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Modulation Lanes in the Dynamic Spectra of Jovian L Bursts

J. J. Riihimaa*
Department of Astro-Geophysics
University of Colorado, Boulder

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The fine structure of the dynamic spectra of Jovian L bursts displays repeated, tilted lanes. A spaced-spectrograph experiment in which two identical radio spectrographs at 21 to 23 MHz were operated over a 160-km baseline indicated that the lanes originate at Jupiter. The interplanetary scintillation only affects the group appearance of the lanes. The sign and magnitude of the drift of these lanes is a strong function of System III central meridian longitude of Jupiter. The lanes are an intensity effect. A possible explanation is that they are produced by wave-like disturbances in the Jovian ionosphere or magnetosphere causing oscillations in the direction of the emission sheet at Jupiter.

Key words: Jupiter — spectra of decametric bursts — lane structure

1. Introduction

The decametric emission from Jupiter can be plotted as an intensity variation in the plane of time and frequency. In such a representation, or "dynamic spectrum", Jupiter's emission appears in several forms. The characteristics of these spectra in a wide bandwidth and approximately 1 second time resolution have previously been discussed (Warwick, 1961, 1963, 1964, 1967; Dulk, 1965). If the time and frequency resolution are increased by factors of 10 to 100, a number of new features emerge (Riihimaa, 1964a, b; Warwick and Gordon, 1965).

The prominent features in the high-resolution spectra are the radiation areas, or envelopes, which take a variety of shapes in the time-frequency domain. Within these envelopes, several different types of fine structure can be recognized. One of the most peculiar of these phenomena are the "modulation lanes". They appear as fairly regular, ridge-like, alternating maxima and minima of intensity, intersecting the envelopes. In the 21 to 23 MHz frequency range, the spacing of the lanes varies from 200 to 400 kHz, the average being close to 300 kHz. The lanes are tilted in the time-frequency plane, and are slightly curved. The average drift rate is close to 100 kHz/s. The sense and magnitude of the drift is a strong function of System III central meridian longitude (CML). Occasional irregularities in the modulation lanes appear as slight changes in the drift rate from lane to lane, and group to group; sudden jumps in the course of drift of a single lane; slight variations in spacing between the lanes; and disappearance of the lanes in some areas of the envelope.

The observations of these lanes during the 1967 and 1968 apparitions of Jupiter were previously described (Riihimaa, 1968a, b). In the present report a new series of observations is outlined, while the new results are combined with the results of the 1967 and 1968 apparitions.

II. Observations

Two identical high-resolution radio spectrographs (Riihimaa, 1961) were operated, one near Boulder, Colo. and the other 160 km east, near Brush, Colo. The frequency range of 23 to 20.7 MHz was swept at the rate of approximately 10/s; no attempt was made to synchronously sweep the two spectrographs. The 3 db IF bandwidth of the receivers was 50 kHz.

The WWVB time signal was continuously recorded at both stations. To avoid errors in the alignment of individual scans and the corresponding time marks, the display and the WWVB indicator were recorded through a slit, 0.25 mm wide. The frequency calibrating markers were also recorded at certain intervals of time.

The antennas consisted of four dipoles in a ring-shaped array over a reflecting screen. The gain over

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* On leave from University of Oulu, Finland.

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an isotropic radiator was approximately 10 db; by using a hybrid ring, the right-circular component was received. The antennas were tilted southward. Observations at Boulder were started on December 17, 1968, and both spectrographs were operated from January 17 to April 27, 1969. The spectrographs were operated for 4 h each night, centered on Jovian transit.

III. Results

The radiation envelopes usually cover the entire 2 MHz frequency range. Their duration varies from approximately 0.5 s to several seconds; less frequently, to tens of seconds. Occasionally, decasecond phenomena are observed which have considerably smaller bandwidths, similar to those described by Riihimaa (1968c).

