SOURCE LOCALIZATION OF JUPITER'S IO DEPENDENT RADIO EMISSIONS

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Abstract

Because of the low angular resolution of antennas at decametric wavelengths, it is difficult to localize the source of Jovian radio emissions directly, and the following new technique was devised for that purpose. The usual hypothesis for the Io–dependent part of such emissions, both the smooth L–radiation and the discrete S bursts, is that they must be emitted at the local electron cyclotron frequency along the Io magnetic flux tube. To test this hypothesis, we have compared the peak frequencies of those emissions, measured with both Voyager and the Paris Radio Observatory at Nançay, France, with the surface gyrofrequency deduced from the Jovian magnetic models. Although certain well–defined features in the dynamic spectra (mainly isolated arcs and certain unusual S–bursts) would seem to fit the hypothesis, the bulk of the Io–controlled emissions were found to be delayed by up to 70° of equatorial longitude from the predicted instantaneous position of the Io flux tube, with the L– and S–emissions both showing this same unexpected behavior. The source of these emissions thus appears to be delayed substantially with respect to Io, by an amount which is hard to explain, either as an Alfvén–wave delay or by errors in the magnetic field models.

1. Introduction

It is well known that there are two major kinds of Jovian decametric radio emissions: One which depends on the position of the Jovian moon Io and appears only when the observer occupies certain positions with respect to both Jupiter and that satellite (Bigg, 1964), and another which does not, and appears regardless of Io's location. The Io–dependent emission also consists of two quite different components. The most frequent is smooth and slowly varying, both in time and frequency, and it is often structured into ≈ 1–sec bursts (known as the L–bursts, with L for "long") by interplanetary scintillations. The other component, known as the S–emission for S–bursts (with S for "short"), consists of intense bursts with very narrow instantaneous bandwidths of a few kilohertz, and rapid drifts toward lower frequencies.

The striking correlation of the Io–controlled emissions with Io's position suggests that both of these emissions could be emitted at or near the magnetic field lines which thread through Io, the so–called "Io flux tube" or "IFT". In order to check this hypothesis, it is necessary to localize the source of these decametric emissions, but because of relatively large beamwidths of radio antennas at such wavelengths (compared to the distance of Jupiter), direct localization is not practical. The first studies to localize the source by other means (Genova and Boischot, 1981; Calvert 1983) were in approximate accordance with the hypothesis, but it was felt that a quantitative statistical study was also needed. Based upon the very reasonable assumption of emission close to the local source gyrofrequency, we have compared the maximum observed frequencies of the emissions to the predicted gyrofrequency at the foot of the Io flux tube, as determined by the magnetic field models deduced from the Pioneer magnetic measurements. The basic idea, of course, was that since the emissions must originate from above the planetary surface and the gyrofrequency decreases with altitude the emissions at the highest frequencies must have come only from those field lines with a sufficiently–high surface gyrofrequency, and if the hypothesis is correct, then those field lines should include the Io flux tube.

2. The observations

For this study, various broadband observations of the Jovian decametric radio emissions were required. Recently the Planetary Radio Astronomy (PRA) experiments on both of the two Voyager spacecraft gave an excellent opportunity to study these emissions with good sensitivity, because of their proximity to Jupiter, and also over a large frequency range (Warwick et al., 1977; Boischot et al., 1981). From the Voyager data covering both of the two encounter periods in 1979, Aubier and Genova (1985) established a catalogue of the high–frequency limit of the Jovian decametric emissions, including mostly that of the smoother L–emissions.

On the other hand, the S–bursts are generally more evident in the ground–based Jovian radio observations, because of their finer spectral resolution. The 144–element antenna array of the Paris Observatory at Nançay, France, has been performing daily observations of Jupiter since 1978, in the 10 to 40 MHz frequency range (Boischot et al., 1980). The dynamic spectra, or time–frequency spectrograms of these radio observations are routinely recorded on several media, and for the study of the S–bursts, the "facsimile" paper recordings were used, of swept–frequency observations with a 20 MHz range one second temporal resolution, and a 20 kHz instantaneous bandwidth, as is illustrated by Figure 1.

Since the Io–controlled decametric emissions are organized by both the observer's position and the position of Io, two coordinates are needed to describe the occurrence of radio events. The most commonly–used coordinates are the central meridian longitude, or "CML", which is the Jovigraphic longitude of the observer in the so–called system III (1965.0) coordinate, measured westward on Jupiter with respect to an arbitrary reference longitude, and the phase Φ of Io, which is the orbital angle of Io from superior conjunction with respect to Jupiter as seen by the observer. Also for the current study, the position of Io with respect to the planet is a relevant parameter, and we shall use the Jovigraphic longitude of Io, given by

$$\Lambda_{Io} = CML - \Phi + 180° \tag{1}$$

3. The smooth Io–dependent L–emissions

During a typical Jovian rotation, the observed dynamic spectrum evolves as illustrated by Figure 2, corresponding to a specific inclined track in the CML versus Φ space shown in Figure 3. From the observations for many such tracks, systematic occurrence patterns develop in this event space, and the different regions of high occurrence generally correspond to recognizable features in the radio dynamic spectra. For example, in Figure 2 above about 15 MHz, only one Io–independent event was observed, at $90° \leq \mathrm{CML} \leq 180°$, and two Io–dependent events, for $\mathrm{CML} > 180°$. In this fashion, as was done for the catalogue of Aubier and Genova (1985), the Io–dependent events can be sorted according to their dynamic spectra (Leblanc, 1981), as well as by their occurrence in CML versus Φ. All such events from the catalogue are reported in Figure 3, where the conventional names for the different Io–dependent regions of the CML – Φ plane are also indicated, along with the typical dynamic spectra of those regions. The most common emissions consist of right–hand polarized (with respect to the wave arrival direction) arc patterns from the northern Jovian hemisphere, with nearly vertical arcs, as indicated

