SOURCE LOCATION OF PLANETARY RADIO–EMISSIONS

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Abstract

The radio emissions of the Earth (auroral or terrestrial kilometric radiation – AKR or TKR), Jupiter (decameter and hectometer emissions) and Saturn (Saturnian kilometric radiation – SKR) exhibit very similar characteristics. One important parameter to study from the observations is the localization of their sources, which is expected to be in regions of electron precipitation. Due to the low angular resolution of telescopes at these wavelengths, no straightforward method of localization is possible. Different approaches to the problem are necessary, in the case of TKR, for which an almost complete geographical coverage of the planet and in situ observations are available, of SKR, which has been observed during the two Voyager fly–by only, and of the Jovian radiation, which is very complex due to the presence of the Io and non–Io emissions. The different observational studies of the source localization will be reviewed for the three planets. It will be shown that no definitive localization of the Jovian emission, especially of its non–Io component, has been possible until now. The contributions of the future ISPM and Galileo missions will be investigated.

1 Introduction

Three of several types of planetary radio–emissions present very similar characteristics: the auroral (or terrestrial) kilomoetric radiation (AKR or TKR), the decameter and hectometer Jovian radiation (DAM and HOM), and the Saturnian kilometric radiation (SKR). These emissions are intense, non–thermal, with a maximum frequency close to the maximum gyrofrequency at the surface of the planet, which suggest an emission close to the local gyrofrequency. They are observed on a wide frequency range (although the instantaneous bandwidth can be very narrow). They present a great temporal and spectral variability on several time scales. The most important observational constraints on the emission mechanism arise from the localization and morphology of the source, frorn the polarization of the emission and from its correlation with possible sources of energy.

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This paper reviews the main results of the observational studies of the localization of the sources of the three emissions.

Due to the large width of the antenna beams at these wavelengths, no direct localization is possible. The methods which have been used to derive the position of the sources will be described in the following. It must be kept in mind that, in general, it was not possible to study the three types or emissions in the same way, because the observations available in each case were very different (Table 1 and Fig. 1). The AKR has been observed by a large number of satellites, allowing a complete observational coverage in local time and magnetic latitude, with direction finding capabilities, and in situ observations. The DAM and HOM were studied mainly from a large set of ground based observations and from the two Voyager spacecraft, supplying two angles of view in local time, close to the equator, with a small excursion in magnetic latitude due to the tilt of the magnetic field with respect to the rotation axis. lhe SKR was observed by the two Voyager spacecraft only, giving access to three angles of view with almost no latitudinal coverage, since the magnetic field axis is nearly aligned with the rotation axis.

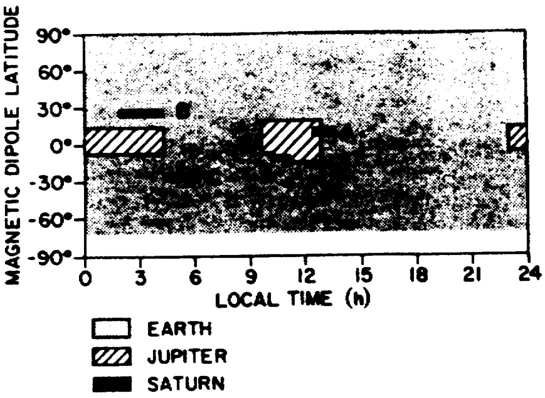

Figure 1: (from Kaiser et al. 1981) Positions in the local time – magnetic latitude plane from which radio observations have been made of the Earth, Jupiter and Saturn (12h = local noon: A = inbound Saturn trajectories of Voyager 1 and 2: B = outbound Voyager 1: C = outbound Voyager 2). The lines corresponding to the trajectories of the spacecraft very close to the planets represent very brief durations of observations and cannot be used to derive statistical properties. Recently, observations by Dynamics Explorer 1 (DE1) have extended the knowledge of the South polar region of the Earth.

2 Localization of the sources of AKR

The large amount of data available allowed a great number of studies using many different techniques:

- the emission pattern in latitude and local time was interpreted directly and from ray tracing calculations (Gurnett, 1974; Kaiser and Stone, 1975 ; Green et al., 1977);

TKR	IMP 6–8 RAE 2 Hawkeye ISEE 1–2 Voyager 1–2 ISIS 1 DE 1
DAM (HOM)	ground based observations Voyager 1–2 (RAE 1, IMP 6)
SKR	Voyager 1–2

Table 1: The satellites which observed the different emissions

- the received intensity was modelled as a function of the distance to the source (Gallagher and Gurnett, 1979);
- spinning satellites allowed to measure the direction of arrival of the radiation (Gurnett, 1974; Kurth et al., 1975; James, 1980);
- Alexander and Kaiser (1976, 1977) attempted to use occultations by the Moon of the source of emission seen from a Moon orbiting spacecraft, but the interpretation of their results were difficult due to scattering of the radiation at high altitudes (Alexander et al., 1979);
- in situ observations gave critical informations about the morphology of the source region, which was found in a plasma depleted cavity (Benson and Calvert, 1979; Benson et al., 1980; Calvert, 1981a, b), where the plasma frequency is much smaller than the gyrofrequency.

The results of these studies are all consistent with sources at high North and South latitudes, low altitudes, confined mostly on the night side (Fig. 2), with perhaps a faint source on the day side (Alexander and Kaiser, 1977). The sources are thus located in the auroral zones of the planet, in regions of precipitation of energetic electrons from the magnetospheric tail (and perhaps also from the day side cusp regions), in accordance with the correlations found between the intensity and spectrum of the emission, and various indices of magnetic activity (Gurnett, 1974; Kaiser and Alexander, 1977a,b; Voots et al., 1977; Green et al., 1971, 1982; Benson et al., 1980). Additional polarization studies have shown that the radiation is emitted in the extraordinary mode (Kaiser et al., 1978; Shawan and Gurnett, 1982).

3 Localization of the source of SKR

The only available observations of SKR were performed by the two Voyager spacecraft during their encounters with the planet, but their trajectories happened to be well suited to the study of the localization of the sources of the emission.

