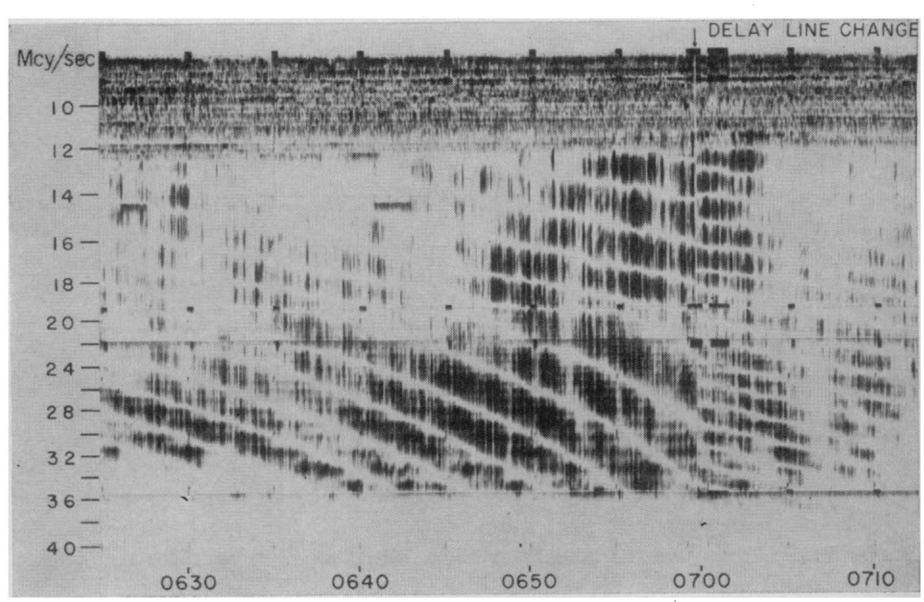

Fig. 1. Spectrograph record of the Jupiter decametric radio emission from 0630 to 0710 universal time, 13 September 1963. Darkness at frequencies less than or equal to 12 Mcy/sec was caused by interference. Diagonal white streaks are interferometer fringes. The horizontal fringes, which are most obvious between 22 and 36 Mcy/sec, were caused by Faraday rotation.

prevalent on 1963 records, and on records of radiation from the "early" source ($\lambda_{III} \approx 120$ degrees). However, at times it also appears on radiation from the "main" source ($\lambda_{III} \approx 240$ degrees.)

Interpretation of the Results

The presence of observable Faraday effect in Jupiter's radio emission from 15 to 40 Mcy/sec is surprising in view of the fact that Faraday rotation on these low frequencies can be produced by quite moderate plasma densities and magnetic fields. The fact that all of the rotation can be explained in terms of the earth's Faraday effect suggests several possible interpretations: (i) Jupiter has no ionosphere, hence produces no Faraday effect; (ii) the emission is generated above Jupiter's ionosphere; (iii) both modes of polarization are generated but only one mode escapes through the planet's ionosphere; (iv) only one mode is generated, and this mode escapes.

The first interpretation seems untenable. Estimates of Jupiter's ionospheric electron density vary (*3*), but indicate at least 10^5 cm^{-3} over a height range of 100 km or more. The total electron content of Jupiter's ionosphere would then roughly equal the earth's F-region at the time of our observations. Estimates of the surface magnetic field of Jupiter vary also, but in general amount to at least 10 or 20 times the strength of the earth's field. If these estimates are of the right order of magnitude, the Faraday rotation in Jupiter's ionosphere should be twenty times as great as the observed values.

The second interpretation is consistent with the suggestion by several authors, notably Ellis and McCollough (*4*), that the decametric emission originates in Jupiter's radiation belts at moderate distances from the planet (within one Jupiter radius, or 70,000 km). If radiation is generated in both magnetoionic modes and escapes Jupiter's magnetosphere without experiencing significant Faraday rotation, the electron density in Jupiter's magnetosphere must be very small all along the ray path. We estimate that the distance the radiation travels in the region of generation is one hundred times the distance through the earth's ionosphere, that the magnetic field strength in Jupiter's magnetosphere is ten times that of earth, and that the Faraday rotation is no more than one-tenth of that in the earth's ionosphere. The average electron density must then be less than 10 electrons per cubic centimeter. Within Jupiter's magnetosphere the electron density is probably many times greater. For instance, Ellis (*5*) estimates that the electron density in Jupiter's magnetosphere is approximately 10^3 per cubic centimeter at 1.5 radii from the planet. If this estimate is correct, we can eliminate the possibility that both modes are generated and escape. Note, however, that Ellis's theory is not affected provided that the radiation is generated in only one mode.

