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A multi-instrument study of a Jovian magnetospheric disturbance

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Abstract. Using observations from different Galileo experiments (plasma wave system, magnetometer and energetic particle detector), we analyze a strong magnetospheric disturbance that occurs on day 311 of 1996 as Galileo was close to Jupiter (less than 15 Jovian radii). This perturbation is characterized by multiple injections of energetic particles in the inner magnetosphere and has been described as a possible analog of the terrestrial magnetic storm by *Mauk et al.* [1999]. We show here that it also corresponds to a large-scale magnetospheric perturbation similar to the "energetic events" described by *Louarn et al.,* [1998, 2000]. It is associated with the development of a particular magnetic activity in the outermost part of the Io torus, over periods of 2-4 hours and in sectors of longitude with a typical 30°-80° longitudinal extension. At distances ranging from 10 to 13 R_j, the activity itself is characterized by the generation of low-frequency magnetic oscillations (18 min periodicity in the present case) that correlate with dispersionless energetic electron injections and modulations of the auroral radio flux. When they are observed a few hours after their formation, these injections present a weak energy-time dispersion and are still periodic. They then progressively mix and finally define a region of limited longitudinal extension where the density of energetic particles is particularly large. We show that this region corresponds to the source of the narrowband kilometric radiation (n-KOM). By combining remote sensing radio observations, in situ particle, and magnetic field measurements, we show that the active zone where the large scale disturbance initially develops most probably does not corotate and would even be almost fixed in local time. In the present case, the magnetospheric event is the consequence of two activations separated by a few hours. They occur in two separated longitude sectors and give rise to two different n-KOM sources. During the event, some 10^{12} W are transferred to the electron population. It is proposed that this set of phenomena is the manifestation of a sporadic dissipation of a part of the Io torus rotational energy and would be thus associated with the development of a large-scale instability in the external part of the Io torus.

1. Introduction

The Jovian magnetosphere is a complex system in both structure and temporal behavior. In short, it can be described as a magnetic environment driven by the fast rotation of its central spinning object, Jupiter, and populated by ions coming mainly from one of its moons, Io. Thus it has common features with the environments of more exotic astrophysical objects such as pulsars and binary systems [see *Goldreich and Lynden-Bell,* 1969; *Kennel and Coroniti,* 1975; *Dessler,* 1983]. As it is also under the influence of the solar wind, three types of processes can drive its activity: (1) the rotation and the radial plasma transport, (2) the satellite-magnetosphere interactions, and (3) the solar wind interaction. It is generally considered that the last process has a modest influence, at least in the inner magnetosphere ($R <$ 20 R_j).

What are the manifestations of these different forms of activity? Since it is dominant in the case of Earth, the externally driven activity is the best documented. It is characterized by sporadic releases of magnetic energy (substorms). They take place over hour timescales and are linked to modifications in the solar wind conditions. On the other hand, from remote observations of the Jovian radio emissions and aurora, it has long been known that the satellite-magnetosphere interaction (in particular, the one associated with Io) leads to a very regular and even predictable type of activity (see *Carr et al.* [1983] for a review of the Jovian radio emissions). It is also widely admitted that the activity linked to the rotation and the associated radial plasma transport is rather regular. This has been anticipated by various theoretical studies [see *Hill et al.,* 1983; *Vasyliunas,* 1983] and partially confirmed by the observation of ever-present radio emissions that could be associated with the relaxation mechanisms of the rotational energy. However, the exact modes of relaxation of this form

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of energy are still not understood. They are connected to radial plasma transport processes and thus to the stability of the plasma reservoir that constitutes the Io torus. The relaxation processes that may develop in this rapidly rotating plasma reservoir can then well be sporadic.

More precisely, very important unknowns include the typical temporal and spatial scales of the processes that evacuate the plasma created at Io's orbit. Do they correspond to microdiffusion mechanisms [*Richardson and Siscoe*, 1981; *Siscoe and Summers*, 1981] or large-scale organized convection patterns [*Hill*, 1979; *Hill et al.*, 1981; *Pontius and Hill*, 1989]? Do they result from large-scale instabilities [*Huang and Hill*, 1991; *Fazakerley and Southwood*, 1992; *Yang et al.*, 1994; *Ferrière and Blanc*, 1996; *Ferrière et al.*, 1999]? Is the relaxation of the centrifugal energy regulated by internal processes only? Does it present an intrinsic burstiness? These are some of the still pending questions regarding the Jovian magnetospheric activity. This is the general focus of the present paper.

Recent Galileo observations have enabled new insights on these questions. They indeed show that the Jovian activity is definitely not stationary. This is not a completely new point since past observations from the Nancay radio telescope, Voyager, and Ulysses have detected important temporal fluctuations in the Jovian radio flux (see, for example, *Zarka and Genova* [1983], *Desch and Barrow* [1984], *Barrow and Desch* [1989], *Kaiser* [1993], and *Prangé et al.* [1993]). Even if they have been interpreted as possible effects of the solar wind interaction, these observations already suggest that the relaxation of the centrifugal energy could result in sporadic behavior. In a much more precise way, the Galileo observations have given evidence for the existence of a new type of large-scale magnetospheric activity. This activity that seems to have characteristics in common with the terrestrial substorm activity [*Woch et al.*, 1998] can be described as the quasi-periodic occurrence of "energetic events" [*Louarn et al.*, 1998]. They typically last a few hours and have shown a periodicity that varies from 2-3 days to more than 8 days during the 1996-1997 period. These "events" correspond to global increases in the flux of the various Jovian radio emissions and to spectral/temporal modifications of their morphology. They are characterized by the simultaneous observation of (1) enhanced auroral radio emissions, (2) creation of new sources of narrowband kilometric radiation (n-KOM) in the Io torus, and (3) large-scale variations in the plasma density of the distant magnetodisc. This activity thus affects almost simultaneously the auroral zones of Jupiter, the Io torus, and the distant magnetodisc. It also corresponds to the detection of quasi-periodic bursts of particles with energies up to the MeV range in the distant magnetodisc [*Krupp et al.*, 1998]. More recently, *Louarn et al.* [2000] have shown that the events trigger sudden thickenings (over a few hours timescale) followed by more progressive thinnings of the magnetodisc (over a few tens of hours). These variations of the width of the disc are particularly visible when Galileo is in the morningside of the magnetosphere, which was the case of the orbits G2 and G7 studied by *Louarn et al.* [2000]. One particularly clear case was studied in detail (orbit G7, day of year 83 in 1997 (DOY 97-083)). It was possible to show that the variations of the width of the disc are not compensated by variations of the density. These variations then actually correspond to fluctuations of the surface density of the disc, this quantity suddenly increasing during the event and then progressively decreasing. This suggests that the events could correspond to sporadic evacuations of plasma from Io's torus and thus initiate phases of strong radial plasma transport across the magnetodisc. The energetic events would thus be an important step in the dissipation of the rotational energy of the torus/magnetodisc system. These new observations lead to the conclusion that the relaxation of rotational energy is far from being a stationary process. The description of the short-timescale processes associated with the relaxation is the main topic of the present paper.

Most of the recent works presented above are based on remote-sensing techniques or on Galileo observations obtained in the distant magnetodisc. To better understand the Jovian activity, in situ observations in the torus/magnetodisc region are essential. Recently, using the energetic particle detector (EPD) on board Galileo, *Mauk et al.* [1997, 1999] have reported on the discovery of energy-time dispersed signatures of energetic particle injections in the inner magnetosphere. For the 10 first orbits of Galileo around Jupiter, over 100 injections have been detected, at distances ranging from 9 R_j (the minimum Galileo-Jupiter distance for the studied orbits) to 27 R_j, in the transition region between the quasi-dipolar magnetic field and the more stretched configuration corresponding to the magnetodisc. These injections do not seem to be organized in local time or in system III longitude. They present some analogies with the substorm-related injections observed in the terrestrial magnetosphere. They may testify to the existence of sporadic energetic processes and the question of their relationship with the "energetic events" must thus be considered in detail.