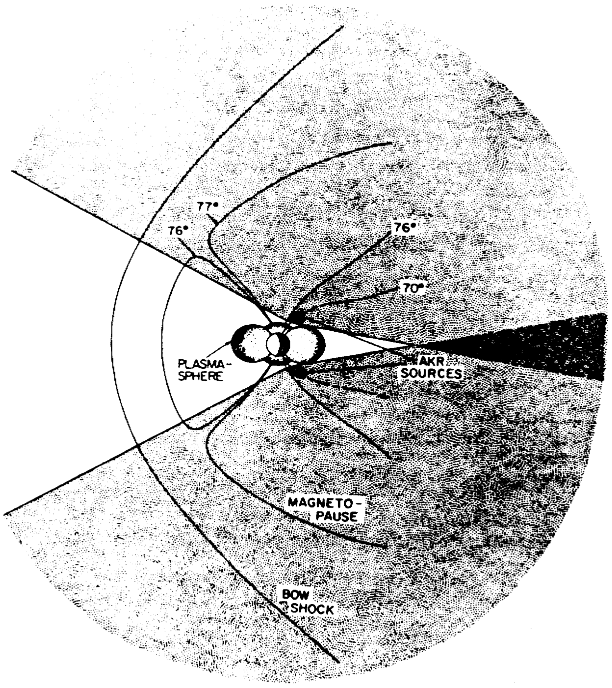

Figure 2: (from Gallagher and Gurnett, 1979) Time–averaged extent of the AKR emission from the night side sources. A shadow zone is observed close to the Earth, in the night side equatorial plane, due to reflexion in the plasmasphere (Gurnett, 1974).

Soon after the encounter of Voyager 1 with the planet it was possible to give a qualitative account of the source position. Comparing pre– and post–encounter observations, it was found that the source was locked in local time, on the day side of the planet, and that emission occurred when a certain meridian crosses a given local time. Moreover, two opposite circular polarizations were observed from North and South latitudes, in accordance with sources emitting in the extraordinary mode, located at high latitudes in the two hemispheres (Warwick et al., 1981, 1982; Fig. 3).

The sources were later positioned more quantitatively, by modelling the difference between the mean intensity of the emissions observed before and after the encounters (Kaiser et al., 1981; Kaiser and Desch, 1982), and by studying the occultations of the two sources viewed from the spacecraft trajectories (Lecacheux and Genova, 1983). The two methods showed similarily that the source must be in small areas close to the North and South poles, near the noon meridian (Fig. 4). These areas correspond to the region where UV aurorae, polar cap boundaries and cusp are observed, which accounts for the strong correlation found between the emission intensity and solar wind parameters (Desch, 1982; Desch and Rucker, 1983). However, the occurrence of emission in a special longitude region is not yet understood, since the magnetic field measured by the Voyager magnetometer is dipolar and aligned with the rotation axis (Acuna et al., 1983).

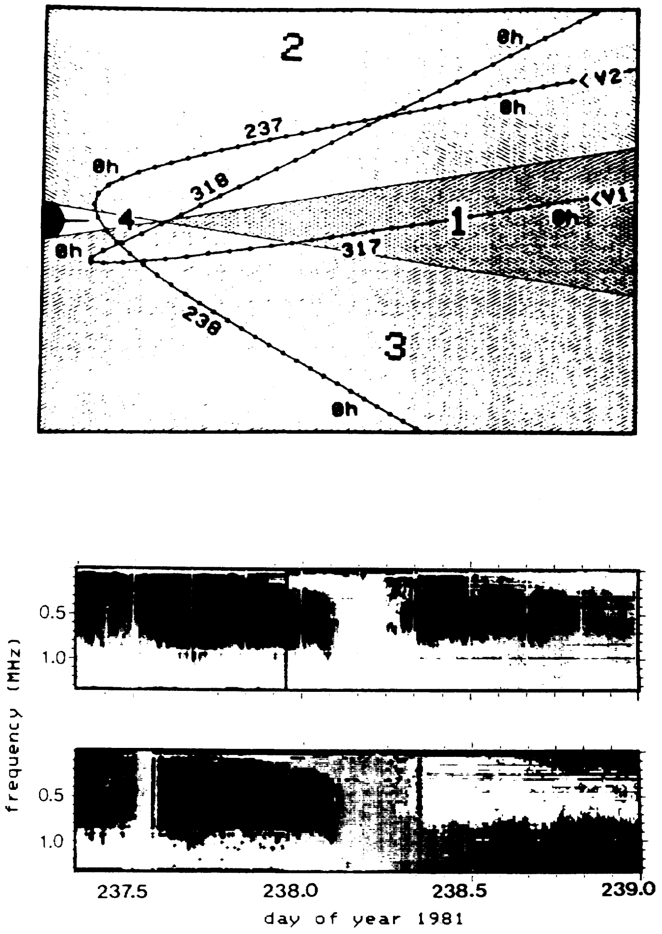

Figure 3: (from Lecacheux and Genova 1983) 3a: The sources of SKR seen from the Voyager trajectories. Hatched regions indicate the regions illuminated by two high latitude sources, in a meridian plane. The two emissions will appear with different polarizations. In region 1, mixed polarization appears; in 2 and 3, only one source is observed; in 4, no emission is seen. The Voyager trajectories are also shown. They cross the four regions. 3b: Voyager 2 observations close to the encounter with the planet. The upper plot displays the intensity of the emission in gray levels as a function of time and frequency ("dynamic spectrum") . No emission is observed, as expected, when the spacecraft is in region 4 of Figure 3a. The lower plot displays in false colours the sense of circular polarization of the emission in the radioastronomical convention, i.e. referring to the direction of propagation of the wave (right hand = black; left hand = white). In regions 2 and 3, right hand left hand polarizations are observed, respectively, in accordance with emission on the x mode.

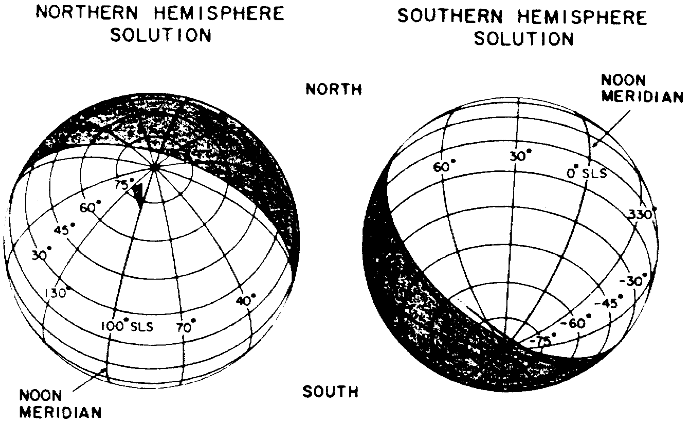

Figure 4: (from Kaiser and Desch, 1982) Source footprints of SKR. The North and South sources are constrained in the small black regions at high latitudes.

