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The global plasma environment of Io as inferred from the Galileo plasma wave observations

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Abstract. We take advantage of a partial and a total occultation of the jovian radio sources observed during the flyby of Io to characterize the plasma environment of this moon. We show that it presents a strong upstream / downstream asymmetry. A dense plasma structure ($n > 5x10^4$ cm^{-3}) extends far from Io (at least 1000 km) in the wake direction whereas no extended dense region is found upstream. The dense region in the wake could correspond to a the stagnation region of the flow of the corotating plasma.

Introduction

In many respects, Io is one of the most extraordinary bodies visited by mankind. It is the most volcanic body of the solar system, immersed in the most active planetary magnetosphere. Io is thus a very prolific source of particles and it contributes to create a dense plasma torus whose existence is important both for the structure and dynamics of the jovian magnetosphere. While many observational facts illustrate the important role of Io as a driver of the magnetospheric activity (specific radio emissions [*Bigg*, 1964], specific auroras [*Prangé et al*, 1996]), little is known about the effect of the magnetospheric plasma, flowing at a high velocity (57 km/s) around Io, on the structure of the close environment of this moon.

Concerning its electromagnetic environment, *Kivelson et al*, [1996] have shown that the flow so strongly disturbs the magnetic field that it makes it difficult to ascertain the existence of an intrinsic magnetic field. Concerning possible effects of the flow on the atmosphere and the ionosphere of Io, things are more mysterious. Indeed, while the existence of a tenuous atmosphere is now proven, its origin and its structure remain unclear. The volcanism and the plume activity seem to play a leading role but the sputtering due to magnetospheric particles can also be important (see *Lellouch et al*, [1992], and the bibliography therein). Futhermore, Pioneer 10 radio science measurements suggest that the ionosphere of Io present a strong upstream/downstream assymmetry [*Kliore et al*, 1975].

In order to better characterize the Io plasma environment, we report here observations made by the Galileo Plasma Wave System (*Gurnett et al*, [1992]) during the close Io flyby on December, 7, 1997. Both local measurements of the plasma frequency and remote sensing techniques (radio occultations) will be used .

Galileo Plasma Wave Observations

In figure 1, a dynamic spectra of the electric component of the wave measured during Io flyby is presented (see also *Gurnett et al*, [1996]). The frequency range (500 Khz -> 5.6 Mhz) is displayed. The closest approach is at 17:45:30. Blue represents the lower intensity and red the highest intensity.

The intense noise at frequencies above 1.5 Mhz is the hectometric emission. Its origin is relatively well known [*Ladreiter et al*, 1994] . It is emitted in the jovian auroral zones, on L-shell ranging from 7 to 15. It is generated at frequencies close to the electron gyrofrequency, rather perpendicularly to the magnetic field. Below 1 Mhz, the kilometric jovian emission is also observed. Its low frequency cut-off (around 500 Khz) corresponds to the upper-hybrid frequency. Due to the low magnetization of the plasma, it is numerically close to the plasma frequency.

The flyby itself is associated with a jump in the density profile. The density rises from approximately 500 Khz in the torus ($n \sim 2.5x10^3$ cm^{-3}) to more than 1 Mhz close to Io ($n \sim 10^4$ cm^{-3}). This sharp increase is paradoxically associated with a reduction of the background noise collected by the electric antenna (transition from blue to black). This noise (likely to be the shot noise) being expected to increase with the density and the plasma temperature, one can conclude that the close plasma environment of Io is relatively cold. This is consistent with the measurements made by the Galileo plasma instrument (*Frank et al*, [1996]).

The hectometric emission, observed near the closest approach, underwent two amplitude reductions. The first one (from 17:30 to 17:35) corresponds to a reduction of the high frequency (f > 4 Mhz) part of the hectometric radiation. The

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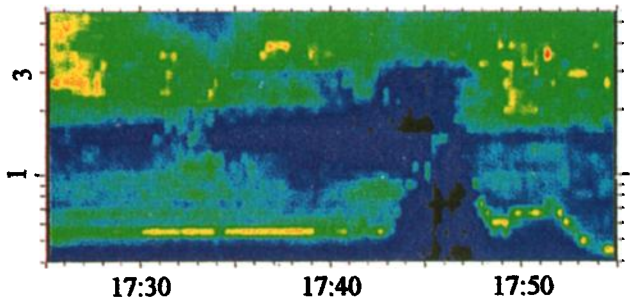

Figure 1. Frequency-time spectrograms of the electric intensity measured during the Io flyby.

second one, observed from 17:42 to 17:46:30, is a quasi-disappearance of the signal at frequencies below 3 Mhz. As shown later on, these two events can be associated with an occultation of the sources of the hectometric radiation by Io itself (first event) or its plasma environment (second event).