We will concentrate here on the study of a particularly instructive example of magnetospheric disturbance that has been observed during the C3 orbit (DOY 96-311). In section 2, we establish the equivalence between "magnetic storm" (EPD observations) and "energetic event" (plasma wave (PWS) observations). We will then combine PWS, magnetic (MAG) and EPD observations to better describe the pertinent temporal and spatial scales of the phenomenon (sections 3 and 4). Then, after energy considerations (section 5), we will conclude with a model of the Jovian activity that synthesizes the present observations (section 6).

Before going into a detailed analysis, it must be acknowledged that our study is based on the observations of a single case. The "C3" event is indeed the only major magnetospheric disturbance that has been observed so far near perijove (at less than 12 R_j). Owing to its uniqueness, this example is particularly important. However, the generality of the reported observational facts is not guaranteed, and the model of the activity that we will propose has thus to be considered with care.

2. On the Relationship Between "Magnetic Storm" and "Energetic Event"

2.1. The "C3" Magnetospheric Disturbance

Mauk et al. [1999] presented data recorded during a very disturbed period corresponding to the first hours of DOY 96-311 (orbit C3) when Galileo was at less than 15 R_j from Jupiter. This period is characterized by a sudden and strong increase in the count rates of energetic electrons. Numerous

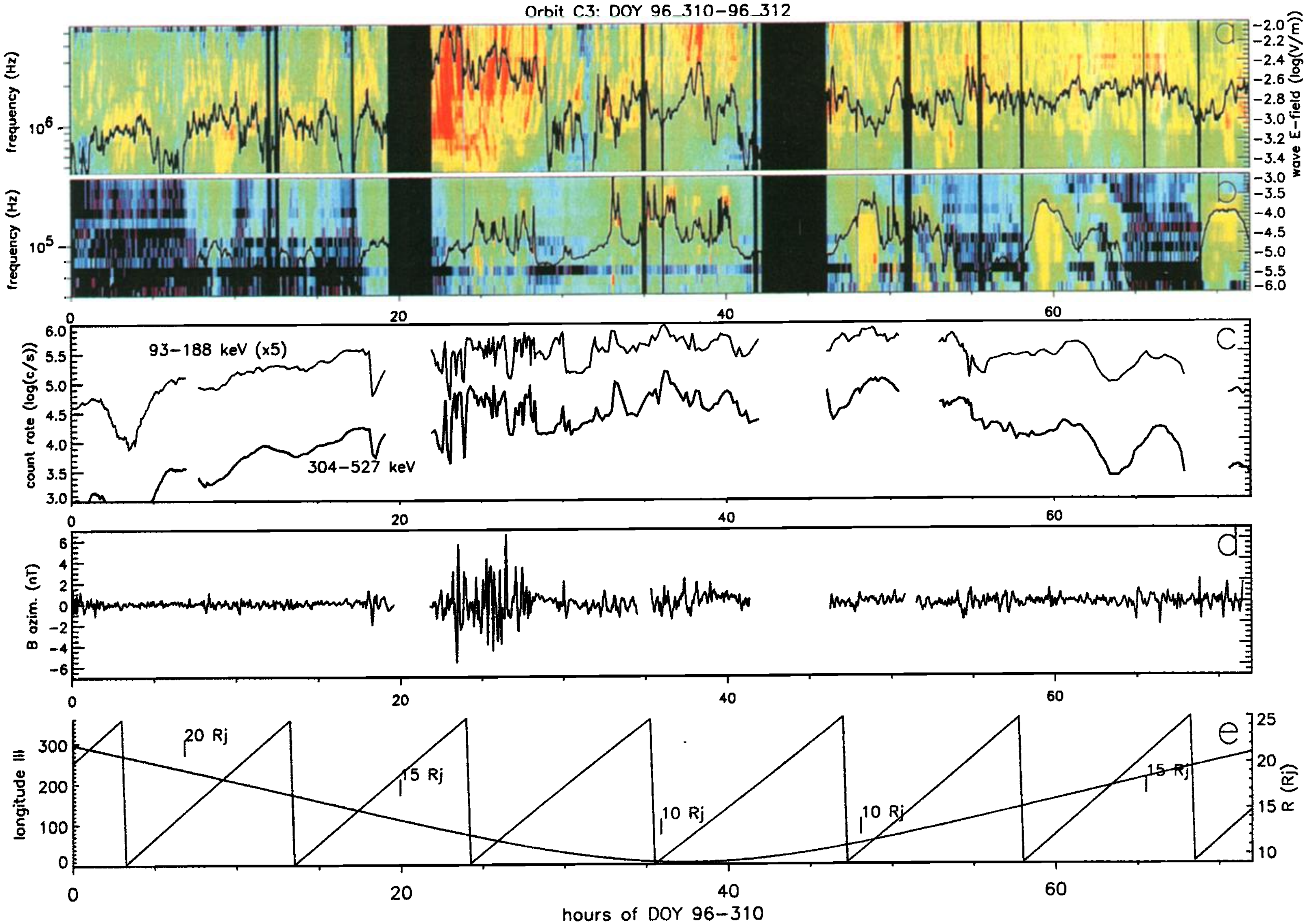

Plate 1. Galileo wave-particle measurements performed during 1996, day of year 310 to 312. (a and b) Dynamic spectra of the radio waves ($Vm^{-1}Hz^{-1/2}$) and corresponding wave electric field (result of the integration over the band) in logarithmic scale. (c) Count rates of 93-188 and 304-527 keV electrons in logarithmic scale. (d) Azimuthal component of the fluctuating magnetic field. (e) Orbital parameters of Galileo.