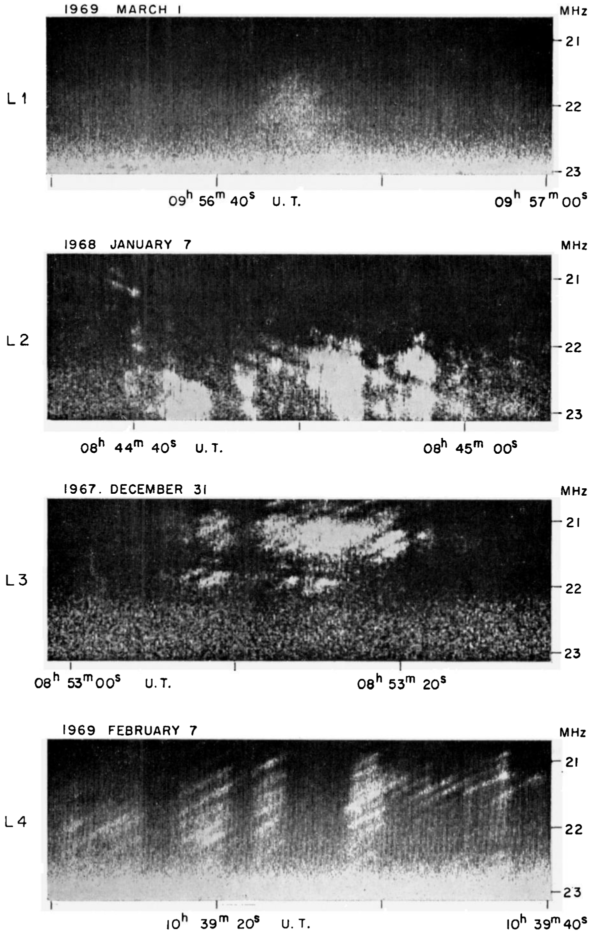

Fig. 1. Sample records of spectra of different spectral types. Type L1 denotes radiation envelopes with no modulation lanes; L2 envelopes which are intersected by positively drifting modulation lanes; L3 envelopes which are simultaneously intersected by positively and negatively drifting lanes; and L4 envelopes which are intersected by negatively drifting lanes

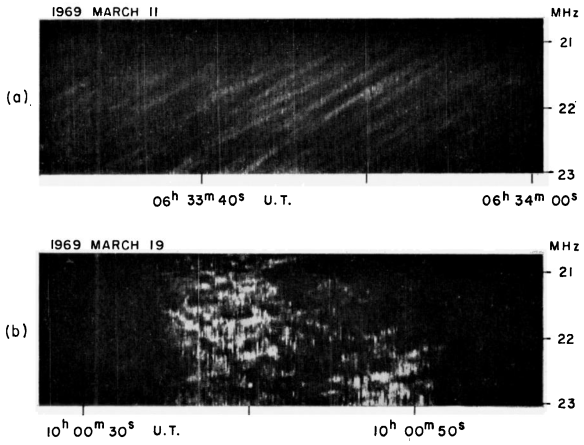

Fig. 2a and b. In (a) an L4 burst in which the drift rate of the modulation lanes vary slightly from lane to lane; (b) an L3 burst, which also is somewhat irregular, and displays simultaneously short-duration pulses (S-pulses) within the over-all pattern of L3

Long duration features of the envelopes are governed by ionospheric scintillations, which have a period of 1 min or longer. The ionospheric scintillation may sometimes be directly responsible for the duration of the envelope, but most often it causes the radiation envelopes to fade in and out independently at the two sites; while the structure within the envelopes appears virtually identical. This is in agreement with the previous observations (Riihimaa, 1968b).

There are four variations of modulation lanes: (1) L 1: no modulation lanes appear; (2) L 2: lanes drift positively (increase of frequency with increase of time); (3) L 3: both positively and negatively drifting lanes are simultaneously present; and (4) L 4: lanes drift negatively (Riihimaa, Dulk and Warwick, 1969). This is based on Gallet's notation of L for "long" bursts from his observations at fixed frequencies (Gallet, 1961). Samples of these four spectral types are presented in Fig. 1.

The most common types of irregularities observed in L 4 and L 3 bursts are shown in Fig. 2. Such irregularities, as the lane jumps and varies drift rates, occur in about ten percent of the bursts. The almost complete similarity of L 4 bursts, as observed at locations spaced by 160 km, is shown in Fig. 3; there may be some slight differences between envelope structures, but the modulation lanes appear identical.

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It is clear from these records that at a fixed receiving frequency the recorded burst duration is determined by either of two spectral characters: the envelope structure or the modulation lanes; in most cases by both. The modulation lanes intersect a given fixed-frequency at intervals varying from 1 to 5 s, the average being 3 s. This is very similar to the typical duration of radiation envelopes. Two important characters of radiation will therefore be continuously confused if a fixed-frequency radiometer is used.

Comparison of spaced-spectrograph records indicates that some structure shows a delay effect from Brush to Boulder, corresponding to a shadow-pattern velocity of the order of 300 km/s across the ground from east to west during January and February 1969. This result is analogous to that found by Douglas and Smith (1967) and Slee and Higgins (1968), based on fixed-frequency observations. The authors interpreted a part of Jovian burstiness as a scintillation effect in the solar wind which flows radially outwards from the sun, and reverses its apparent direction of motion across Jupiter within a few days of Jovian opposition.