Possibilities (iii) and (iv) cannot be distinguished by their effects on Faraday rotation alone. Both magnetoionic modes must be present for Faraday rotation to occur. Therefore, the case of two modes being generated and one mode escaping is equivalent (in Faraday effect) to the case of just one mode being generated and then escaping.

The polarization characteristic of a single mode is fixed by the geometrical relation between the magnetic field and propagation direction. Radiation in one characteristic mode will remain in that mode as long as the ray path traverses a slowly varying medium. To distinguish between (iii) and (iv) we can use the least well established of our results: that the major axis of the polarization ellipse lies roughly parallel to the magnetic equator at Jupiter. Let us assume that in Jupiter's ionosphere the collision frequency is small compared to the electron gyromagnetic frequency. (This is true in the earth's ionosphere, and, in view of Jupiter's strong magnetic field, is likely to be true for Jupiter.) Then the characteristic modes are such that for the ordinary mode the major axis of the polarization ellipse lies in the same direction as the magnetic field. For the extraordinary mode it lies perpendicular to the magnetic field (*6*).

From these considerations we can exclude the possibility that both modes are generated and only one escapes. The basis is that the blocked mode would, in general, be the extraordinary mode (*7*). As indicated by both decimetric and decametric emissions, the magnetic field of Jupiter is approximately that of a dipole inclined 8 degrees to the axis of rotation (*8*). The ordinary mode would have the major axis of its polarization ellipse roughly parallel to Jupiter's magnetic field direction, and hence roughly parallel to Jupiter's axis of rotation. However, the emission we observe has its major axis perpendicular to the rotation axis. Therefore, we conclude that only one mode, the extraordinary mode, is generated and escapes.

Our observational results might follow in another way. If the collision frequency in Jupiter's ionosphere is sufficiently high, say 10 Mcy/sec or more, and, if the plasma frequency also is very great, exceeding the wave frequency, it would be possible for a wave in the ordinary mode to escape with its major axis at right angles to the magnetic field. However, these two circumstances seem to us highly improbable.

Both gyromagnetic radiation in a weakly ionized plasma and Cerenkov effect generate radiation in the extraordinary mode (*9*). Either of these generation mechanisms is consistent with our results.

Conclusions

We draw several conclusions from our analysis of the Faraday rotation on the Jupiter decametric radio emission.

1) The entire amount of Faraday rotation is acquired within the earth's ionosphere.

2) The apparent axial ratio (with the assumption that the waves are 100 percent polarized) varies from burst to burst but averages about 0.6 in the frequency range from 20 to 35 Mcy/sec.

3) The major axis of the polarization ellipse at Jupiter is approximately parallel to the magnetic equator of Jupiter, and the polarization properties show no radical changes over the frequency range from 15 to 40 Mcy/sec.

4) The radiation is generated in the extraordinary mode and, since only one mode is present, passes through Jupiter's ionosphere unaffected by Faraday rotation. The radiation then arrives at the top of the earth's ionosphere with a polarization which is not characteristic for the given direction of propagation, decomposes into the two characteristic modes (which are very nearly circularly polarized), undergoes Faraday rotation, and arrives at the ground with the observed Faraday rotation and axial ratio.

The conclusions we have drawn are tentative since they are based on the analysis of a small number of records. We expect that the investigation of other records which exhibit Faraday rotation, and an analysis of the Jupiter-Earth relationship at times when Faraday rotation is present, will provide more conclusive evidence on the radiation generation mechanism at Jupiter.

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10. We express our appreciation to W. M. Sherrill of the Southwest Research Institute for providing polarimeter measurements, and to several persons from the Boulder Laboratories of the National Bureau of Standards, in particular, S. M. Ostrow, for providing ionosonde data, R. G. Green and Mrs. G. B. Goe for acquiring and reducing the topside sounder data, and R. S. Lawrence for too many contributions to itemize. This work was performed at the High Altitude Observatory of the National Center for Atmospheric Research and was supported in part by the Air Force Cambridge Research Laboratories and by the National Aeronautics and Space Administration. One of us (G.A.D.) holds a National Science Foundation graduate fellowship.