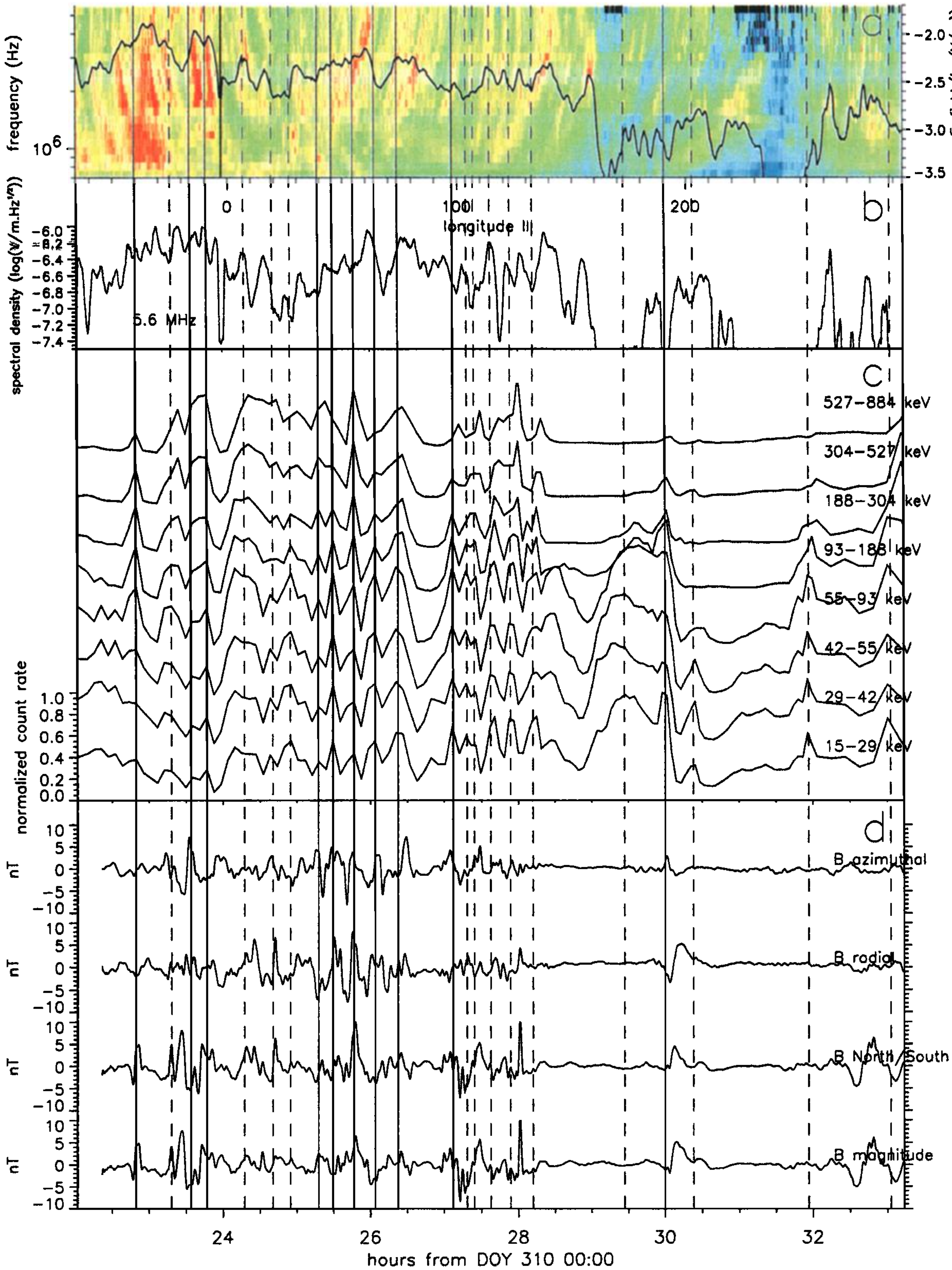

Plate 2. Wave-particle observations made during the event. One complete Jovian rotation is presented. (a) Wave dynamic spectra from 0.7 to 5.6 MHz and corresponding integrated wave electric field (black line). (b) Wave spectral density at 5.6 MHz. (c) Normalized energetic electron count rates (20 to 800 keV). (d) Components and magnitude of the fluctuating magnetic field. The vertical lines correspond to dispersionless (solid line) and weakly dispersed (dashed line) injections.

transient signatures are observed, some of them being energy-time dispersed. They are described as being clustered since more than 15 of them are observed in less than 6 hours. These transient signatures present all the characteristics of the energetic particle injections that occur in the terrestrial magnetosphere. The term "injections" was thus used for describing them by *Mauk et al.* [1999].

In the terrestrial context, the injections of energetic particles in the inner magnetosphere are considered direct consequences of the substorm expansion phase activity [*DeForest and McIlwain*, 1971; *Mauk and McIlwain*, 1974; *Lopez and Lui*, 1990] (see *Rostoker* [1996] for a review). By analogy, if one admits that each transient signature is associated with a defined magnetospheric disturbance, the DOY 96-311 disturbed period would be interpreted as a suite of substorm-type processes over a timescale of a few hours. At Earth, the observation of such a suite is one of the signatures of magnetic storms (see the review by *McPherron* [1995]). These phenomena correspond to major magnetic perturbations and to strong increases of the density of energetic particles in the inner regions of the magnetosphere. Along this line, *Mauk et al.* [1999] proposed that the DOY 96-311 disturbed period is an example of a Jovian magnetic storm. They were nevertheless cautious in their interpretation, given the difficulty of distinguishing between temporal and spatial effects from the observations of the particle experiment alone. We will go back to this critical question later. We will first relate what could be defined as a "storm" from the particle signatures to the large-scale magnetospheric phenomena defined as "energetic events" from PWS observations.

Note that we will only describe and discuss transient phenomena here. The reader will find detailed presentations of the basic static state of the magnetosphere in papers describing the Voyager observations of the particle populations and their role in the magnetospheric equilibrium [*Armstrong et al.*, 1981; *Krimigris et al.*, 1983; *Paranicas et al.*, 1991; and *Mauk et al.*, 1996], the magnetic field observations being summarized in *Acuña et al.* [1983].

2.2. A General View of the Observations

In Plate 1, we present measurements made by the PWS, EPD, and MAG experiments during the period from DOY 96-310 through DOY 96-312 (see *Gurnett et al.* [1992], *Kivelson et al.* [1992], and *Williams et al.* [1992] for detailed presentations of these experiments). The plate is divided into five panels. PWS observations are displayed in Plates 1a and 1b, EPD in Plate 1c, and MAG in Plate 1d. In Plate 1e, the orbital parameters of Galileo (distance from Jupiter and system III longitude) are given. Note that Galileo is close to the ecliptic plane so that its magnetic latitude is always in the range [-10°, 10°]. In the rest of the paper, since we will only discuss observations made during the year 1996, we will systematically omit the reference to the year in the notation. For simplicity, we will also systematically use DOY 96-310 00:00:00 as the reference for time in both the figures and the text.

Let us first consider the PWS observations. They consist of dynamic spectra measured by the PWS electric antenna. In order to enhance legibility, the original data set (spectra from 5 Hz to 5.6 MHz recorded each 36.7 s) is divided in two spectral domains: from 400 kHz to 5.6 MHz (Plate 1a) and from 70 kHz to 140 kHz (Plate 1b). The wave dynamic spectra (unit: $Vm^{-1}Hz^{-1/2}$) are coded by using a "rainbow" color scale, the maximum (minimum) intensity corresponding to red (deep blue). The wave electric field integrated over the bands is displayed in Plates 1a and 1b (black line superimposed in the plots, units: V/m). The two frequency domains correspond to radio emissions of different origins. In the upper band (Plate 1a), the experiment mainly detects emissions generated along the auroral field lines. They present similarities with the terrestrial auroral kilometric radiation. They are likely to result from a direct amplification of the electromagnetic waves by populations of accelerated electrons in the 10 keV range (the cyclotron maser instability). They are thus related to the auroral activity, and their flux can be considered as a good proxy for magnetospheric activity (see *Kurth and Gurnett* [1998] for a discussion in the terrestrial case). This characteristic of the auroral radio emissions has been largely used by *Louarn et al.* [1998, 2000] for surveying the long-term temporal variations of the jovian magnetospheric activity. In the lower-frequency band (Plate 1b), two types of emissions are detected: (1) the so-called b-KOM, which is simply a low-frequency extension of the auroral emissions (for example, the emission above 100 kHz around 10:00), and (2) a brighter narrowband emission presenting a pronounced 10 hour periodicity and a spectral peak around 100 kHz. This is the so-called n-KOM. This emission is particularly visible during DOY 312. Its organization in regular flashes presenting a 10 hour periodicity (around 48:00, 59:00, and 70:00) is explained by the rotation of its sources in the outermost regions of the Io torus [*Reiner et al.*, 1993].

Before the data gap that occurs from approximately 19:30 to 22:00, the intensity of the auroral radiation is low (wave electric field smaller than 10^{-3} V/m in average) and no n-KOM is detected. This is already the case on earlier days (DOY 308 and 309; data not shown here). After the data gap and during the first hours of DOY 311 (period centered at 25:00), the auroral flux is larger by almost 1 order of magnitude (wave electric field larger than 5×10^{-3} V/m in average). This period of large flux is also characterized by the observations of numerous bright spectral features. The flux then decreases (after 29:00) but still remains relatively high during DOY 312. At comparable distances from Jupiter, it is indeed typically a factor of 2 larger during DOY 312 (2×10^{-3} V/m in average) than during DOY 310. It is clear that the magnetosphere is more active after DOY 311 than before. This is confirmed by the observation of bright sources of n-KOM on DOY 312 and for successive days after that are not seen on DOY 310 and before. Following *Louarn et al.* [1998, 2000], we conclude that an energetic event occurred during the last hours of DOY 310 (perhaps starting during the data gap) and the first hours of DOY 311 (before 29:00).