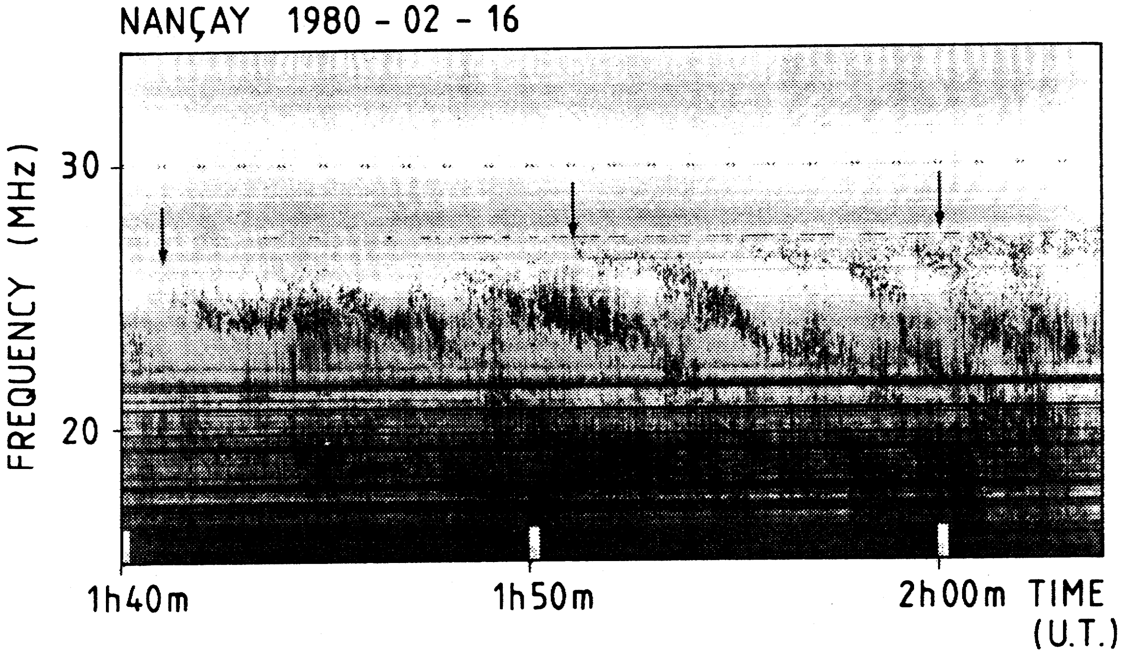

Fig. 1: (from Genova and Calvert, 1988) A dynamic spectrum showing Jovian radio S–bursts (dots) recorded at Nançay, with arrows indicating the times at which the high–frequency limits of the S–bursts were measured. Smoother L–emission also appears at lower frequencies. Fixed–frequency lines are interferences.

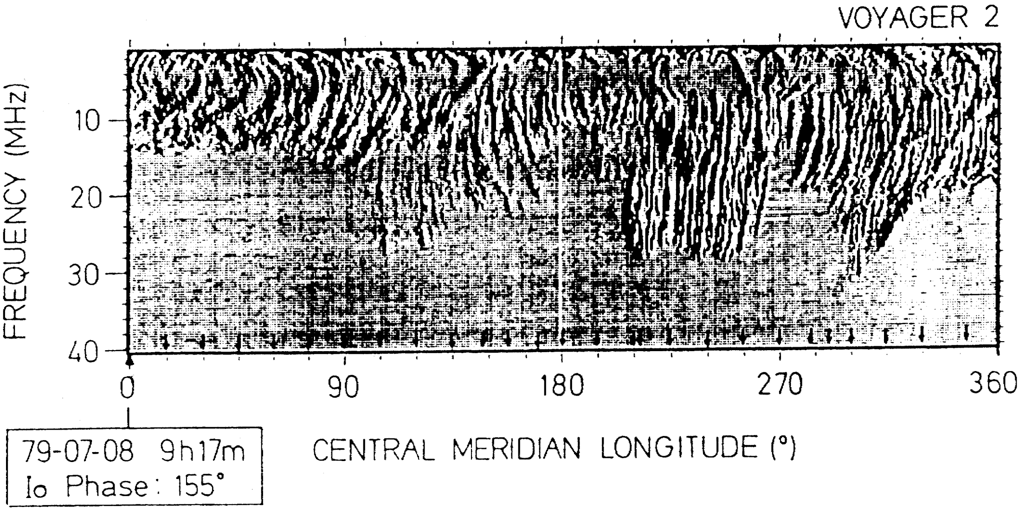

Fig. 2: (from Aubier and Genova, 1986) Differential dynamic spectra of Voyager PRA observations in the 1–40 MHz frequency range during one Jovian rotation in which, separately for each of the frequency channels, the intensity measurements were compared to the previous and following ones and the sense of their variation was plotted as black and white shadings to indicate the local increases and decreases of intensity, respectively. This eliminates many of the fixed–frequency interferences of the PRA and it makes the fainter emissions appear more obvious. The arrows in this figure also indicate where the highest emission frequencies were measured.

by A, A' and B in Figure 3. Such events are known to be Io–dependent, and they are distinguishable from the other, non Io events which occur in the same regions by their arcs exhibiting less curvature. In region D, on the other hand, which corresponds to left–handed emissions from the southern hemisphere, the emissions appear as a single, broad arc, whereas in region C, the spectra exhibit overlapped patterns of both polarization and arcs of different curvature, presumably including oppositely–polarized emission from both hemispheres, although the right–handed emissions from the northern hemisphere are generally dominant.