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Mass Expulsion of Zooxanthellae from Jamaican Reef Communities after Hurricane Flora

Abstract. *Very extensive bleaching of coral reef communities occurred after severe flood rains over eastern Jamaica. The loss of color was due to the mass expulsion of zooxanthellae from the tissues of* Millepora, *Scleractinia, Zoanthidea, and Actiniaria living in the shallow reef zones. The polyps of the bleached individuals continued to expand and feed in their normal fashion. It is believed that expulsion of the zooxanthellae was induced by contact with water of lowered osmotic pressure on the surface of the sea, rather than by sedimentation or fouling. Regeneration of the depleted zooxanthellar populations was very slow; many of the bleached colonies survived well despite the near total absence of zooxanthellae from their tissues for over 2 months.*

Flood rains accompanying the near passage of hurricane Flora between 5 and 7 October 1963 caused severe damage of an unusual kind in Jamaican coral reefs. The inundation of the shallow parts of inshore habitats by fresh water flood run-off induced wholesale bleaching of Scleractinia, *Millepora*, Zoanthidea, and Actiniaria through the expulsion of their zooxanthellae. The damage was confined to very shallow reef communities and appears to be due entirely to physiological injury; mechanical destruction as such was slight, since during this period the eye of the hurricane was over central Cuba, more than 200 km away, and there was no storm surge. The track of this hurricane is shown on the inset in Fig. 1.

From 5 to 7 October the eastern half of Jamaica received approximately 550 mm of rain. The rivers reached flood level within hours and produced the worst inundations in the memory of the populace. The sea off the south coast was discolored to the horizon with reddish mud; large patches of floating detritus were sighted by ships' crews 50 km SSE of Kingston. On 8 October the marine station of the University of the West Indies at Port Royal reported nearly fresh water to a depth of more than 2.5 m off the laboratory's jetty. The floods receded by 9 October, but rivers remained in spate because of continued heavy rainfall over the center of the island. In the Port Royal area, the salinity decreased to less than 3 per mil on 9 October and remained below 30 per mil for more than 5 weeks. Salinity values recorded by B. Wade at two localities near the entrance to Kingston Harbor are shown in Table 1.

In Kingston Harbor, a land-locked bay, the accumulation of fresh water caused widespread mass killing of bottom communities which in turn fouled large areas outside with their decomposition products. For almost a week this contaminated water was observed drifting slowly out to sea over the coral reefs south and southeast of the entrance to Kingston Harbor. The normal easterly trade wind pattern did not become reestablished until 20 October. There can be no doubt that the unusually calm windless weather after Flora hindered the dispersal of the diluted sediment-laden surface water and prolonged the physiological stresses to which these reef communities were subjected. Most of the studies described in this paper were made on the coral reefs of the Port Royal region shown on the map in Fig. 1. This area was one of the worst affected because of its proximity to the outlet of Kingston Harbor and to the mouths of the Rio Cobre and Ferry rivers. At the height of the cloudburst innumerable temporary gullies, some of which are shown on the map, also poured large volumes of fresh water into the harbor. Moreover, immense amounts of sediment were brought to the sea by the Hope and Cane rivers, 13 and 14 km east of Port Royal.

Five days after the flood rains, most of the reef tract was overlain by foul-smelling, dark greyish-green water littered with floating debris and patches of slime. Owing to the turbidity it was possible to see only corals at the surface, the majority of them bleached to a striking bone-white color, whereas some others were covered by greyish-black ooze. At Maiden and Lime cays the water was a little clearer, and direct underwater observations could be made. These showed that the bleached corals had not been killed, as was at first assumed, but were alive and in good condition although their tissues had been rendered colorless by loss of nearly all the zooxanthellae. Most of the bleached colonies had a clean and healthy appearance; the polyps were expanded to a normal degree and were responsive to tactile stimulation; the dactylozooids of bleached *Millepora* had unimpaired stinging powers.

The appearance of killed individuals was very different: soon after death they became covered by thick greenish-brown slime, and the coenosarc disintegrated into mucous blebs that trailed off in strings and patches; subsequent