Strictly speaking, the energetic events have been defined by the simultaneous observation of an increase in the auroral radio flux and the creation of a new n-KOM source. In the present case, the fact that Galileo is close to Jupiter and in dense plasma regions precludes the direct observation of the n-KOM during DOY 311. Wave activity is nevertheless observed in the frequency domain of the n-KOM during the first hours of DOY 311 (for example, at 25:00 and 35:00). As discussed later, this suggests that a new n-KOM source actually begins to emit during this period.

The comparison with the EPD observations is straightforward. In Plate 1c, two time series corresponding to spin-averaged electron count rates (plotted in logarithmic scale) measured in the 93-188 keV and 304-527 keV channels (the count rate is multiplied by 5 in the first case for the legibility of the plate) are presented. It is clear that the energetic event identified from the PWS observations corresponds exactly to the period of clustered injections described by *Mauk et al.* [1999]. It is indeed associated with a strong increase in the flux of the energetic electrons (increase by almost 1order of magnitude at 304-527 keV) that seems to begin just after the data gap of DOY 310. As detailed later, the count rates present spiky variations at a few minutes timescale. Almost 15 of these transient events, interpreted as injections by *Mauk et al.* [1999], are identified during the first four hours of DOY 311. Note that we will not discuss ion signatures in detail in the present paper. They are generally more subtle than the electron ones and present less temporal contrast (see the discussion of *Mauk et al.* [1999]). The use of the ion observations would add little to the present study. The interested reader can nevertheless find the observations corresponding to the event described here in Figure 4 of *Mauk et al.* [1999].

Concerning the magnetic field measurements (from MAG), the disturbed period corresponds to the detection of strong magnetic perturbations (Plate 1d). We present the azimuthal component of the fluctuating magnetic field (right-hand orientation) in a system of reference aligned with the Jovian spin axis. This fluctuating component is obtained by subtracting from the initial data the static field calculated by a boxcar average over 40 min. A further filtering (boxcar averaging over 4 min) has been applied for removing fluctuations of higher frequencies. We have checked that reasonable changes in the parameters of the filtering procedure do not affect the main characteristics of the fluctuations seen here. They reach 8 nT, which represents a few percent of the static field (the field magnitude is close to 200 nT in the equatorial plane at 12 R_j).

2.3. The "C3" Magnetic Storm as an "Energetic Event"?

In conclusion, the wave/particle instruments on board Galileo give evidence for the development of a strong magnetospheric activity during the first hours of DOY 311. These observations suggest that the energetic events described by *Louarn et al.* [1998, 2000] correspond to phases of strong energetic particle injections in the external part of the Io torus (the "storm" described by *Mauk et al.* [1999]). They also show that there is a close relationship between the development of this major magnetospheric disturbance and the generation of strong magnetic perturbations in the inner magnetosphere. Does this really mean that all these phenomena are the manifestations of the same basic magnetospheric process? We will now try to answer this critical question by a more detailed analysis of the phenomena.

3. Direct in Situ Analysis of a Jovian Magnetospheric Event

3.1. Identification of the Injections

In Plate 2, we present a detailed view of the PWS, EPD, and MAG data obtained during the complete Jovian rotation that starts DOY 310 22:00, just after the data gap. It is divided in four panels (Plates 2a-2d). The following measurements are presented:

Plate 2a shows the high-frequency PWS dynamic spectra ($Vm^{-1}Hz^{-1/2}$). Red corresponds to maximum spectral density, and deep blue corresponds to minimum. As for Plate 1, the superimposed curve corresponds to the wave electric field integrated over the frequency band (V/m, in logarithmic scale). Plate 2b shows the time series of the wave spectral intensity at 5.6 MHz ($Vm^{-1}Hz^{-1/2}$ in logarithmic scale). Plate 2c shows the time series of the energetic electron count rates (from 15 keV to 800 keV). In each energy channel, the count rates have been normalized to their maximum value, and the same linear vertical scale is used (from 0 to 1). To simplify the identification of possible energy dispersions, the curves corresponding to successive energy channels are shifted along the vertical axis. Plate 2d shows the time series of the fluctuations of the three components of the magnetic field and of its magnitude. The averaging and filtering procedure is identical to the one used in section 2. Polar coordinates are used in a system of reference aligned with the spin axis of Jupiter: "*B* radial" is the radial component (pointing away), "*B* north/south" points southward, and "*B* azimuthal" has a right-hand orientation.

Let us first identify the injections (the term "injection" is used here as a synonym of "transient signature"). The continuous vertical lines in the plate correspond to injections presenting little or no dispersion (no delay between the 15-29 keV and the 304-527 keV channels). Given the time resolution, this corresponds to a dispersion smaller than 5 min. The dashed vertical lines indicate the averaged position of more dispersed injections. A total of 18 injections have been detected during the first part of the rotation (until 28:30). They are observed in a wide longitudinal sector (160°), from approximately -30° to 130° in system III longitude (x axis of Plate 2a). Most of the injections described here are short (typically a 10 min duration) compared to the injections that are observed during other orbits, generally not in conjunction with the occurrence of an event. Such longer injections are shown in Figures 1, 6, or 8 of *Mauk et al.* [1999]. An injection of this type is observed here around 29:30. This long-duration (1 hour) signature presents the largest dispersion, more than 20 min between the 15-29 keV and the 93-188 keV channels, but does extend towards the highest energies (at more than 400 keV). It thus differs from the short injections in many points. This suggests that various types of injections have to be distinguished. We here concentrate on the short injections and on the related phenomena.

With the exception of the transient signature occurring at 29:30, the energy dispersion of the injections is smaller than 10 min and even smaller than 5 min for 10 of them (in particular, for five short injections occuring during a 1 hour period around 26:00). Using a classical formula for the bounce average drift velocity of particle in a dipolar field: $<v_B> \sim (6\ W/qBR)(0.35 + 0.15 \sin \alpha)$, where W is the particle energy, q is the charge, α is the pitch angle, B is the equatorial magnetic field and R is the distance to the planet [see *Cravens*, 1997], one gets approximately a drift of 6 km/s at 12 R_j (for 400 keV electrons, α=60°, and B=200 nT). The observation of a 10 min dispersion between the 20 and 400 keV channels thus means that the injections have been generated approximately 4 hours before (see also the

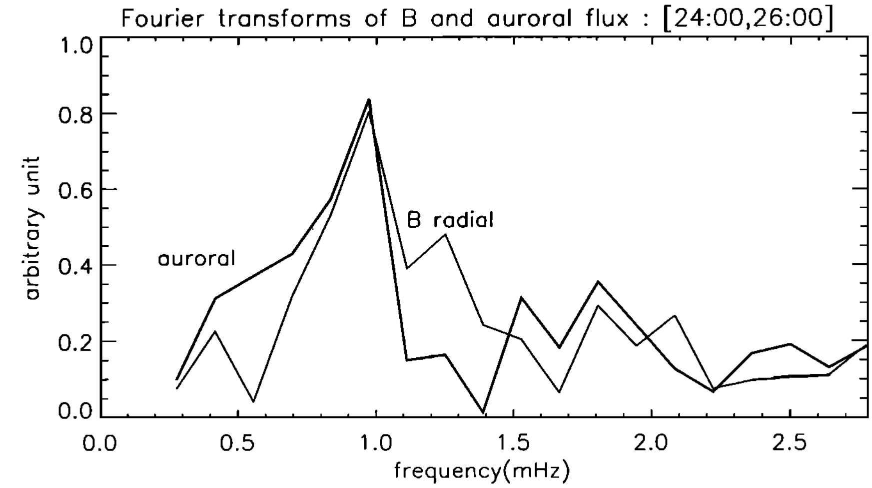

Figure 1. Spectra of the magnetic fluctuations (radial component) and of the radio modulations (at 5.6 MHz) for the period [24:00, 26:00].

estimates proposed by *Mauk et al.* [1999]). The injections observed around 26:00 are even more recent. This period (24:00-26:30), during which most of the nondispersed injections are detected, will be called "period 1" in the following.