4 Localization of the source(s) of DAM and HOM

Several factors make the case of Jupiter much more complex. First, Io plays a prominent role, for some of the emissions only, as discussed in the following. Moreoverr, the sources are probably not locked in local time, but rotate with the magnetic field, contrarily to the sources of AKR and SKR. Due to this complex geometry, to the incomplete surface coverage, and to the absence of direction finding capabilities on the Voyager spacecraft, the methods applied for the localization of AKR and SKR do not fit to this case. Although numerous attempts to model the source were made, only two observational studies of the source position were performed, with, as will be seen in the following, no definitive answer. One clue to the localization problem is certainly the difference between emissions related or not to Io, which is not yet well understood. Thus the observational characteristics of the two types of emissions will be first reviewed. The results of the observational studies of the localization will be described afterwards.

4.1 Io Control of the Jovian Emissions

From the early ground–based studies of the DAM, it has long been known that more emissions are observed when the observer is in certain positions with respect to the rotating magnetic field of the planet and to the satellite Io (Bigg, 1964). This determines the two parameters usually chosen to organize the data (Fig. 5a), the subobserver longitude L and the departure of Io from the direction opposite to the observer (Io-phase Φ). When observed from a fixed point, L and Φ vary slowly with time. If emissions observed at frequencies higher than about 15 MHz are plotted versus L and Φ, regions of higher occurrence appear, which are usually called sources (Fig. 5b).

These areas of high occurrence in the L–Φ plane do not necessarily correspond to different source regions in the Jovian magnetosphere. To distinguish between the two concepts, care will be taken in the following to distinguish the "sources" (areas in the L–Φ plane) from actual sources (in the magnetosphere). Some of these "sources" are seen in a given longitude range, whatever the Io–phase (non–Io–controlled "sources"), and the others appear only for certain values of Φ (Io–controlled "sources"), at nearly the same longitudes than the previous ones. At lower frequencies, the position of the "sources" in the L–Φ plot changes. In the following, the differences between the Io– and non–Io emissions will be discussed successively.

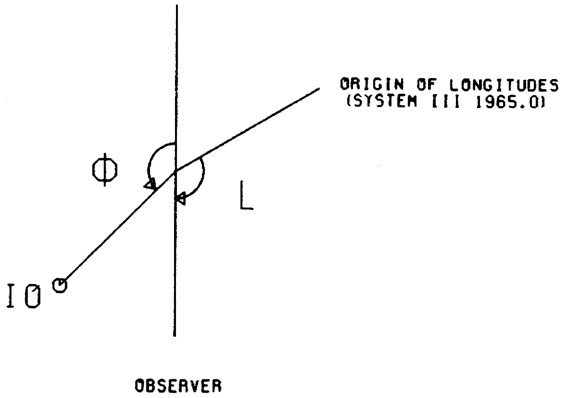

Figure 5a: Definition of the coordinate systems

a) Intensity

As can be seen from Figure 5b, the Io–emissions are observed more often than the non–Io ones (the Io–"sources" appear darker in the L–Φ plot than the non–Io ones). This has long been interpreted as an Io influence which increases the number of emissions–seen from the directions of observation located in the Io "sources". But the observed higher occurrence can also be due to a higher intensity of the Io emissions, which could then appear more often above the intensity threshold of the instrunents. A more precise study of this problem can be made by using the more sensitive spectral observations available at this moment, which were recorded by the Voyager spacecraft close to their encounters with the planet. On these observations, it appears that, when the direction of observation is inside a Io– or non–Io "source", emissions at frequency higher than about 20 MHz are nearly always observed. This implies that the higher occurrence of the Io–emissions is probably due to a higher intensity. Outside the previously recognized "sources" only emissions at lower frequencies are observed.

b) Spectrum

Ground–based observations are limited by the ionospheric cut–off, close to about 10 MHz, but early measurements indicated that the appearance of the "sources" in the L–Φ diagram at these frequencies is different from that at higher frequencies (see Carr and Desch, 1976). This had been confirmed by observations made by Earth orbiting satellites (Desch and Carr, 1978) and by Voyager. From Voyager data, Alexander et al. (1981) studied the effect of Io on the whole frequency range of DAM and HOM emission. They showed that the control by Io decreases from high to low frequencies, but can be seen down to 2 MHz.