The high frequency limits of the Io–dependent L–emissions in the catalogue were studied by Genova and Aubier (1985). As expected for these emissions, the high–frequency limit was found to vary considerably, from about 15 MHz to the highest frequencies observed with Voyager, of about 38 MHz. The high–frequency limit for these smooth emissions are shown as crosses (+) in Figure 4, as a function of the Io phase with respect to Jupiter, Λ_{Io}. It is clear from this figure that the observed high–frequency limits are concentrated into a single longitude range which becomes more narrow as the frequency increases.

To test the hypothesis of emission from the IFT in the northern hemisphere, we have plotted in Figure 5a the predicted positions of the IFT footprint on a map of the surface gyrofrequency computed from the O_4 magnetic model of Acuña and Ness (1976a). From its interactions with the gyrofrequency contours, this should have given the maximum frequencies which could have been emitted from the IFT, and we have compared that to the observed maximum frequencies in Figure 4 by plotting as double–headed arrows of

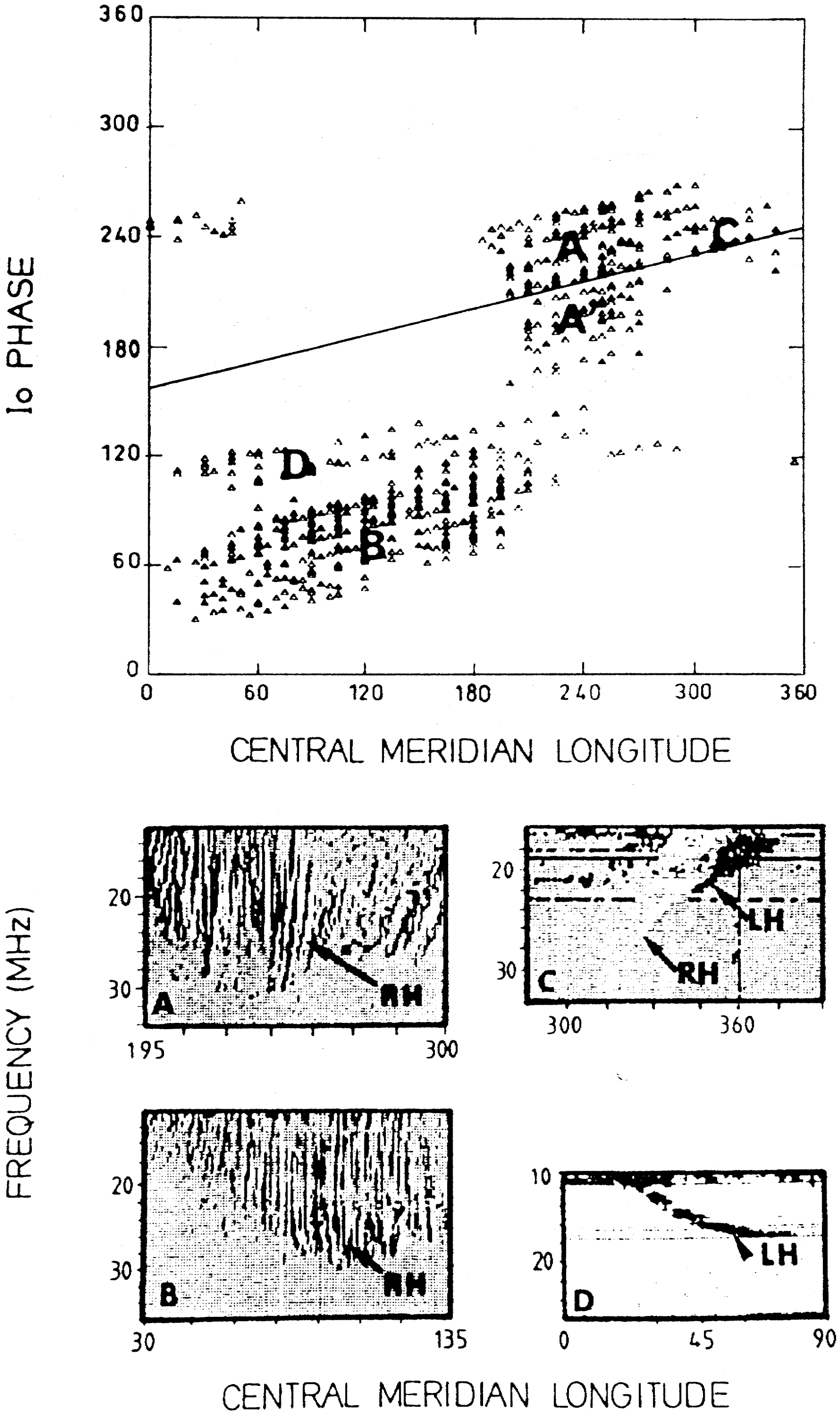

Fig. 3: Central meridian longitude and Io phase of the Io–controlled smooth emissions above 15 MHz, from the catalogue by Aubier and Genova (1985). The conventional names for the different occurrence regions are indicated, and examples of dynamic spectra of the Io–dependent emissions within those regions are shown. The inclined line represents the track of Io phase versus CML corresponding to Figure 2.