One also notes that the injections occur in a quite regular way. They present a typical periodicity of 18 min from 23:00 to 28:00. This periodicity concerns both weakly dispersed and dispersionless injections. As described now, the same type of periodicity is observed for the other measured quantities.

3.2. Associated Phenomena

Let us consider the magnetic measurements (Plate 2d). The whole period characterized by the presence of strong magnetic fluctuations, from 23:15 to 28:10, corresponds to the observations of the clustered injections. The fluctuations are particularly strong around 26:00 when most of the dispersionless injections are detected. At that time, Galileo is likely to be very close or even inside a region of local energization of the particles. From 23:30 to 26:30, the magnetic field displays regular fluctuations with a periodicity close to 18 min. More precisely, a close inspection shows that from 25:00 to 26:30 each increase in the flux of the energetic electrons corresponds to a strong variation in the amplitude of the three components of the fluctuating magnetic field. With the exception of a peak at 25:45, one also notes that the fluctuations of the north-south component (less than 3 nT) are smaller than the fluctuations of both the azimuthal and radial components (up to 8 nT). Still, with the exception of the peak at 25:45, the fluctuations of the magnitude remain modest (less than 3 nT). The magnetic fluctuations that correlate with the dispersionless injections are then more torsional than compressional as expected for Alfvén waves. Strong magnetic fluctuations are also observed just before 24:00 and around 30:00 in correlation with dispersionless injections. The contrast with the observations performed from 27:00 to 28:15 is interesting ("period 2" in the following). For this period, most of the injections are weakly dispersed (by typically 10 min) and thus likely result from processes that were active about 4 hours before (see *Mauk et al.* [1999], who already studied this period). The magnetic fluctuations

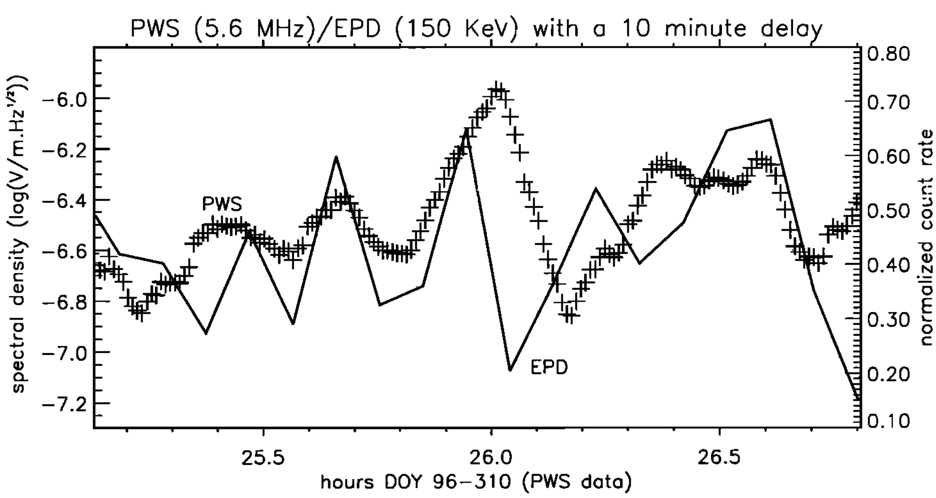

Figure 2. Radio and energetic electron fluxes measured with a 10 min delay ([25:00, 26:30] for radio, [25:10, 26:40] for electrons).

are also significantly smaller than for period 1 and do not correlate with the injections. We conclude that the strong magnetic fluctuations are closely related with the energization process responsible for the injections.

One of the surprises of this study is the possibility of detecting 18 min oscillations in the auroral radio flux (see Plate 2b). These oscillations are visible during most of the disturbed period, from 23:00 to 28:30, and are particularly apparent in the fluxes measured at high frequency (above 5 MHz). This point is illustrated in Figure 1 where we present a spectral analysis of the magnetic fluctuations (for the radial component) and of the radio flux (at 5.6 MHz) measured during the period 24:00-26:00. The two spectra present a clear common peak around 0.9 mHz, which corresponds to an 18 min period. Examining Plates 2a and 2b again, one notes that the radio flux oscillations are shifted with respect to the dispersionless injections. The best linear correlation coefficient between the two time series (for period 1) is obtained if the particle measurements are delayed by 10 min. The corresponding plot is presented in Figure 2 (5.6 MHz radio flux and 150 keV electron count rates). A classical interpretation of the temporal shift would be that the auroral radio flux fluctuations are delayed with respect to the equatorial phenomena due to the finite transit time along the magnetic field lines. The 10 min delay corresponds to a speed of 2000 km/s (between the equator at 12 R_J and the auroral region), which is consistent with the value of the average Alfvén speed along the field line.

3.3. Jovian "Magnetic Storms" and "Energetic Events" as Manifestations of the Same Magnetospheric Activity

As discussed now, one can use the detailed analysis performed above to demonstrate that the relationship between the "energetic event" and the "magnetic storm" cannot be coincidental. One might indeed imagine that Galileo had simply entered a region more heavily populated by energetic electrons more or less in coincidence with the development of an energetic event (see the discussion about the spatial versus temporal character of the injections in the work by *Mauk et al.* [1999]). In such a scenario, the two types of phenomena would be physically disconnected. This is very unlikely.

Let us first note that the 18 min oscillations actually correspond to important modulations of the radio flux. During the event, the auroral flux is already almost 1 order of magnitude stronger than during quiet periods. The fluctuations associated with the injections correspond to variations of 20% to 50% of this high flux. If similar phenomena (repetitive injections) develop before or after the disturbed period studied here, they should be clearly visible in the radio flux. As shown in Figure 3, this is not the case. We here compare spectra of the radio flux observed in the same longitude III sector (from 0° to 65°) before the event [14:00, 16:00], during the event [24:00, 26:00] and after it [34:00, 36:00]. Before the event (dashed line), the flux is weak (it is multiplied by a factor 5 in the plot) and does not produce any clear spectral peak. One concludes that the magnetosphere is quiet and the injection process is still not active. After the event (thin solid line), the radio flux is relatively high and produces two spectral peaks: one at 0.5 mHz (period of 33 min) and the other at 2 mHz (period of 8 min). The magnetosphere is active, but the characteristics of this activity have changed compared to what is observed during the event. The 18 min oscillation is thus a typical signature of the energization process associated with the magnetospheric event. The present observations also imply that the energetic event and the multiple injections have occurred simultaneously and are most probably two manifestations of the same basic magnetospheric process.

4. Longitudinal Organization of the Phenomena: Relationship Between the n-KOM Sources and the Injections

The examination of Plate 1 suggests that a good correlation exists between wave phenomena in the 100 kHz range and the transient particle signatures observed near perijove (from 32:00 to 42:00). This is shown with more detail in Figure 4, where we present an expanded view of the wave dynamic spectra in the n-KOM frequency range (from 70 kHz to 200 kHz), the associated integrated wave *E* field, and the electron flux measured in the 93-188 and 304-527 keV channels (in medium, and thick lines, respectively). A

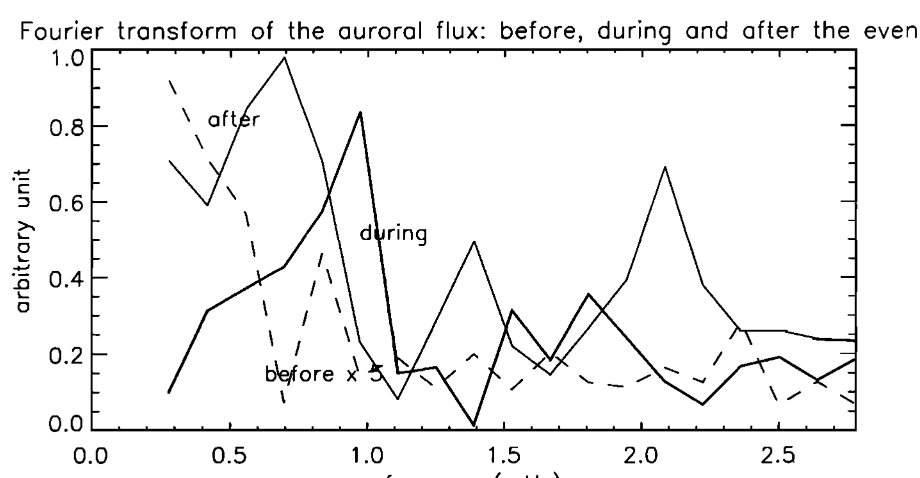

Figure 3. Spectra of the radio modulations observed in the same longitude III sector for successive rotations: [14:00, 16:00] (dashed line, multiplied by 5), [24:00, 26:00] (thick solid line) and [34:00, 36:00] (thin solid line).