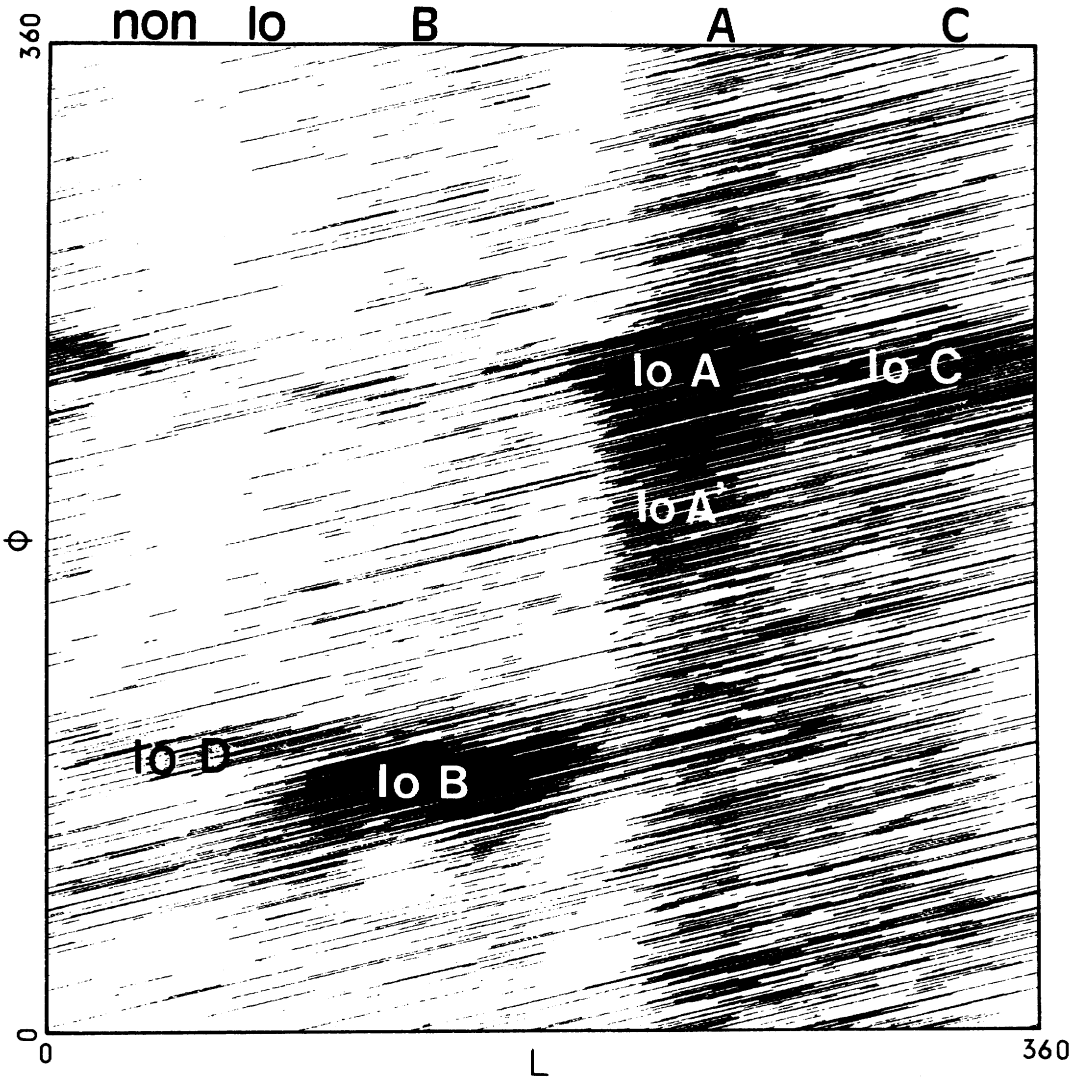

Figure 5b: Longitude and Io phase of the emissions observed from Boulder in 1960–1975 and from Nancay in 1978–1981. Due to the variation of L and Φ with time, each emission is represented by a segment in the plot. Only the emissions which reached frequencies higher than 15 MHz have been plotted. The letters indicate the conventional names of the "sources".

c) Spectral Patterns

The Jovian emission displays several types of spectral patterns with different time and frequency scales. These spectral features depend in general strongly on the Io position: some kinds of spectral features appear only in Io–controlled directions; the properties of some others differ when observed in Io– or non–Io "sources" (see e.g. Riihimaa, 1976, 1978; Leblanc et al., 1980; Genova et al., 1981).

The most prominent feature observed in the "dynamic spectra" of the emission (which displays the intensity as a function of time and frequency) is the arc pattern, which covers nearly the whole emission (Fig. 6). Leblanc (1981) showed that the shape of the arcs is different when observed in Io and non–Io regions. This property can be used to derive very precise limits for the "sources" in the L–Φ diagram, which coincide well with the

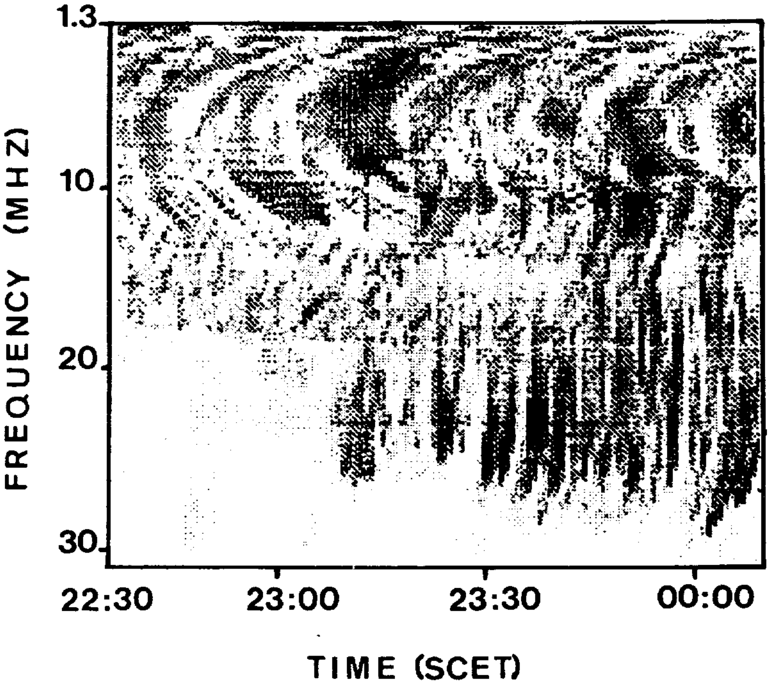

Figure 6: Dynamic spectrum of Jovian radiation observed by Voyager. At least two arc patterns appear in the frequency ranges 1–13 MHz (lesser arcs) and 15–29 MHz (greater arcs).

ones defined from the higher occurrence of the emissions (Fig. 7: Aubier and Genova, 1985, in preperation).

d) Maximum Frequency of the Emission

The maximum frequency of the DAM emission is nearly 40 MHz, which corresponds approximately to the maximum gyrofrequency close to the planetary surface. This maximum frequency is observed for Io–emissions, and it has long been thought that the non–Io emissions were confined at much lower frequencies, less than about 28 MHz (Carr and Desch, 1976). This led to theories for the generation of the non–Io emissions by electrons trapped along the magnetic field lines. Then the maximum gyrofrequency would be the minimum between the gyrofrequencies at the North and South feet of the field line, fitting well a maximum gyrofrequency of about 28 MHz (Smith and Wu, 1974; Goldstein and Eviatar, 1979). But recent studies by Barrow and Desch (1980) and Barrow and Alexander (1980) showed that the cut–off frequencies for the Io– and non Io– controlled emissions are probably not different (Fig. 8).

e) Correlation with the Solar Wind

Several studies, from ground–based and spacecraft observations, have shown consistently that the non–Io emissions at DAM and HOM wavelengths are correlated somehow to the solar wind, whereas no correlation was found for the Io ones (Barrow, 1978; Terasawa et al., 1978; Oya and Morioka, 1978; Zarka and Genova, 1983; see the review by Barrow, this issue). This crucial point implies that there is some difference between the source regions of the Io– and non–Io emissions (Zarka and Genova, 1983). It is unclear, whether this difference pertains to differences in the energetic electron populations involved in the