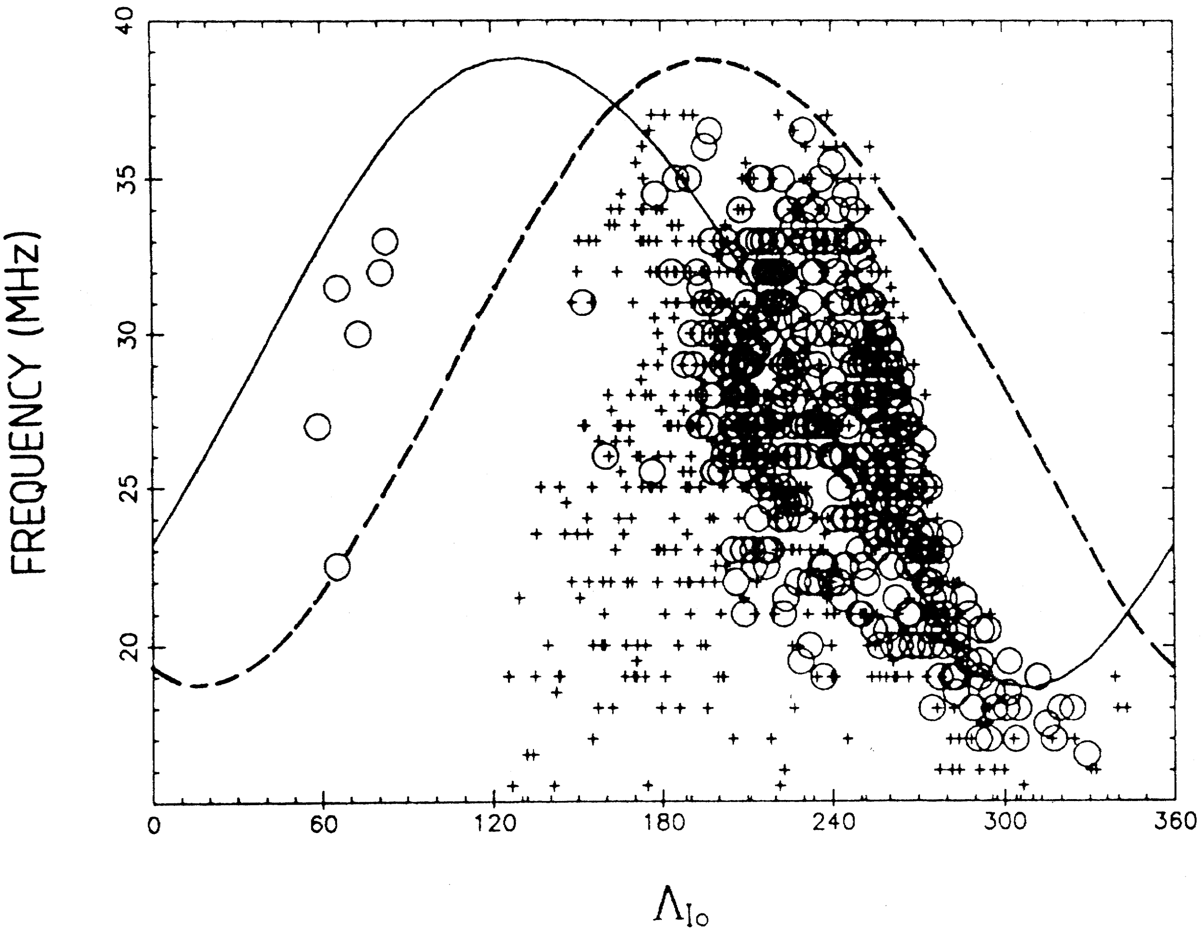

Fig. 4: (adapted from Genova and Calvert, 1988) The highest observed frequencies of Io–controlled emissions from the northern hemisphere as a function of Λ_{Io}*, for the smoother L–emissions (+) and the discrete S–bursts (○). The full and the dotted curves represent the gyrofrequency at the foot of the Io flux tube and that at the foot of the field line which intersect Io's orbit with a delay of 70°, computed from the* O_4 *model of Acuña and Ness (1976a).*

increasing size the corresponding positions along the IFT track for 25, 30, and 35 MHz. From this comparison, it is quite obvious that most of the high–frequency emissions could not come from the predicted instantaneous Io flux tube. In fact, in order for the observed emissions to have come from field lines which were capable of emitting at the observed frequencies, the source field lines would have to have been shifted from their predicted positions by about 40° of longitude at the surface of Jupiter, or else by up to 70° of longitude at the equatorial orbit of Io, these two being different because of field–line distortions in the O_4 model (see also Figure 4).