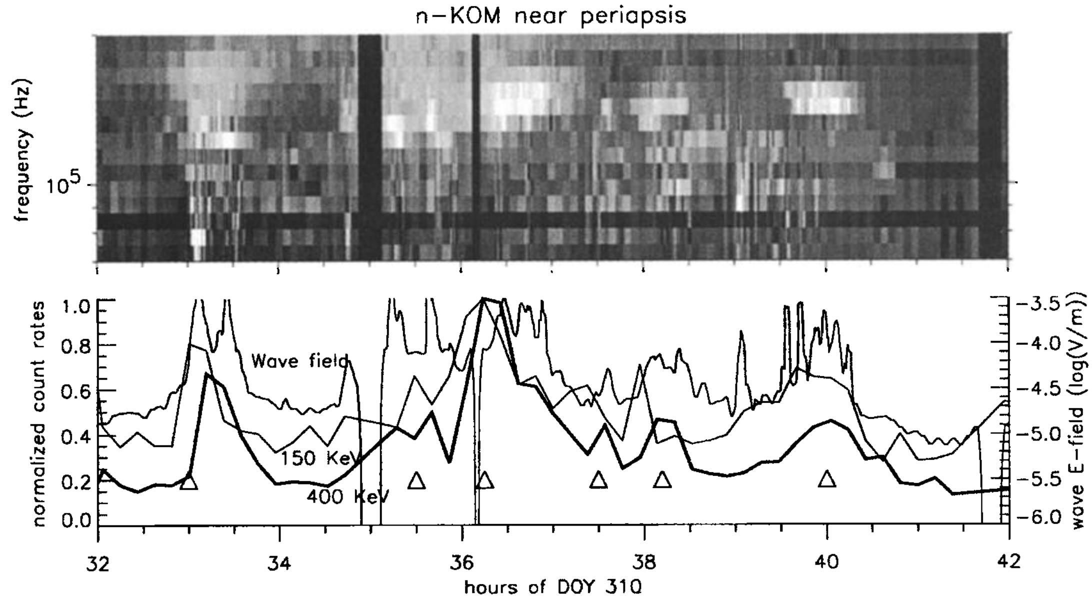

Figure 4. Details of the energetic electron fluxes at 93-188 and 304-527 keV (thick line) and wave spectral density in the n-KOM frequency range observed near perijove (10 R_j)

gray scale is used: black (white) for minimum (maximum) intensity. Triangles indicate the average position of the significant injections that may be identified during this time period. Each of them can be related to wave intensifications around 110 kHz (increases by almost 1 order of magnitude of the integrated field). These spectral intensifications over one or two frequency channels are observed just above the low-frequency cutoff of the waves. This is a typical signature of electrostatic waves. Nevertheless, the observed noise also has a broad extension to higher frequency and thus cannot be attributed to local plasma waves only. Both local electrostatic waves and radio waves (most probably in the form of both b-KOM and n-KOM) are then observed together. The injections observed near perijove (around 10 R_j) are thus well correlated with the generation of intense electrostatic and radio waves in the n-KOM frequency domain.

To discuss with more detail the relationship between injections and n-KOM sources, we plot the dynamic spectra from 70 to 150 kHz for successive Jovian rotations in Figure 5. The same abscissa (system III longitude of Galileo) is used. The plots start at a longitude of 294°, which is the longitude of Galileo just after the data gap occurring on DOY 310. The event occurs during rotation 1. The jovian distance is 12, 10, 12, 15, 20, 27, and 35 R_j in average for rotations 1 to 7. In each panel, we also plot the integrated wave electric field over the band. A well-known characteristic of the n-KOM is the progressive longitudinal shift of its sources with respect to the corotation. This effect is obvious in the figure. The oblique lines correspond to a shift of 15° from one rotation to the next. One can check that this shift adequately fits the observed longitudinal drift of the source. Lmes A and B delimit a longitudinal sector where the n-KOM is the most intense. Line C corresponds to a second sector in longitude where the radio flux presents a secondary maximum (around 140° during rotation 2). This is also the average position of a second source of n-KOM which is readily apparent from rotations 4 to 7.

Using lines A, B, and C, one can relate the wave phenomena to the injections observed during the event or just after it (rotations 1, 2, and 3). In Figure 6, we plot the time series of the 42-55, 93-188, and 304-527 keV electron fluxes for these three rotations (respectively in dashed, thin, and thick solid lines). The abscissa is again the system III longitude of Galileo (same as in Figure 5). Let us first consider the sector [A, B]. When it is extrapolated to rotation 1, this sector corresponds to the period [24:00, 26:00] during which most of the dispersionless injections and the strong magnetic fluctuations have been observed (period 1 defined in section 3.1). Taking into account a drift of 15° per rotation, this sector is also the one where the most intense fluxes are observed during both rotations 2 and 3. These high fluxes are thus closely related to the injections occurring during period 1. A possible explanation would be that the shortscale injections have progressively mixed and finally determine a longitudinal sector of broad extension where the flux of energetic particle is particularly high. Concerning line C, its extrapolation to rotation 1 corresponds to the weakly dispersed clustered injections observed around 28:00 (period 2, defined in section 3.2). During rotation 2, it again correlates with a local maximum of the electron count rates.

The n-KOM sources, the clustered injections observed during the event (rotation 1), and the large electron fluxes observed after the event (during rotations 2 and 3) are thus related. The n-KOM sources indeed correspond to longitudinal sectors characterized by a large phase space density of the energetic electrons and presenting a drift of 15° per rotation. These local maxima in the phase space density are well organized in system III longitude and persist over a few rotations (at least, we directly observe them from rotation 1 to 3). They are directly related to the clustered injections that have occurred during the magnetospheric event (defined as periods 1 and 2) and then, to the active sectors of longitude where the large-scale disturbance corresponding to the magnetospheric event has first developed.