Density profile along Galileo trajectory

The plasma density profile along Galileo trajectory is shown in figure 2a. The density deduced from the plasma frequency (upper grey level scale) is compared with the density deduced from the classical hydrostatic equilibrium: $n(r)=n_0 \exp(-r/r_0)$ where r is the distance to the planet (lower grey level scale). n_0 and r_0 have been adapted in order to reproduce the density variations observed as the spacecraft approaches the planet. The crossing of the wake center corresponds to a relatively sharp maximum in the density. This maximum is obtained as the spacecraft already moved away from Io which is very different from what would be expected in the case of a classical ionosphere. On plot 2-b, the density is presented as a function of the distance to Io. The density deduced from the Pioneer 10 radio science experiment [*Kliore et al*, 1975]. is also presented. The comparison between the two types of measurements is pertinent since they both correspond to the same side of Io (downstream side). An extrapolation of the Galileo observations down to Io surface would lead to densities orders of magnitude larger than those obtained by *Kliore et al*, [1975].

A first explanation of this difference of observed densities could be that Io is much more active nowadays than 20 years ago. This would accord with the fact that the Io torus density seems to have increased by a factor of 2 since the Voyager epoch [*Gurnett et al*, 1996]. Another possibility of discrepancy could be linked to the methodology of the measurements. The interpretation of the radio science observations relies on the hypothesis of an ionosphere having a spherical symmetry. Figure 2a clearly shows that this is not the case for Io.

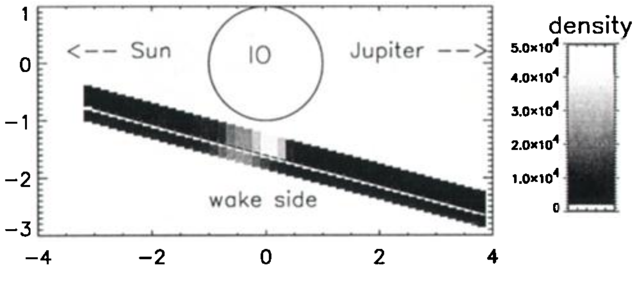

Figure 2 a. Density profile along the trajectory.

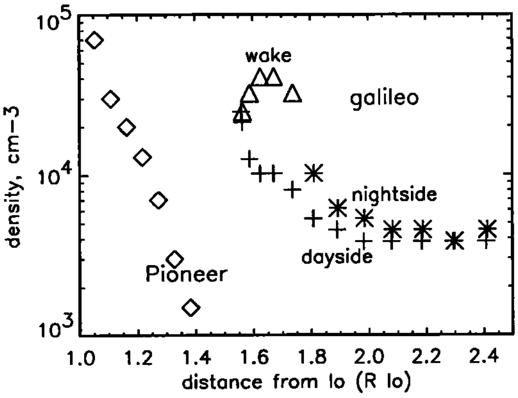

Figure 2 b. Galileo / Pioneer 10 observations.

The value of the maximum of the density and its position are difficult to determine because of the fast speed of Galileo. By extrapolating the density variations observed just before and after the wake crossing, one expects to have the maximum of the density to reach 5×10^4 cm^{-3} around 17:46:30. This would correspond to the spectral peak at 3.2 Mhz that appears in the spectrum at that time (see figure 1).

The existence of a so dense plasma environment, far from the surface of Io, is a surprise. Let us now study its global geometry using the two radio occultation events.

Density Profile from Radio Occultations

In figure 3, the sources of the hectometric radiation seen from Galileo during the period of the flyby are sketched. Following the results of the Ulysses radio experiment [*Ladreiter et al*, 1994], the sources are assumed to be in the Northern and the Southern auroral zones, on L-shell between 10 and 15 (we choose L=14 for the figure). They have an annular shape centered on the dipole axis. Since the waves are generated at the local electron gyrofrequency, each altitude corresponds to a particular frequency of the emission. The longitudinal extension of the sources is not known precisely and thus, we do not make any assumption about it.