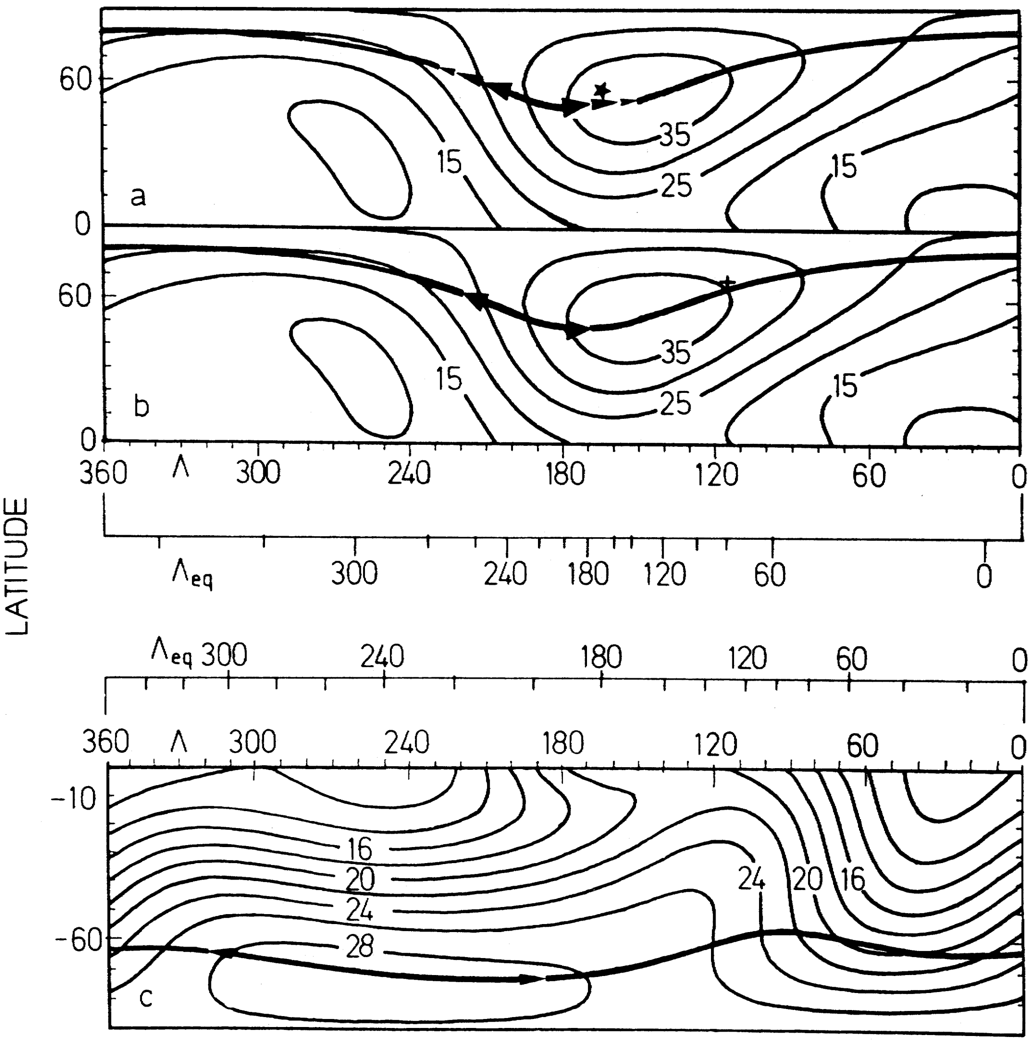

Fig. 5: Isocontours of the surface gyrofrequency at Jupiter (in Megahertz), deduced from the O_4 *model and shown in Jovigraphic coordinates. The heavy line represents in each case the track of the IFT across Jupiter, with each field line characterized by* Λ*, which is the Jovian longitude of its northern footprint, and* Λ_{eq}*, which is the longitude of its intersection with the equatorial plane: (a) For the northern hemisphere, showing the range of observed L–emissions at 25, 30, and 35 MHz as multiple headed arrows of decreasing length and the position for maximum occurrence of Riddle's "great arcs" shown as a star; (b) Also for the northern hemisphere, showing the corresponding position ranges for the S–bursts, with those of the two unusual S–burst storms shown as a cross; and (c) For the southern hemisphere, showing the range of footprint positions for the left–hand–polarized diffuse D–region arcs.*

Among all the observations of the Io–dependent L–emissions, there is only one exception to this unexpected result. These are the peculiar "great arcs" in the Io–AA'C region, first pointed at by Riddle (1983), which were excluded from the catalogue study, but which are included in Figure 5a as a star at the position of the IFT when these arcs were observed. In complete agreement with Riddle's deductions about these arcs, it appears from this figure that these emissions are consistent with emission from the instantaneous Io flux tube. In the discussion below, concerning possible explanations for the 70° discrepancy, this observation may play a very significant role, since, like other radio observations that will be discussed later, it would tend to vindicate the O_4 model and imply that the discrepancy may not be attributable to the errors in that model.

The study is somewhat more difficult for the southern hemisphere, since the two available models, the O_4 model and the P11(E2,I3) model of Smith et al. (1976), give different results for the position of the IFT. The emissions from the southern hemisphere are the left–hand polarized isolated arcs which appear in the D region for $\Phi \approx 120°$ and also some isolated arcs appearing in the C region for $\Phi \approx 240°$. The comparable study of the high frequency limit of those emissions is shown in Figure 5c, and it is in reasonable agreement with the O_4 model, but not with the P11 model. Although the highest observed frequency was only about 25 MHz, compared with the ≈ 29 MHz predicted by the model, this is probably not significant, since that would correspond to a relatively small altitude difference for the height above Jupiter at which the highest frequencies are produced. The two occurrences of left–handed emissions, in the C and D regions, are quite symmetrical with respect to the O_4 gyrofrequency contours, and we would conclude from this that these emissions, like the great arcs in the northern hemisphere, are consistent with emission from the IFT.

4. The S–burst emission

The S–burst events used for a similar comparison with the surface gyrofrequencies at Jupiter were recorded at Nançay during 1978, 1979, 1980, 1986, and 1987 (Genova and Calvert, 1988). Including a great many individual S–burst events with the occurrence patterns shown in Figure 6, the results of this comparison are shown as circles (∘) in Figure 4 and by the double–headed arrows in Figure 5b.

In general, the occurrence regions of the S–bursts in CML and Φ, as shown by Figure 6, were included within the same domains as the L–emissions in Figure 3, although their relative occurrence as a function of Φ were not quite the same. In the Io–B domain, the S–bursts tended to occupy only the upper portion of that for the smoother L–emissions, whereas in the Io–AC domain, they tended to occur more toward the middle of the L–emission domain. In both cases, the S–bursts also tended to occur somewhat later in CML than did the corresponding L–emissions. An exception to this generally–similar occurrence pattern were two unusual S–burst noise storms which occurred well outside the conventional regions for the Io–dependent L–emissions, at $100° \leq \mathrm{CML} \leq 140°$ and $\Phi \approx 230°$, as will be discussed below.