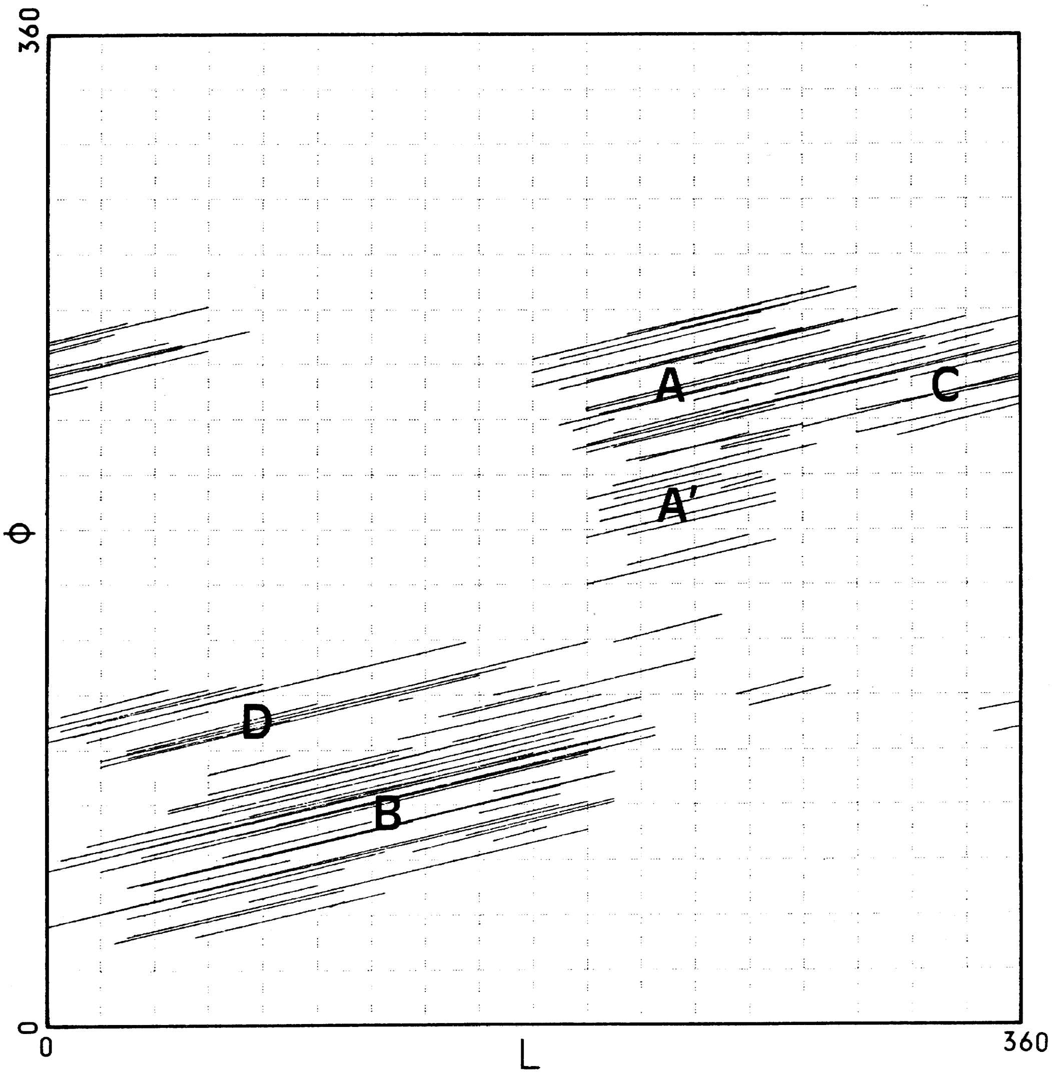

Figure 7: Io "sources" observed by Voyager, defined from the spectral properties of their arc patterns.

generation of the emission, or in the source positions themselves. But it must be kept in mind that the inner magnetosphere of Jupiter is dominated by the magnetic field rotation, unlike the Earth's magnetosphere where the effect of the solar wind is dominant (Hill et al., 1983). A direct action of the solar wind is expected only at high latitudes: it has been observed in the magnetospheric tail of the planet (Lepping et al., 1983), and exists probably also in the magnetically connected polar caps, which have not yet been explored by spacecraft.

f) Local Time Effects

The Voyager observations have shown that there are no local time effects on the Io emissions, whereas the local time of observation affects the intensity of the non–Io emissions (Alexander et al., 1981; Leblanc, 1981). But, unlike SER or AKR, the sources are probably rotating with the magnetic field of the planet. The cause of the local time influence has not been yet understood.