To determine the feature in the spectral records displaying delay effects, 22 bursts recorded on January 23, 31; February 7, 12, 14, 17, 21; March 11, 18, were studied as follows: the 35 mm records of bursts from Boulder and Brush were printed on 5″ × 7″ sheet film together with WWVB time marks

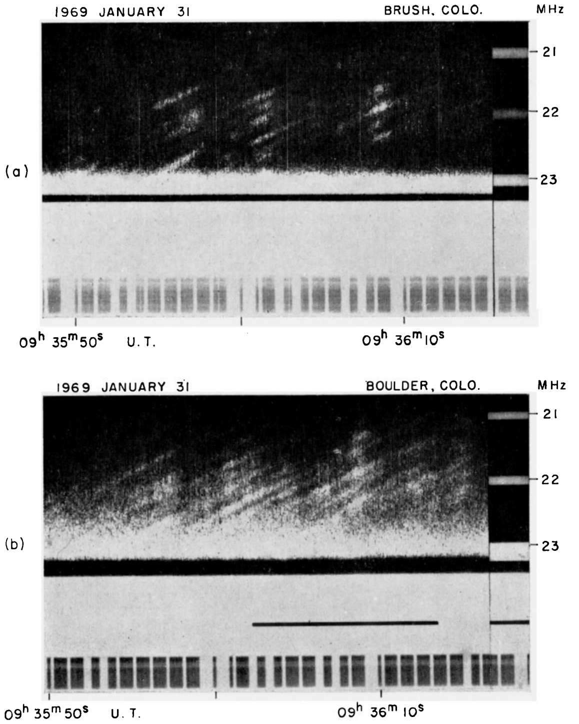

Fig. 3 a and b. A pair of spectral records of L4 bursts recorded at locations spaced by 160 km. The frequency calibrating markers appear at the right edge, and the WWVB time signal at the bottom edge of the records. The spectra of Jovian bursts are essentially similar at the two stations

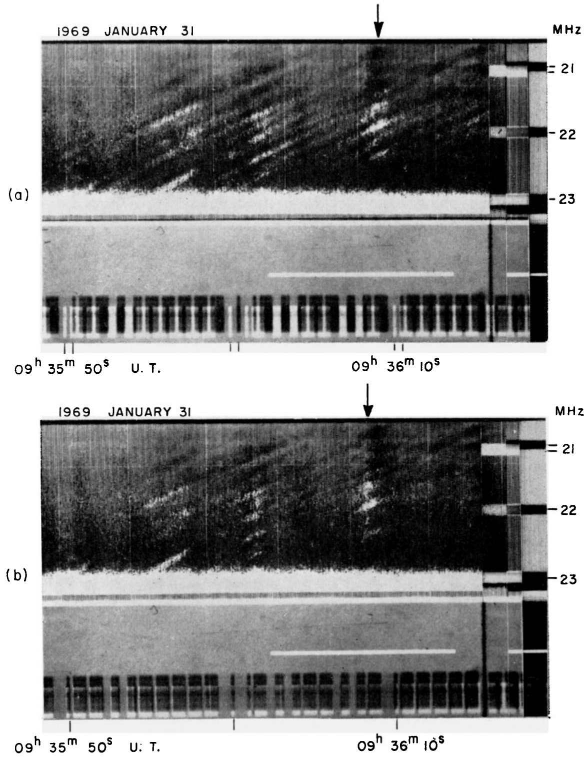

Fig. 4 a and b. Superposition of Boulder and Brush records to demonstrate the Jovian origin of the modulation lanes, and the interplanetary origin of the radiation envelopes. A negative transparency of the Boulder record of Fig. 3 (darker areas denote high radiation intensity), is superimposed on a positive Brush transparency (lighter areas denote high radiation intensity). In (a) the records are aligned so that Boulder lags Brush by 0.5 s (white time marks at the bottom belong to the Boulder record). The frequency markers are aligned at 23 and 22 MHz; the slightly unlike scales cause some misalignment at 21 MHz. The modulation lanes appear clearly, while the envelopes coincide (indicated by an arrow). In (b) the time marks are aligned. The modulation lanes disappear almost completely, because a "masking" effect arises. The envelopes are not simultaneous, as evidenced by the white area (marked by an arrow). The radiation envelope at Brush is advanced in time from that at Boulder by approximately 0.5 s. Some of the dark, broad, vertical bars elsewhere in the record are produced by the Moiré effect due to a slight difference in scanning rates used to obtain the two records and frequency calibrating marks. From these positive transparencies, contact (negative) transparencies were made. By superposing positive and negative transparencies of the same burst observed at different locations, a "masking" effect occurs, tending to cancel out similarities in the spectra while emphasizing differences. Thus, the alignment of the spectra, the time and the frequency markers are easily seen by the eye. This is important, because in aligning diagonal spectral patterns in the time-frequency plane, an alignment can be achieved by having a small error either in time *or* frequency. Also there are two pairs of records for each event, of opposite polarity, which can be aligned.