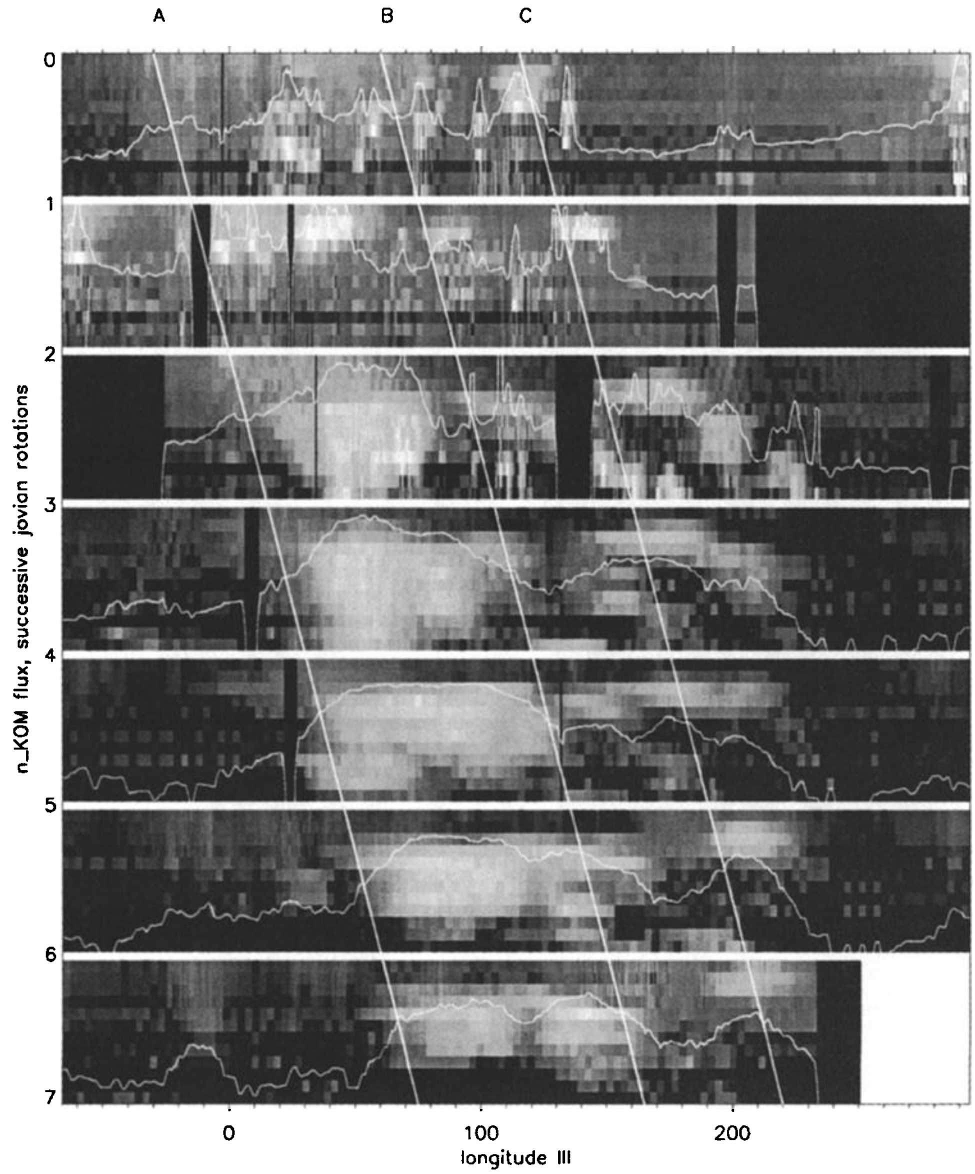

Figure 5. Wave dynamic spectra in the n-KOM range for seven successive rotations. The corresponding integrated wave field is also plotted. The oblique lines A, B, and C correspond to a 15° per rotation drift.

Two other interesting points must be noted. First, there is not a one-to-one relation between injections and sources of n-KOM. For example, the strong injection observed at 33:00, which is associated to a local wave intensification (Figure 4), does not give rise to a persistent n-KOM source. A more detailed study would then be needed to understand why injections of apparently similar characteristics may or may not give rise to n-KOM. Second, the shift in longitude taken into account here (15°per rotation) is larger than the one estimated from the bounce-averaged drift velocity in a dipolar field. From the formula already given, we indeed get a drift of 11° at 10 R_j (B=400 nT). More precise estimates of the drift using a distorted magnetic field model [see *Mauk et al.*, 1999] lead to 8° at 10 R_j and 11° at 12 R_j (for 400 KeV electrons). The difference with the observed values can be linked to the corotation lag. It would thus be of the order of 4°-7° per rotation at 10 R_j.

5. Analysis of the Energy Dissipation

As already mentioned, the radio observations suggest that the magnetospheric event corresponds to a phase of strong energy dissipation in the magnetosphere. We note that the flux is more than 1 order magnitude larger during the event than before and that it remains relatively large (a factor of 4 larger) for a few tens of hours after. An estimate of the average flux of the Jovian auroral radio emission is 10^9 W (this number depends on the assumed directivity of the emission [see *Carr et al.*, 1983]). From this estimate, we would thus obtain emitted power of the order of 10^{10} W during the event and 4x 10^9 W after the event. Would it be possible to get any direct evidence for an associated energy dissipation in the internal magnetosphere?

In Figure 7, we analyze the evolution of the energetic particle content of the inner magnetosphere as a function of

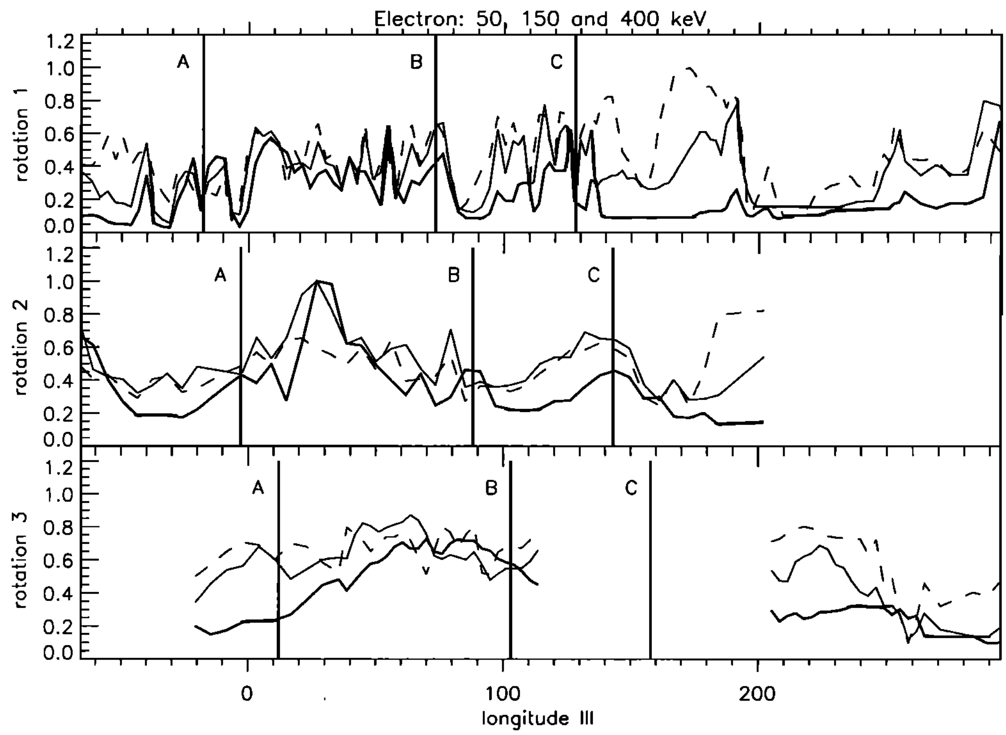

Figure 6. Normalized electron fluxes at 42-55 (dashed line), 93-188 (thin line), and 304-527 (thick line) keV as functions of the longitude III. The observations made during three successive Jovian rotations are presented.

distance. We average the count rates for the different energy channels and species over successive Jovian rotations. Five successive rotations are taken into account (referenced as –2, -1, 0, 1, and 2). The rotation 0 is centered on perijove. The corresponding average count rate is presented in the left part of each plot (referenced as "rot. 0" on the abscissa axis). Then, the average count rates for rotations –1 and 1 (middle part of each plot, referenced as "rot. –1, 1") and for rotations –2 and 2 (right part of each plot, referenced as "rot. –2, 2") are displayed. The dashed lines correspond to rotations –1 and –2. The event occurs during rotation –1. We use a linear scale that varies from one channel to the other (the dynamic range is indicated in ordinates). From this figure, it is possible to compare measurements performed at comparable distances from Jupiter (10, 12, and 15 R_J). Since the local time asymmetry is small at close distances from Jupiter [see *Armstrong et al.*, 1981], it is then pertinent to directly compare fluxes calculated before the closest approach (in the morning and noon MLT sector) and after it (in the midnight sector). One difficulty of this analysis comes from the rather long data gap that occurs during rotation 1. One third of this rotation is not sampled, and we will thus only focus on the most important evolutions seen between rotations –1 and 1.