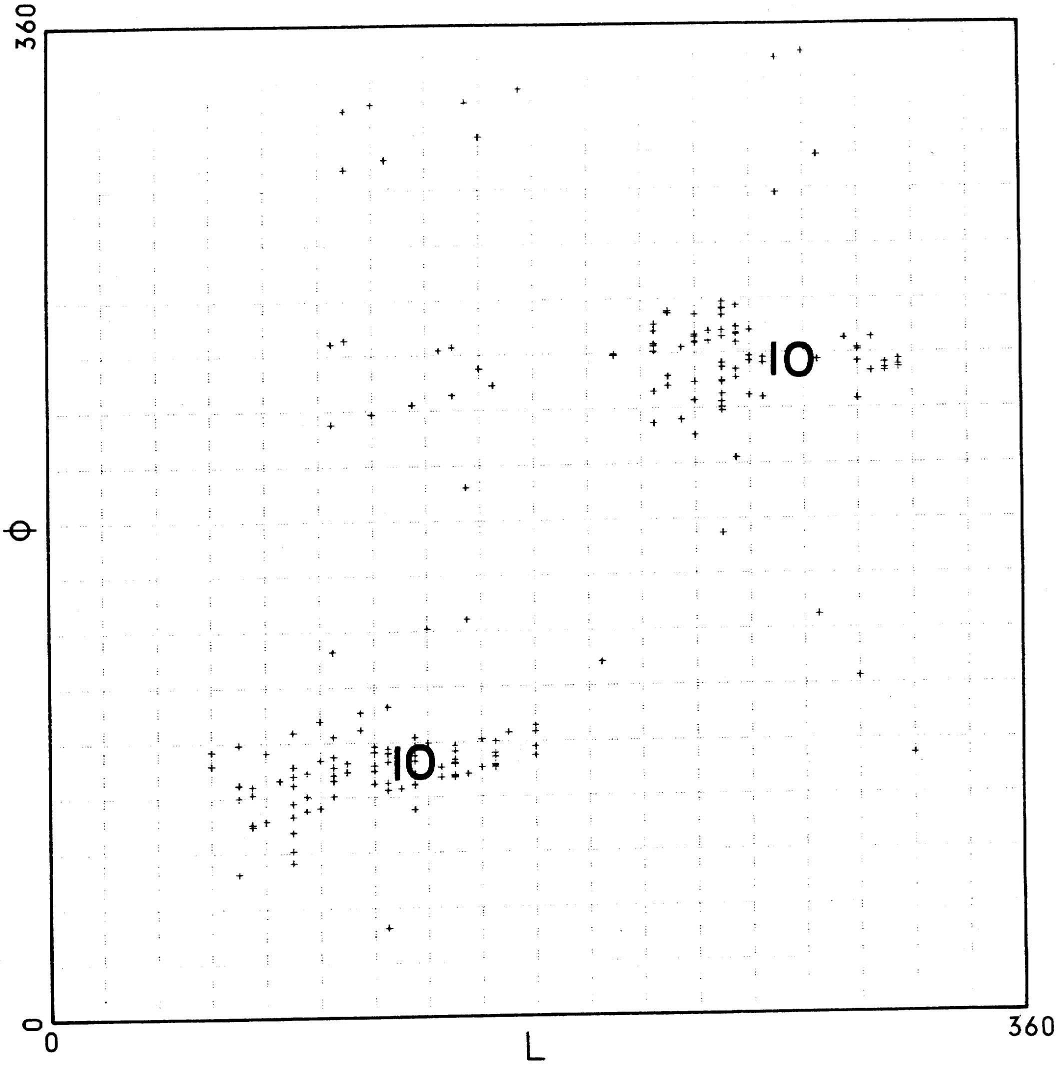

Figure 8: Emissions observed by Voyagerr with a high frequency limit greater than 30 MHz. These emissions appear in the Io–controlled regions, but also in the non–Io ones.

4.2 Observational Studies of the Source Localization

The main constraint on the localization of the source is given by the observed frequency of the emission: the high frequency emissions must occur in the area where the local gyrofrequency reaches large enough values, if it is supposed as usual that the radiation is emitted close to the local gyrofrequency. Only a small region, close to the surface in the Northern hemisphere, fulfill this condition (Fig. 9). The fact that the required frequencies cannot be emitted from the southern hemisphere is consistent with the polarization observations at these frequencies: only one sense of circular polarization – with the radio–astronomical convention – is observed (except in particular cases which will be discussed later), which corresponds to an emission in the extraordinary mode if coming from the Northern hemisphere. Frequencies lower than about 25 MHz could be emitted from both hemispheres, and emissions with the two senses of circular polarization are actually observed at low frequency. On the other hand, energetic electrons are also present in this region: the auroral zones of the planet occur over an extensive area of Jupiter's polar region, which includes most of the high gyrofrequency region (Strobel and Atreya, 1983).

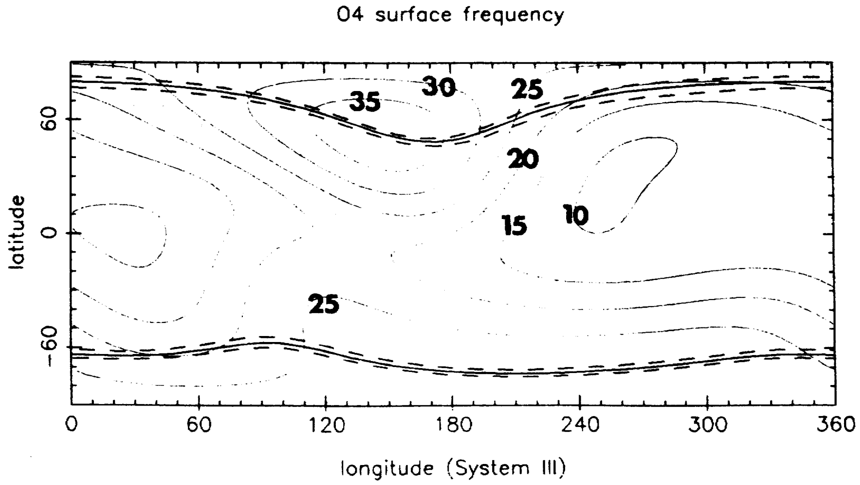

Figure 9: Isocontour maps of the gyrofrequency at the surface of Jupiter, from the 04 model (Acuna and Ness, 1976). The footprint of the L = 6 shells (Io field lines) is plotted as a heavy full line, the footprints of the L = 5 and L = 7 shells (Io torus field lines) as heavy dotted lines.

In the case of the Io–controlled emissions, it is generally supposed that the emission occurs along or near the Io flux tube (IFT), on the L = 6 shell (full line on Figure 9). This would explain the role of Io, and is consistent with the fact that the high frequency emissions are observed when the foot of the IFT is close to the regions of high magnetic field. It has been suggested (see Goldstein and Goertz, 1983, and references therein) that Alfvén waves due to the movement of Io in the surrounding magnetized plasma might play a role in the generation of the emission, for instance as a source of accelerated electrons; many models use the a priori assumption that the source is along the IFT, or, as an Alfvén wave pattern is supposed to be trailed behind Io after multiple reflexions on the ionosphere, on a nearby field line supporting a mirror image of the original Alfvén wave current system.

The case of the non–Io emissions is more unclear. It is likely that the sources at high frequencies occur in the same region, since the highest frequency limits of the two types of emission are not very different. One possible location is along field lines which intersect the Io torus (L = 5 to 7 – dotted line on Fiqure 9), where energetic electrons might be present. But this does not account for the observed solar wind effect on the emissions, since, as discussed earlier, the inner Jovian magnetosphere is supposed to be dominated by rotational dynamics. It can be remarked that field lines at high L shells, linked to the tail or the cusp, also intersect the surfaces of the planet in the same high magnetic field region, which extends to high latitudes . If only one of these regions was involved, this would imply a source locked in local time, which is probably not the case. Until now, no interpretation of the local time effect observed for the non–Io emissions has been attempted in this context.