A sample of superposition of positive and negative transparencies is given in Fig. 4. In (*a*) the records are aligned so that the Boulder record is delayed by 0.5 s from the Brush record. The modulation lanes are not well masked and appear clearly, while the envelopes coincide. In (*b*) the time and frequency marks are aligned as well as possible. The modulation lanes now disappear almost completely, while the envelopes are slightly displaced.

The results suggest strongly that the time delay effect concerns mainly the radiation envelopes. Observations made 50 to 30 d before opposition show the Brush envelope leading the Boulder envelope by approximately 0.5 s. (Close to opposition, the envelopes tend to have long duration, as discussed below, and appear more diffused. While the amount of delay is more difficult to determine, it is considerably shorter than 0.5 s.) The modulation lanes, on the other hand, appear almost simultaneously at the two sites. There is some evidence for a slight (less than 0.2 s) time shift in the modulation lanes in which the Boulder modulation lanes lead those at Brush, independent of Jupiter's elongation. No error can be found in the time or frequency marks or the symmetry of receiver pass-bands or display system which can explain this shift. Unfortunately, the effect is of marginal significance and should be verified by further observations. The spectral delay previously reported (Riihimaa, 1968d) concerned the intersection of the modulation lanes with the envelopes; the 70-km baseline used at that time was not adequate to determine which one of these two was responsible.

The interplanetary origin of the envelopes is further evidenced by study of the envelope durations. The envelope duration should increase near opposition, when the component of the solar wind velocity perpendicular to the Earth-Jupiter line decreases

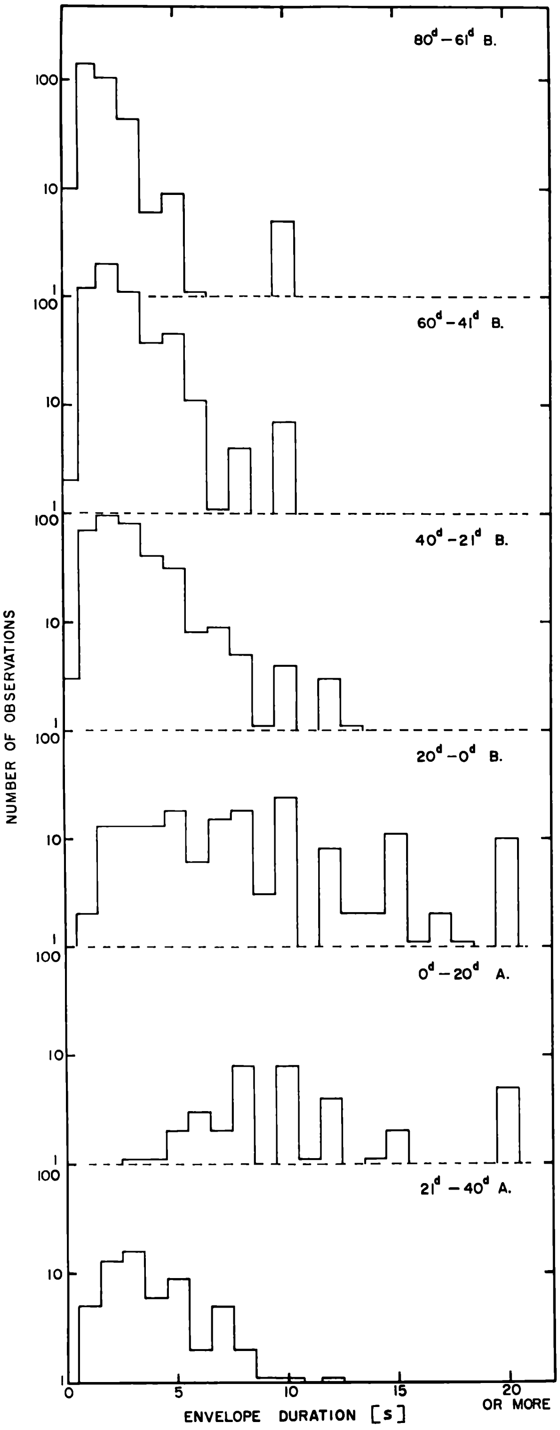

Fig. 5. Number of observed envelopes with various durations, plotted for four 20-day intervals before opposition and two 20-day intervals after opposition. The elongations for 80, 60, 40, 20, days before and 0, 20, and 40 days after opposition are 97, 119, 139, 161, 180, 198, and 219°, respectively. There was a tendency to scale even values such as 8, 10, 12, and 15 s