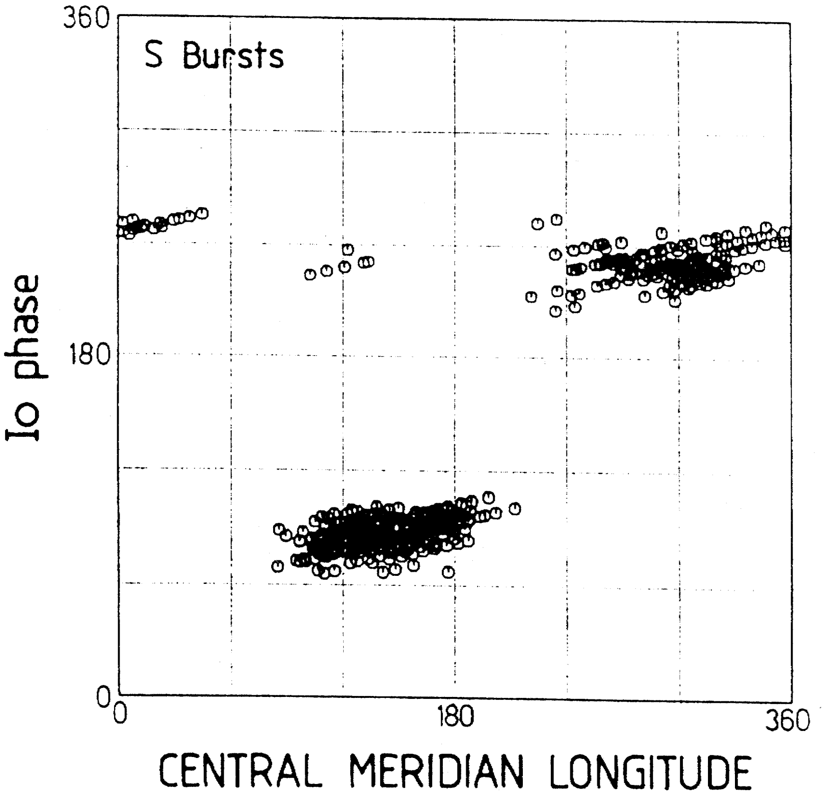

Fig. 6: (from Genova and Calvert, 1988) Central meridian longitude and Io phase of the observed S–burst events.

In order to test the hypothesis of S–burst emissions also occurring at or near the IFT, these data were also organized as a function of Λ_{Io}, as shown in Figure 4, and the corresponding allowed positions for emission from the IFT are shown in Figure 5b. Here the highest observed frequency was 36.5 MHz, again in good agreement with the maximum gyrofrequencies at the surface of Jupiter in the northern hemisphere. Just like for the northern–hemisphere L–emissions, there is clearly a discrepancy of about 40° at the surface of Jupiter and 70° at the orbit of Io between the predicted and observed positions of the highest S–burst frequencies.

As with the "great arcs" of Riddle, the two unusual S–burst storms pointed out above do not require a shift for agreement with the predicted gyrofrequencies. These two storms occurred within the same one–week period, and it could be that they are not typical and correspond to some unknown unusual conditions of emission. However, it must also be noted that they occurred for the same Io phase range, centered $\Phi \approx 230°$, as that where Alexander and Desch (1984) observed CML–independent S–bursts for frequencies below 15 MHz, and these might also be some sort of high–frequency extension of that feature. Nonetheless, these anomalous S–burst events, which have been checked very carefully for validity, would also tend to vindicate the current O_4 magnetic model as the source of the 70° discrepancy, since they, too, would be consistent with an unshifted cyclotron source.

5. Discussion

With only certain minor differences, therefore, the Io–controlled L– and S–emissions generally occupied the same regions of Λ_{Io} for the same maximum emission frequencies. This implies that both emissions are generated at approximately the same locations at Jupiter, and presumably also by the same or similar processes of excitation by Io. This, in fact, was the original motivation for an independent study of the S–bursts, in order to test whether or not there were significant differences which could be attributed to the L– and S–emissions coming from fundamentally different sources, as might have been expected from their strikingly different spectral behavior. Our conclusion is that the peak frequencies of the two emissions are almost identical with respect to the position of Io, and hence that this test yielded no significant differences.

This conclusion has implications for the new theoretical result that the S–bursts at Jupiter, like the similar AKR (auroral kilometric radiation) at the Earth, can be attributed to natural radio lasing (Calvert, 1982; Calvert et al., 1987). Whereas the AKR and the S–bursts both exhibit discrete spectra which are attributable to the inherent monochromaticity of radio lasers, the L–emissions do not, and no comparable smooth emissions have been detected from the Earth. This raises the question of whether the L–emissions are simply unresolved S–bursts, or they might correspond to similar non–lasing sources, which for some reason are undetectable at the Earth.

On the other hand, this result might still be consistent with two different emission mechanisms, such as those of Zaitsev et al. (1986) or Melrose (1986a) to account for the S–bursts and the original one of Melrose (1976) or Wu and Lee (1979) to account for the L–emissions, so long as they are powered similarly by Io, although perhaps by different aspects of the energetic electron velocity distributions.

For both of the Io–controlled Jovian emissions, the major difficulty is in explaining the delay which has been found to occur, for the bulk of those emissions, between the predicted and apparent source field lines.

From Figure 4, it is clear that a shift of about 70° from the predicted IFT would put the observed and predicted highest frequencies into agreement. It also seems from Figure 4 that this shifted source should be more compact at the higher frequencies, perhaps because of beaming towards higher latitudes, for an observer situated near the equator, or else because the source does not reach the surface at the sides of the high–field region. One might also notice that a 70° shift is necessary only for the highest frequencies in Figure 4 (≥ 35 MHz), and that a smaller shift would suffice at the lower frequencies ($\approx 30°$ at 25 MHz). The corresponding temporal delays with respect to the orbital motion of Io around Jupiter would be about 2.5 and 1.1 hours, respectively, since Io moves with respect to Jupiter at an angular velocity of about 27.8 degrees per hour.