The particularly complex characteristics of the Jovian radio emission also impede the observational studies of the source location, and only two have been published so far. One, which uses the properties of the interplanetary scintillations in an unusual way, allowed a qualitative ground–based study of the source (Genova and Boischot, 1981). The other investigated the Faraday rotation in the Io torus, which gave informations about the location of the source and the density in the source region (Calvert, 1983).

a)Interplanetary Scintillations

The interplanetary scintillations (IPS) are due to the inhomogeneities of the electronic density of the interplanetary medium. The spatial variations when convected by the solar– wind, produce temporal fluctuations of the intensity of radio–emission with a time scale ~ 1 sec. These fluctuations, observed on the Jovian DAM emissions recorded at a fixed frequency, are called L–bursts (Vouglas and Smith, 1967). Genova and Leblanc (1980) have shown on DAM dynamic spectra that the intensity fluctuations have a large bandwidth at decameter wavelengths. On the other hand, if the DAM emission occurs close to the local gyrofrequency, the spatial structure of the source corresponds to the frequency structure of the emission. Figure 10 explains how these two properties can be used in an ideal case to study the spatial morphology of the source. Modelling the IPS at 34 MHz, Mitchell and Roelof (1976) showed that at these frequencies a thick scintillating screen is involved, which can extend up to 1 AU along the ray path. Moreover, the value of the solar wind velocity of the "screen" cannot be known easily. This will prevent to perform a quantitative study of the source, but the method permitted the first qualitative investigation of the source position (Genova and Boischot, 1981). From the sketches presented on Figures 10 and 11, one predicts that, if the angular distance between sources at different frequencies is frequency dependent, then the frequency drift of the bursts is frequency dependent. Moreover, sources located on the East and West sides of Jupiter must show bursts with opposite drifts (for a given direction of the solar wind). The fact that drifts are effectively observed, implies that the source is distributed in space. The frequency drift increases with frequency, as expected if the source is distributed along a magnetic field line. It was also demonstrated that during Io–B emissions, for which the foot of the IFT is in the East quadrant of Jupiter, the sign of the frequency drift corresponds to Figure 11a; on the other hand, during Io–A emissions, the foot of the IFT is on the other side of the planet, and the sign of the observed frequency drift reverses (Fig. 11b). The same kind of study for the non–Io emissions shows that during non–Io B emissions, when the large magnetic field area is on the East side of Jupiter, the drift corresponds to Figure 11a, while during non–Io A emissions the large magnetic field area is on the other side of the planet, and the drift sense reverses (Boischot, 1984, private communication). Therefore this localization method allows a first observational test of the above discussion: the observed sense of drift is consistent with Io–emissions close to the Io field lines, and with high frequency non–Io sources in the area where large gyrofrequencies are reached.

b) Faraday Rotation in the Io Torus

Close to the encounters of the Voyager spacecraft with Jupiter, unusual events were observed when the two spacecraft were close to the equator: the dynamic spectra of the emissions displayed polarization fringes, in regions of the L–Φ diagram and at frequencies where right hand circularly polarized emissions are usually observed. This was interpreted as Faraday rotation which occurred when the ray path of the emission encountered regions of transverse propagation in the Io torus, where the plasma density is large enough

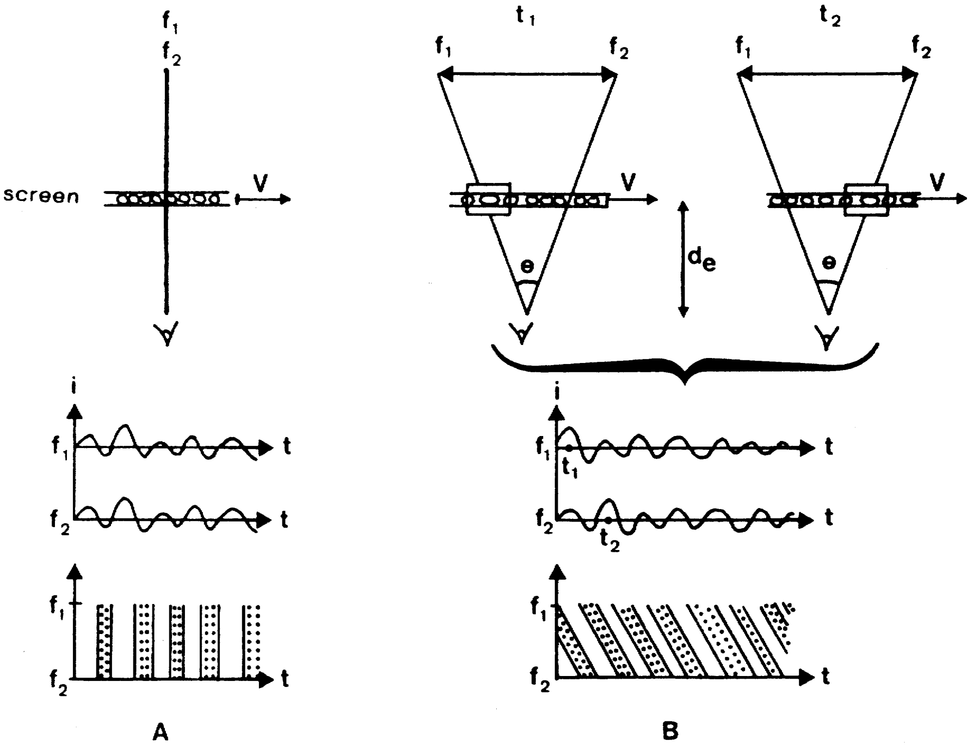

Figure 10: (from Genova and Boischot, 1981) Principle of the method of localization. 10a: A single source emits at two frequencies f_1 and f_2 close enough for IPS to be well correlated. Then IPS modulation is simultaneous at the two frequencies. In the case of continuous emission by the source between f_1 and f_2, vertical features will appear in the dynamic spectrum of the emission. 10b: Two spatially distinct sources emit radiation at f_1 and f_2. At instant t_1, a given part of the scintillating screen (box) produces IPS on radiation at f_1. Convected by the solar wind, the same part of the screen will be seen later, at instant f_2, in front of the source at f_2. Then the IPS modulations at the two frequencies present a delay equal to the time taken by the screen to move between the directions of the two sources. In the case of continuous emission between f_1 and f_2, drifting features appear in the spectra.