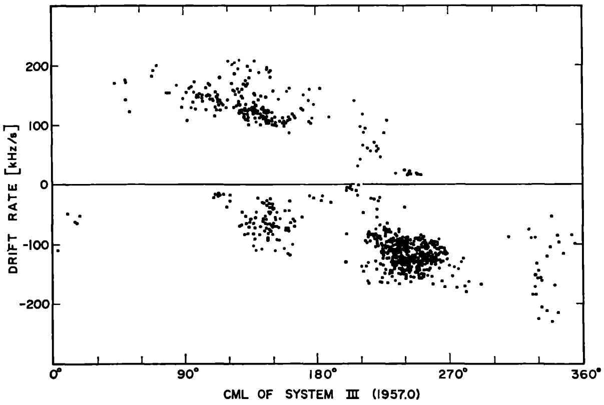

Fig. 6. Drift rates of the modulation lanes plotted as a function of CML

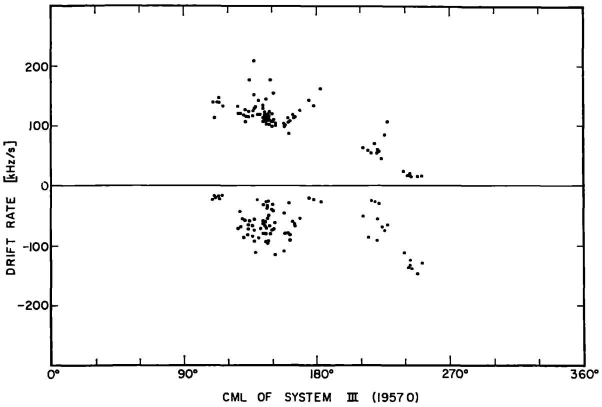

Fig. 7. Similar diagram to Fig. 6, but for L3 bursts only

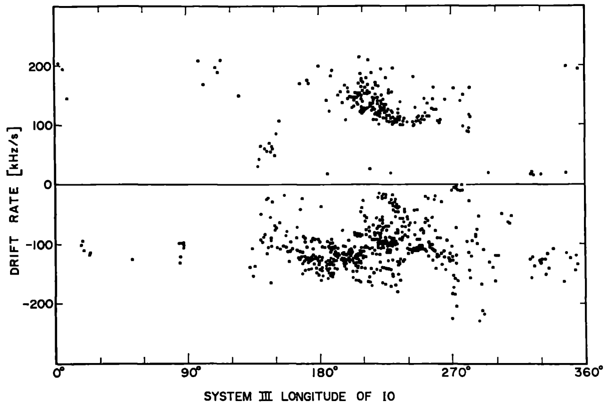

Fig. 8. Similar diagram to Fig. 6, but as a function of Io's zenographic longitude

and then reverses direction. Figure 5 shows the duration of radiation envelopes as a function of Jupiter's elongation for the 1968 and 1969 apparitions. The data are plotted in 20-day intervals. There is a clear indication that within ± 20 d from the opposition, the envelope durations increase, as expected. Groupings performed in 10 d intervals indicate that the envelope lengthening extends to 30 d before and after opposition.

When the drift rates of modulation lanes are plotted as a function of the elongation of the planet, no relationship is observed; this result also applies for regions A, B, and C separately [the region designation is that of Carr *et al.* (1961)]. If the number of L 2, L 3, and L 4 bursts is similarly plotted, L 2 and L 3 bursts form similar profiles, but those differ from L 4 profile. This is what may be expected, because the $\lambda_{\rm III} - \lambda_{\rm Io}$ configuration is approximately the same for L 2 and L 3 bursts, but is different for L 4 bursts.

If the burst drift rates are plotted as a function of CML, a strong dependence can be seen. Such a diagram is shown in Fig. 6. The rates are derived from bursts of type L 2, L 3, and L 4, during the three observing periods at the 1967, 1968, and 1969 apparitions. The diagram indicates clearly that the CML determines the signs and magnitudes of the drift rates of the lanes. Region B has both positive and negative drifts, and region A mainly negative drifts; while region C only has negative drifts. L 3 bursts are largely responsible for the negative drifts at region B and for the positive drifts at region A.

The spacing of the modulation lanes probably depends slightly on the CML, but this dependence is far less convincing than that for the drift rate.

In Fig. 7, only L 3 bursts are plotted. Note that the positive values of drift rate in regions B to A decrease approximately linearly with increasing CML. Figure 8 shows the drift rates of L 2, L 3, and L 4 bursts as a function of Io's zenographic longitude. The concentration of data points in a limited sub-Io longitude range indicates the joint Io, CML control of bursts containing modulation lanes.

The positions of storms displaying L 2, L 3, and L 4 bursts in the CML – Io longitude plane are shown in Figs. 9, 10, and 11, respectively. Figure 9 indicates that there is a limited occurrence area for L 2 bursts in the B-region; similarly, there is another area for L 3 bursts, also in B-region, as indicated in Fig. 10. Figure 11 shows that L 4 bursts are mainly emitted from regions A and C. If Figs. 9 and 10 are superimposed, a "hole" appears, centered at

$\lambda_{Io} \sim 85°$ and $\lambda_{III} \sim 125°$. This is the main region for millisecond pulses (Riihimaa, Dulk and Warwick, 1969).