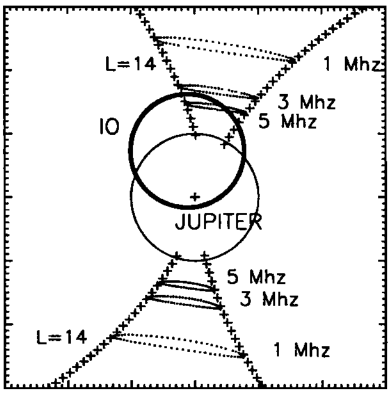

Figure 3. Position of the sources of the hectometric radiation.

We just take into account the fact that the radiation is generated at large angle with respect to the local magnetic field. Thus, for a source to be visible; the angle between the line of sight and the magnetic field in the source region must be close to 90° (typically from 70° to 90°) which corresponds to the magnetic field lines materialized by crosses in the figure 3. One can thus distinguish four different potential sources: two in the northern and two in the southern hemisphere, either on the left and the right sides. In the figure, Io, as it is seen from Galileo at 17:35, is supperposed. At that time, it occults the left side northern sources. Let us now study with more details the occultation of these sources by Io.

Occultation at ~ 17:33

This occultation concerns frequencies above 4 Mhz. The study of the relative position of Io and Jupiter shows that this event corresponds precisely to the disappearance of the North sources behind Io (figure 4). The South source remains always visible, thereby explaining the residual low amplitude radiation observed during the occultation. We will not use this occultation for a precise determination of the location of the source. Let us simply note here that if the sources are on the limb, on a L-shell of the order of 14, the main features of the occultation are relatively well explained by the apparent motion of Io/Jupiter as seen from Galileo. For the right side sources, the occultation only occurs for f > 4 Mhz and it begins well before 17:30. From 17:30 to 17:36, this occultation progressively ceases, first at low frequencies (around 17:33 at 4 Mhz) then, at higher frequencies (around 17:35 at 5 Mhz). Conversely, on the left side, the sources are visible before 17:30. The occultation begins around 17:31 at 5 Mhz. The lower frequencies are occulted later on (17:32 at 4 Mhz). The complete occultation (simultaneously the right and left side sources) thus only occurs for f > 4 Mhz. Its duration increases with the frequency. It lasts approximately 5 minutes at 5 Mhz which is consistent with the observations.

The right side sources reappear a little too soon for exactly describe the end of the occultation. This can be optimized by considering oblique propagations. Indeed, for smaller angles of propagation (for example 70°), the apparent sources are closer to the axis of the dipole. Longer occultations will be thus obtained which can be used for a better description of the observations. Nevertheless, a good result is already obtained with 90° and the benefit of this optimization will be marginal. The possible refraction by the dense regions near the surface has also been neglected. For reasonnable density profile, this effect is not fundamental here.

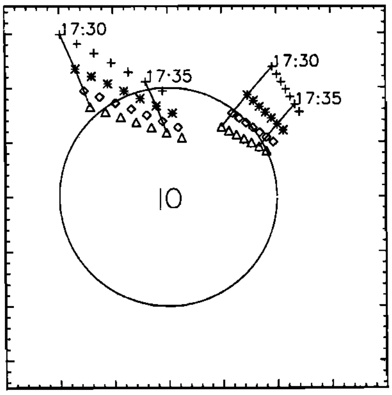

Figure 4. Occultation of the northern sources by Io between 17:30 and 17:36. The southern sources are far below Io. The crosses correspond to the 2 Mhz sources, the double-crosses to 3 Mhz, the squares to 4 Mhz and the triangles to 5Mhz.

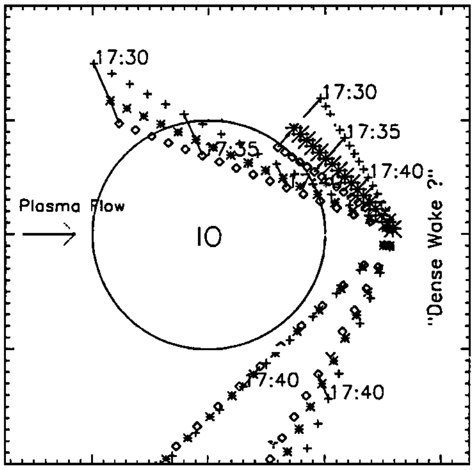

Figure 5. Relative position of Io and the jovian sources (at 2, 3 and 4 Mhz) from 17:35 to 17:46. The crosses correspond to the 2 Mhz sources, the double-crosses to 3 Mhz and the squares to 4 Mhz.