(Calvert, 1983). For two events it was possible to track the ray path back to Jupiter. It was found that the waves come from the Northern hemisphere, and were emitted on the extraordinary mode, which is consistent with the previous discussion, and from lower altitudes with increasing frequencies, in accordance with emission occurring along a field line. If the source was assumed to be on an L – 6 field line,it was in the same region than the Io flux tube (but the studied source is a non–Io one). The limit polarization was found to be non–circular, which implies a low source plasma density, estimated to be less than 0.8 cm^{-3} (plasma frequency ~8 kHz).

c) The Future

It is clear at this point that no definitive observational determination of the position of the sources of the Jovian DAM and HOM has been possible. They are hints that the sources are spread along field lines, and that the Io sources are near the Io flux tube, but for the moment the exact location of the non–Io emissions is not known.

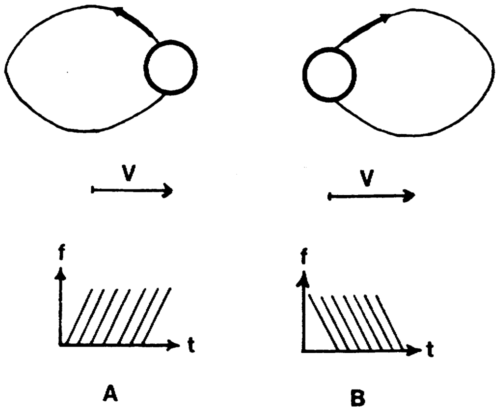

Figure 11: (from Genova and Boischot, 1981) IPS observed in two configurations of the source, with the same solar wind direction. The source is supposed to lie along a field line –11 a: on the East side of Jupiter; 11 b: on the West side of Jupiter. The arrows indicate the direction of decreasing frequencies along the field lines.

We need now to overcome the current observational limitations, which demands adequate spacecraft observations. To a certain extent, the two next space missions to encounter Jupiter will meet this purpose, and give access to new regions of the planet: the International Solar Polar Mission (ISPM), on its way to the high ecliptic latitudes, will fly by Jupiter at high North and South latitudes in 1987; Galileo will orbit around Jupiter from 1988 to 1990. Some limitations will arise from the fact that the highest observed frequencies will be ~1 MHz for ISPM and ~5 MHz for Galileo, far lower than the highest frequency of the DAM emission, but tile experiments on both spacecraft will have direction finding capabilities.

5 Conclusion

AKR, HOM and DAM, and SKR, exhibit very similar global characteristics. When the positions of the sources are known, they are in all cases consistent with emission on the extraordinary mode, close to the local gyrofrequency, in regions of precipitation of high energy electrons. In the case where the plasma frequency at the source could be estimated, it was far lower than the local gyrofrequency. It is thus likely that the three emissions arise from the same basic mechanism, probably from the Doppler–shifted cyclotron instabilities (see e.g. Melrose, 1976; Wu and Lee, 1979; Le Queau et al. 1984). The differences in the spectral and temporal fluctuations observed for the three planets, and between the Io and non–Io decameter emissions, probably arise from differences at the source: the sources are localized in different magnetospheric regions, and the origins of the energetic electrons involved in the generation of the emission are certainly not similar.

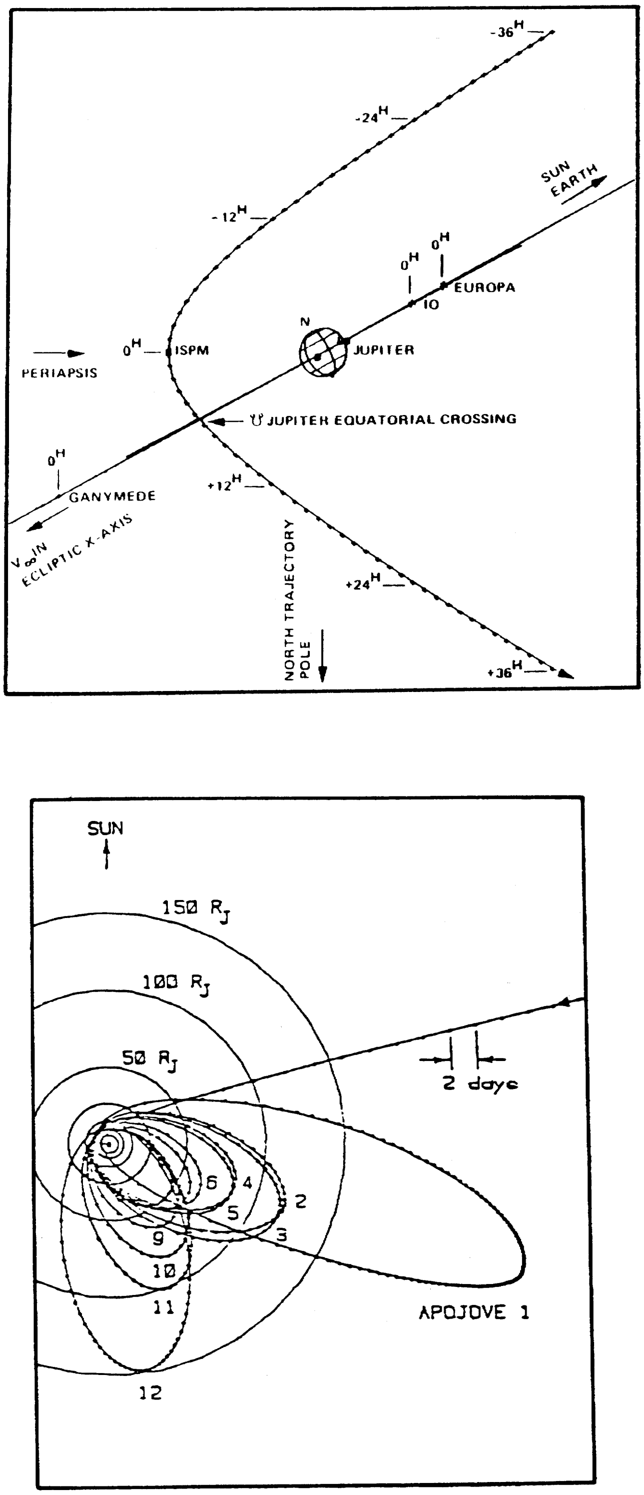

Figure 12: 12a: Predicted trajectory of ISPM close to Jupiter (South Jupiter flyby, seen in a rneridian plane). 12b: Predicted trajectories of the Galileo orbits around Jupiter (seen in the equatorial plane).

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Discussion

Question:

Why is the SKR source extension different in the Northern and Southern hemispheres?

Genova:

The main reason is the spacecraft trajectory. We got more adapted data from the Northern hemisphere, so the dispersion of the Southern hemisphere data is greater!