If the drift rates of L 2 bursts and the positively drifting portions of L 3 bursts are plotted in the $\lambda_{III} - \lambda_{Io}$ plane as a 3-dimensional diagram, one can see that the drift rates tend to increase away from the B-region center. For the drift rates of L 4 bursts, no such trend is apparent.

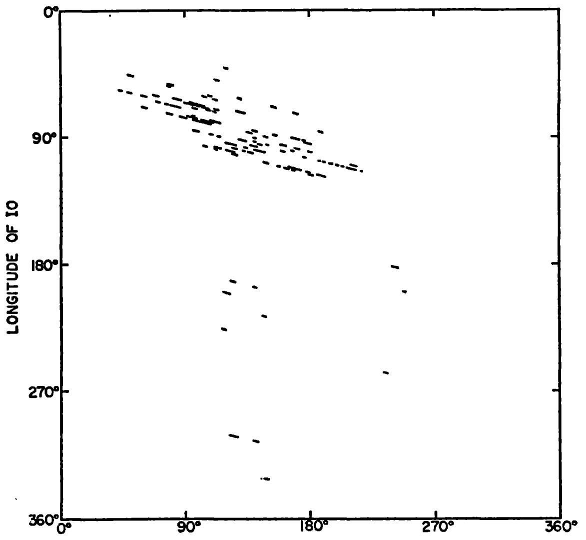

Fig. 9. Events of type L2 for the observing periods during the apparition of 1967, 1968, and 1969, plotted as a function of CML and Io's longitude from superior geocentric conjunction

An occurrence histogram of spectral types L 1 to L 4 is given in Fig. 12. The data result from three periods of observation, the 1967, 1968, and 1969 apparitions. In defining an "event", a burst or group of bursts with interruptions shorter than 1 min is considered as a single event. This diagram clearly illustrates the strong dependence of L 2, L 3, and L 4 bursts on CML. L 2 bursts generally favor region B, and L 4 bursts region A. The L 4-histogram is tri-lobed, with secondary peaks in regions B and C. The L 3 histogram favors intermediate longitudes between regions A and B.

The number of data points in Fig. 6 may differ from the number of data points included in Fig. 12 because some events may be so long that more than one drift rate measurement can be made; while, on the other hand, some modulation lanes may be so weak that only the drift sense (spectral type) but not the rate can be determined.

IV. Discussion

Repeated lane structure in the spectra, similar to the modulation lanes described here, can be produced by any of the three effects: (*a*) Faraday rotation effect, (*b*) polarization diversity effect, (*c*) intensity variation of the emission. These possibilities are now considered:

(*a*) Jupiter's decametric emission is elliptically polarized predominantely in the right-hand sense. If the polarization of the receiving antenna is mainly