Concerning this first occultation, our main conclusions are the following:

(a) If a dense plasma region exists upstream of Io, it cannot extend far (more than 100 km) from the surface. Indeed, a dense ionosphere with a plasma frequency above 4 Mhz at a few 100 km upstream to Io would have produced a visible occultation at frequencies below 4 Mhz which is clearly not the case.

(b) In the 4-5 Mhz frequency range, the radiation reappears on the downstream side of Io as soon as this is geometrically possible. Therefore, the plasma frequency is not above 4 MHz in the downstream side, except maybe very close to the moon.

Occultation before 17:46: 30

This event is characterized by the disappearance of the hectometric radiation at frequencies below 3 Mhz, from 17:42 to 17:46:30. It is preceded by a smoother decrease of the intensity at frequencies below 3 Mhz starting around 17:35. The occultation ends at 17:46:30, just after the crossing of the wake.

An interpretation of these observations is sketched in figure 5, where the locations of the sources at 2, 3 and 4 Mhz are shown, each minute from 17:30 to 17:46. To build this figure, Io is assumed to be fixed in the sky and its apparent size is kept constant. As Galileo approaches Io, the jovian sources seem to move and to change their size relative to Io.

After 17:42, Io itself no more occults the jovian sources that would be thus perfectly visible. The occultation must therefore be attributed to something downstream to Io, in the wake. A simple hypothesis is that this screen corresponds to the dense plasma region encountered by Galileo during the wake crossing. All radio emissions with frequencies below the maximum of the plasma frequency along the line sight will be occulted. The observed cut-off frequency around 3 Mhz is thus the maximum of the plasma frequency along the line of sight. This corresponds to a maximum of the density close to 9×10^4 cm^{-3}.

The relative Io/Jupiter motion then allows for an actual radio sounding of the plasma environment of Io. The occultation from 17:42 to 17:46:30 corresponds to a sounding from the surface of Io to an altitude of the order of 1000 km (case of the north sources) and from high south latitudes to the equator (case of the south sources). In all this region, it is thus possible to deduce that the maximum of the plasma frequency is of the order of 3 Mhz. Moreover, the smoother decrease of the intensity observed before 17:42 can be explained by assuming that the plasma screen has also a northward extension comparable to the size of Io. In such a case, the north sources are always occulted from 17:35 which explains the cut-off at 3 Mhz observed well before 17:42. A short lasting radio emission is observed around 17:41 suggesting that the waves have been able to propagate across an inhomogeneity of the occulting screen.

The complete occultation lasts until the crossing of the structure by Galileo. As already mentioned, the crossing of the denser regions of the wake is not easily inferred from in-situ measurements alone. However, the suggestion made earlier that the peak observed at 3.2 Mhz, mixed with the hectometric emission, corresponds to plasma frequency measured locally in the wake center is reasonable.

The Io plasma environment: a dense plasma sheet in the wake ?

By comparing two types of measurements: (1) a determination of the plasma density along the Galileo trajectory and (2) a sounding of the plasma environment thanks to occultations of the Jovian radio emissions, it is possible to characterize the Io plasma environment. It is strongly asymmetric: if no extended plasma region exists upstream of Io, a dense plasma structure is present in the wake. It extends at more than 1000 km and its north/south size is of the order of Io diameter. The density profile suggests that it is rather thin (300 - 400 km) along the Galileo trajectory. It is relatively homogeneous down to the surface of Io (constant maximum density of the order of $9\ 10^4$ cm^{-3}) and is composed of a rather cool plasma (at least cooler than the torus plasma) as shown by the reduction of the antenna noise.

Let us note here that these results does not depends on our assumptions concerning the condition of generation of the hectometric radiation. The unic important point is that the waves are generated at the gyrofrequency (which is firmly confirmed by Ulysses results). The exact longitudinal position of the sources and their exact angle of propagation (typically between 70° and 90°) are not of fundamental importance.

This region of dense plasma has to be related to the specificity of the Io/Jupiter interaction. Recent simulation studies of the MHD interaction between Io and the corotating plasma suggest that a stagnation region of the plasma flow exists just behind the satellite. It could correspond to the dense region that occults the hectometric radiation described in the present paper.

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