It is quite clear that the points reported in Figure 4 were measured to sufficient accuracy for this study, with the only significant uncertainty being the possibility of missing events due to limited receiver sensitivity or to the limited number of events studied. The addition of missing events, however, could only have increased the observed delay, by raising the envelope in Figure 4, and they could not have caused any sort of fictitious delay. Moreover, the relatively sharp trailing edges for the emissive region in Figure 4, which is the same for both types of Io–controlled emissions, would also imply that missing events are probably not a problem.

The principal uncertainty of the measurement is that of the magnetic field model as was stressed by Connerney (1981), the magnetic models deduced from the Pioneer flyby magnetic measurements are not unique, and certain combinations of the magnetic moments could have gone undetected. The models, in fact, could be off by a substantial amount, particularly for the higher–order moments which determine the exact distribution of the highest gyrofrequencies, and upon which our study mostly depends. In this regard, if no other explanation can be found for the observed discrepancy, then the current measurements might be used to improve the magnetic models, or at least to set some limits for their validity. According to Figure 4, then, the peak magnetic field strengths in the northern hemisphere at Jupiter would have to be shifted westward (from CML $\approx 135°$ for the O_4 model) by a few tens of degrees. The exact amount of this shift cannot be determined directly from the measurements, since the position of the IFT footprint depend upon the model itself, because of the field line distortion introduced by its higher–order terms.

On the other hand, certain other observations of the decametric radiation are in agreement with the magnetic model as it is, and they would have to be taken into account if the discrepancy is to be attributed to errors in the model. As discussed above, the isolated arcs of Riddle (1983) are already in agreement with emission from the predicted IFT. If the magnetic model were to be modified to account for the apparent delays in Figure 4, then this result could probably be kept in agreement with the new model. In addition, the anomalous S–bursts also discussed above are consistent with the magnetic model as it stands, and they would certainly cause some difficulty for a modified magnetic model in which the peak gyrofrequencies were simply shifted westward.

We have also tested the validity of the current magnetic model with another approach. In this case, only the position of the observer with respect to the surface magnetic field was considered, and we examined what happens as the high–field region progressively disappears behind the limb of the planet as Jupiter rotates. During this progressive shadowing of high–frequency source by Jupiter, the higher frequencies should disappear first, at a rate which is predictable from the O_4 magnetic model, and when this is compared to the actual disappearance of such signals, essentially perfect agreement is obtained (Genova and Aubier, 1987). Figure 7 illustrates this phenomenon and shows the nature of the observed agreement. For some of the Io–dependent emissions, however, there were signals above the expected frequency limit for shadowing. However, their dynamic spectra were very peculiar and they thus might have come from emissions behind the limb of the planet, somehow made visible by complex propagation paths, whereas the dynamic spectra below this limit had the very normal appearance of nested arcs. This observation, which is quite independent of the frequency–limits studied above, also favors the current magnetic field models.

Another possible explanation for the observed discrepancy would be an actual temporal delay as Io's influence propagates down to the surface of Jupiter along the Io flux tube. In order to account for both the delayed emissions and what appears to be prompt emissions which are currently consistent with unshifted magnetic models, this would require both a direct influence which is propagated from Io with little delay, and another which is delayed by up to two and one–half hours.