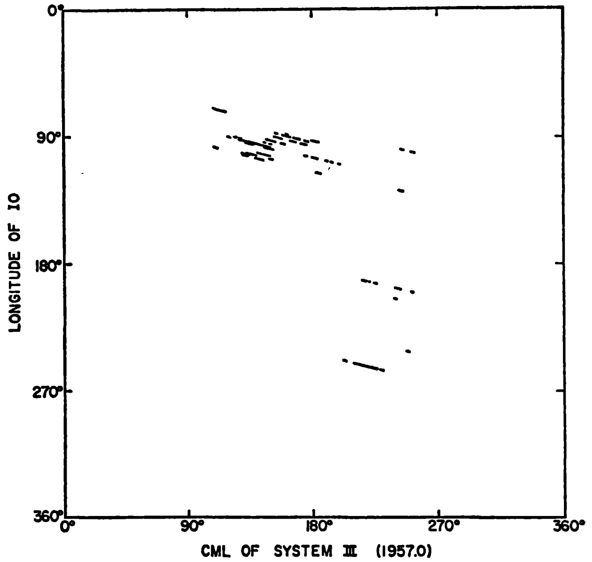

Fig. 10. Similar to Fig. 9, but for L3 bursts only

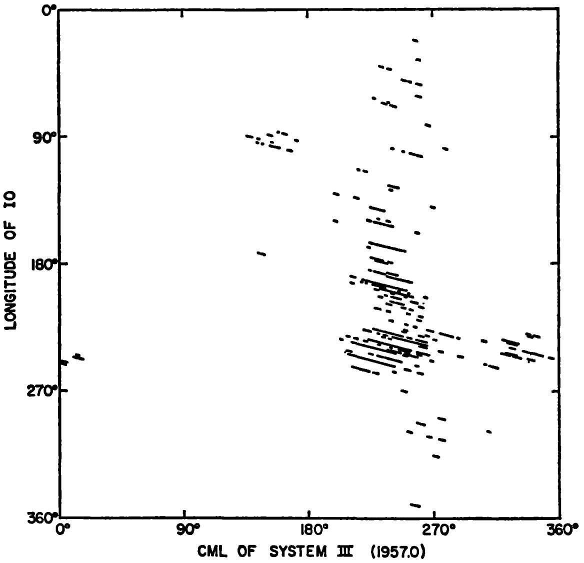

Fig. 11. Similar to Fig. 9, but for L4 bursts only

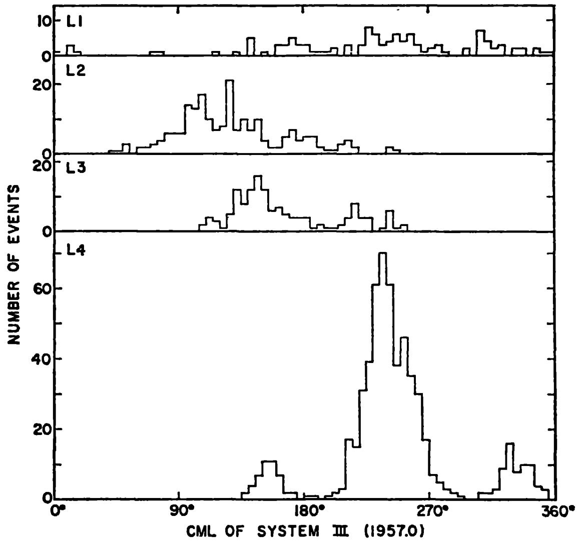

Fig. 12. Number of events of spectral types L1 to L4 as a function of the CML

linear, alternating maxima and minima appear in the spectrum. This is due to the fact that the polarization ellipse of the incoming wave assumes different orientations at different frequencies at the antennas. If the electron content over the ray path remains constant, the Faraday fringes appear parallel with the time axis. If the electron content gradually changes, they will appear tilted.

Warwick and Dulk (1964) have shown that the Jovian Faraday effect does not appear. At least 90 percent of the Faraday rotation is produced by the terrestrial ionosphere. This can be explained by assuming that the wave emanating from Jupiter is in one magnetoionic mode (probably extraordinary), and therefore cannot undergo Faraday rotation at the planet. The observed radiation is elliptically polarized, implying that propagation is in the quasi-transversal mode. In the terrestrial ionosphere, however, the propagation mode is almost always quasi-longitudinal. Thus the characteristic waves are circular waves rotating in opposite senses, into which the incoming elliptical wave degenerates. As the ordinary and extraordinary waves have different phase velocities, terrestrial Faraday rotation occurs.

The absence of Jovian Faraday rotation, therefore, makes it unlikely that the drift rates of the modulation lanes would depend on Jupiter's longitude. Also, as shown in a spectral experiment in which a linearly polarized antenna was used (Riihimaa, 1968a), the Faraday fringes and modulation lanes clearly appear as two separate and independent patterns. In any case, in the present experiment in which a predominantely circular antenna was used, Faraday fringes would not appear. It is therefore concluded that the modulation lanes cannot be Faraday fringes.

(*b*) Polarization diversity describes a phenomenon in which the sense of polarization of Jovian radiation flips back and forth periodically as a function of time and frequency (Warwick and Gordon, 1965; Gordon, 1966; Gordon and Warwick, 1967). Although observed in connection of millisecond pulses, a similar phenomenon may well occur in the spectra of 1-s and 10-s bursts. In the present experiment in which right-circular component is received, the polarization diversity effect would manifest itself as lanes, void of emission, at areas where the emission turns left-handed.

There are two arguments against this interpretation: (1) as noted above, modulation lanes were recorded with a linearly polarized antenna (Riihimaa, 1968a). Lanes produced by polarization diversity would not be observed, because a linear antenna receives equally well right- and left-circular waves; (2) during another experiment (Riihimaa, 1968b), one spectrograph was used to receive right-circular and the other left-circular component of radiation for a few nights. The two spectra and their modulation lanes appeared virtually identical but the left-circular spectrum was consistently weaker. It is concluded that the modulation lanes are not produced through a polarization diversity effect.

(*c*) The modulation lanes must therefore be produced by variations in the apparent intensity of the emission. Intensity fluctuations can be a result of a diffraction process in the transmitting medium; or it could be intrinsic to the source. There are three possible regions responsible for scintillation: (1) terrestrial ionosphere; (2) interplanetary space; (3) Jovian ionosphere. These cases are now considered: (1) In the present and the previous spaced-spectrograph experiment (Riihimaa, 1968b), the baseline was an order of magnitude longer than the scale size of the scintillation-causing electron density irregularities in the ionosphere. If the lanes are produced by ionospheric scintillation, the patterns recorded at spaced sites should therefore be independent. Because the lane patterns are observed to be virtually identical, they cannot be due to the scintillation effect in the terrestrial ionosphere. (2) As discussed in Chapter III, the study of the delay effects of various spectral features over an east-west baseline suggests strongly that the interplanetary scintillation gives rise to the radiation envelopes. It is not involved in the production of the modulation lanes. The lanes must therefore be produced in the vicinity of the planet. This is also indicated by the fact that CML controls the drift rates of the lanes. (3) The scintillation effect in Jovian ionosphere or magnetosphere would be a special case in which the diffraction screen is close to the source, while the observer is at a large distance. There are several severe requirements for the diffracting region, such as the constancy of its distance from the source and the homogeneity of the shape and size of the electron density variations. As previously discussed (Riihimaa, Dulk and Warwick, 1969), this possibility is considered highly unlikely.

Hence the modulation lanes must be intrinsic to the source. The regular appearance of the lanes, again, suggests three possibilities: (1) Jupiter's emission is confined to an interference pattern created by an array of coherently excited sources at Jupiter; the pattern rotates in space with the planet or with a sub-Io point at the planet; (2) the interference pattern is produced by a direct and reflected ray or two partially reflected rays from an incoherent source; (3) a periodic process of some other sort at the source controls the emission.

There are difficulties in (1) and (2). On the spectra, at a fixed frequency, the time interval between maxima of modulation lanes is, on the average, 3 s. Letting this, together with Jupiter's rotational rate, define the interference lobe spacing, the implied source size at Jupiter is of the order of 10^4 wavelengths. This is consistent with the recent measurements of source sizes (Dulk, 1969). However, if we take $t =$ const. and let the frequency vary from 23 to 21 MHz (10 percent of the center frequency), there should then be approximately 10^2 fringes in the frequency domain. The observed number is about 7. One might instead hypothesize that the source spacing at Jupiter is much smaller and its lobe motion is much faster than that associated with Jupiter's rate, but this creates another problem: modulation lanes may be present over an entire storm lasting for tens of minutes and even hours, during which a fast moving source would cover an excessive distance.

A similar problem arises in the interpretation utilizing interference between two reflected rays. The characteristic time for such a process to occur is only a few minutes, which is shorter by an order of magnitude than the duration of the occurrence of modulation lanes during a major storm.

Another possibility, some kind of repeating mechanism such as a wave-like disturbance present in the environment of the emitting source, offers some advantages over a continuously growing time function at Jupiter. The radiation from Jupiter is highly directive; it escapes into a narrow cone (Warwick, 1963) or perhaps a thin conical sheet (Dulk, 1967). In the latter case, the base of the cone is close to the sub-Io point (along Jupiter's magnetic field lines) in Jupiter's ionosphere or just above it. Emissions of regions A and B are received from different sides of the sheet of the cone of radiation.

Suppose that ripples in the ionosphere periodically affect the direction of the sheet of emission, either by causing variations in the cone angle or in the orientation of the cone. This oscillation could probably be relatively small, perhaps just a few degrees. An additional requirement is a slight difference of the point of origin of the radiation as a function of frequency, introducing gradual changes in the cone orientation with varying frequency. As the planet rotates approximately 120° and Io's longitude increases by approximately 150° from region B to region A, the origin of radiation flips from one side of the planet to the other. If low frequencies originate at higher altitudes than high frequencies and hence, in projection, farther from the disc center, then the sense of drift of the modulation lanes may be reversed from region B to A.

Qualitatively, then, the two main emitting regions (regions A and B) could display modulation lanes with opposite sense of drifts (L 4 and L 2), and the overlapping region simultaneously both senses of drifts (L 3). The difficulty lies in the description of the waves responsible. The gravity waves in the top of Jovian ionosphere can travel only a relatively short distance in the time required for a full cycle of modulation lanes as seen at a constant frequency. If the waves co-rotate with the planet, the sub-Io point rides through them with a velocity of approximately 5 km/s; this requires a source size at a given frequency of only a few km. Such an extremely small source may not be feasible in view of the extreme requirements it imposes on the possible radiation mechanisms. Perhaps a considerably faster moving wave system, such as hydromagnetic waves, is required.

V. Conclusion

Observations of the modulation lanes are very important in studying the Jovian radio phenomena. It is worth noting that for this kind of work the resolution limits of at least 50 kHz in frequency and 0.1 s in time are required. These requirements are not excessively severe. However, the present range of 21 to 23 MHz should be extended, perhaps to 15 – 40 MHz; also the spectra of right- and left-circular components should be recorded. In addition, a spaced-spectrograph experiment baseline longer than 1 000 km is needed.

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J. J. Riihimaa
Department of Electrical Engineering
University of Oulu
Kirkkokatu 14, Oulu, Finland