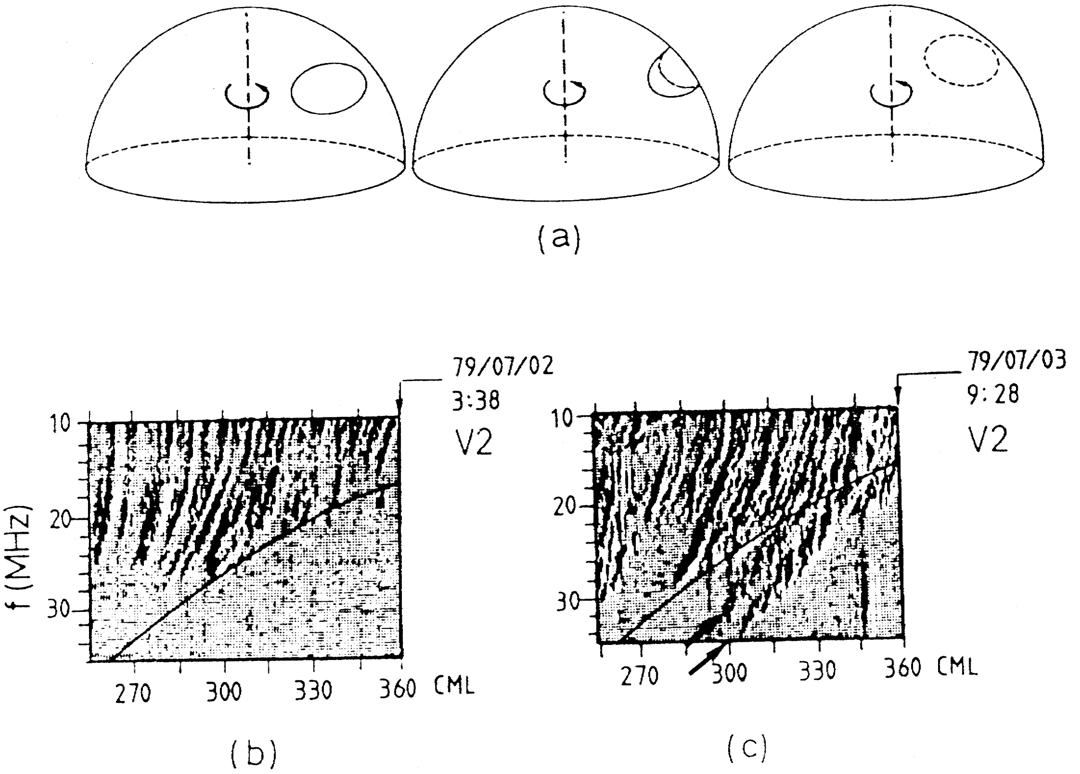

Fig. 7: (adapted from Genova and Aubier, 1987) Schematic view of the progressive disappearance the high–field region behind the limb of the planet when the planet rotates (a). The high frequency limits of normal non–Io emissions (b) and of Io–C emissions are in agreement with the predicted maximum surface gyrofrequencies, excepting in the second case the two broken arcs indicated by arrows. Having an unusual dynamic spectrum and a narrow bandwidth, the latter has been attributed to emission from behind the limb of Jupiter which is somehow made visible by complex propagation paths.

Just such a delay would be expected if the influence from Io was carried by the Alfvén waves which should be generated by Io's super–Alfvén motion through Jupiter's magnetic field (Goertz and Deift, 1973; Neubauer, 1980; Wolf–Gladrow et al., 1987), where the bulk of the delay occurs within the relatively–dense Io plasma torus. Hashimoto and Goldstein (1983) imagined a double trip through the torus when the highest frequencies are observed, the stronger Alfvén waves must be launched towards the south, and that these would be responsible for the Io emissions only after reflection in the southern hemisphere and a second crossing of the torus. They calculated an equivalent delay of about 20° for such double transits of the torus, using the torus density model originally deduced by Bagenal et al. (1985) this might be increased to as much as twenty percent, this would still leave a three–fold discrepancy between the expected and observed delays. Since the Alfvén speed varies as the square root of the density, it would thus require an approximately ten–fold increase of the torus density or else a three–fold increase of its thickness (at least within the region immediately behind Io through which the Alfvén waves must travel), in order to account for the observed discrepancy as an Alfvén–wave propagation delay. Even though this would provide a most convenient explanation for the observed delays, it does not seem likely that the torus models, even locally, could be off by that much.

Another possibility would be for Io to have its own magnetic tail, comparable to those of the Earth or Venus, with magnetic reconnection occurring at some point downstream, as was suggested to us by C. K. Goertz (private communication, 1987). This would be consistent with magnetotail aspects ratios comparable to those of the Earth or Venus, extending for a few hundred Io radii, or up to one–fifth of its orbit, behind Io with respect to Jupiter and hence before it when viewed from the Earth. Although this could account for the launching of an Alfvén–wave disturbance quite far from Io, it isn't very likely that such an Io magnetotail would produce the very consistent delays which are observed at the abrupt trailing edge of the pattern in Figure 2, since the length of such a magnetotail would be expected to vary considerably.

It must be emphasized that the apparent 70° delay constitutes as fundamental discrepancy, given our current understanding of the Jovian system its Io–controlled gyroemission. It isn't likely to be attributable to observational error, nor can it readily be explained by errors in the magnetic field model, by Alfvén–wave propagation delay, or by a previously–undetected Io magnetotail, without raising certain other questions. It implies quite directly, if the magnetic models are correct, that the principal decametric source must be displaced eastward of Io's meridian at Jupiter by about one–fifth of an orbit, regardless of how the emissions might be beamed or otherwise modulated.

Although a single suitable explanation for the discrepancy remains lacking, there is always a possibility that it could be attributed to a mixture of effects: minor errors of the magnetic model's high–order moments giving a partial shift to the west or a second maximum, a somewhat more dense and broader torus immediately behind Io which went unmeasured during the Voyager 2 Jovian encounter, and perhaps also some lag in the launching of Alfvén waves by Io.

4. Conclusions

Both components of the Io–controlled Jovian radio emissions above about 15 MHz, the so–called L–emissions and S–bursts, appear to originate from approximately the same locations near the surface of Jupiter, and probably also under similar conditions of excitation by Io, since they exhibit virtually the same behavior of their maximum emission frequencies versus the phase of Io with respect to the planet. This could be understood (among other possibilities) either if the smooth L–emissions consisted of unresolved S–bursts, or else if the two emissions came from similar lasing and non–lasing sources (Calvert, 1982), but powered by the same cyclotron wave instability (Melrose, 1976; Wu and Lee, 1979).

If the current Jovian magnetic field models are correct, then this common source for the bulk of the S–bursts and L–emissions in the northern hemisphere must be delayed by up to 70° with respect to the instantaneous Jovigraphic longitude of Io (or else by about 40° of Jovian longitude, when magnetically–projected down to the surface). Corresponding to temporal delays of up to two and one–half hours, it is hard to account for such long delays by Alfvén–wave propagation, given the currently–measured densities of the Io plasma torus, nor is it easy to imagine that some hitherto undetected Io magnetotail, extending up to one–fifth of an orbit behind Io with respect to Jupiter, could have produced the very consistent delays which are observed.

Although the Jovian magnetic field models might conceivably be off by enough to account for the observed discrepancy, requiring a shift of the high field region near the surface of Jupiter westward by several tens of degrees, this would produce disagreement with other aspects of the radio emissions which are already accounted for by the current magnetic models (specifically with the O_4 model of Acuña and Ness (1976a). These include the isolated "great arc" of Riddle (1983) and certain anomalous S–bursts, both of which are consistent with emission from the unshifted instantaneous Io flux tube. Such a shift of the high–field region at Jupiter would also be inconsistent with other measurements of the shadowing of that region by the limb of the planet as Jupiter rotates, as well as possibly also with the peak–frequency observations of the L–emissions from the southern hemisphere, which are in accordance with an unaltered O_4 model.

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