The effects of the energization are particularly clear when one considers the electrons (in the left part of the figure). For example, in the 15-93 keV range, the average count rates increase by 50% from rotation –1 to rotation 1. Above 93 keV, the increase reaches 100%. At the highest energies, the flux also significantly increases from rotation –2 to 2 (a factor of 3). Let us note here that because of possible saturation effects, the observed increases in the count rates can be underestimated. As already mentioned by *Mauk et al.* [1999], the ion evolution is more subtle (in the right part of the figure). No significant evolution is seen in the proton channels. For sulfur, the only significant evolution appears with respect to rotation 2 since the flux roughly doubles as compared to rotation –2.

Let us now estimate the quantity of energy transferred locally to the particles. Since the event occurs during rotation –1, a part of the dissipation is already taken into account in the calculation of the corresponding fluxes. Nevertheless, the quantity of energy already transferred during rotation –1 cannot be estimated. By simply comparing rotation –1 and 1, we will then assume that over a timescale of 5 hours (the duration of the event), the density of electrons with energy above 10 keV has doubled in a volume of 3 R_j (radial extension) x 10 R_j (longitudinal extension) x 4 R_j (height). This volume corresponds to the surface explored by Galileo in the equatorial plane when it observed enhanced count rates (from 10 to 13 R_j, in a typical longitudinal sector of 60°), the height of the volume being deduced from the wobbling of the torus. To get estimates of the density of energetic electrons that contribute to the process, we use numbers found in the literature. *Scudder et al.* [1981] have estimated that, at 13 R_j, the fraction of suprathermal electrons (with temperature of 2 keV) is of the order of 8%, which correspond to a density of 1-2 cm^{-3}. *Divine and Garrett* [1983] proposed fitting the distribution function at intermediate energies (from 500 eV to 100 keV) by kappa functions. At 12 R_j, the proposed parameters (estimated from their Figures 8a, 8b, and 8c) are 500 eV (temperature), 1 cm^{-3} (density), and 2 (kappa value). More recently, still using Voyager data, *Mauk et al.* [1996] proposed a value of 0.03 cm^{-3} at 12 R_j for electrons with energies above 26 keV (population with a temperature of 300

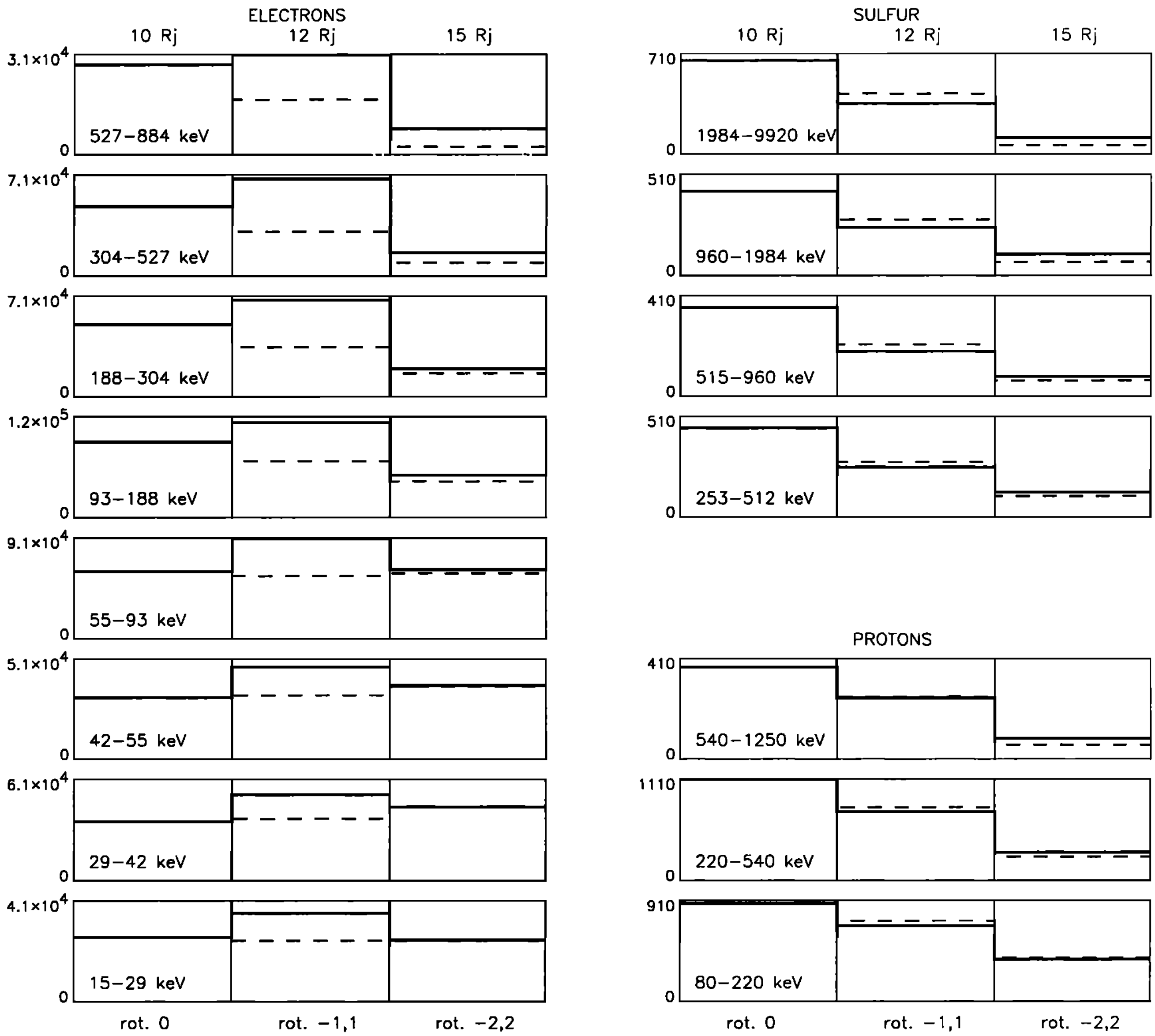

Figure 7. Averaged fluxes for the energetic electrons and ions over rotations preceding and following the magnetospheric event. Couples noted "rot −1, 1" and "rot −2, 2" depict average fluxes calculated at similar distances from Jupiter.

keV). We thus conclude that a density of 0.05 cm^{-3} for particles with energy above 10 keV is not unreasonable. Taking an average energy of 40 keV, we get an energy density of the order of 3×10^{-10} J m^{-3} and a total energy associated with the energetic electrons of 9×10^{15} J in the volume under consideration. Assuming that the number of energetic electrons has doubled during the event, the dissipated power would be 0.5×10^{12} W. From the observations reported here, this power is certainly not underestimated by orders of magnitude. These estimates are close to those concerning other types of energy transfer mechanisms in the Jovian magnetosphere [see *Hill et al.*, 1983]. For comparison, this corresponds to the full dissipation of the rotational energy of 125 kg of material in the Io torus (at 8 R_J) per second.

Let us now consider individual short-scale injections. The pertinent volume is certainly reduced since the azimuthal extension of the phenomena would now be 10° at maximum (see Plate 2). Nevertheless, since the number of particles sometimes increases by factors larger than 4, the associated energy is also of the order of a few 10^{15} J. The timescale now being 18 min, the power can reach a few times 10^{12} W. This can be compared to the energy associated with the magnetic fluctuations. They reach an amplitude of 8 nT. The energy density for these fluctuations is of the order of 7×10^{-9} J m^{-3}. Assuming that they are Alfvén waves, their Poynting flux would be of the order of 10^{-4} W m^{-2} (taking an Alfvén speed of 1000 km/s). Integrated over a surface of 2 R_J (longitudinal extension of a 10° sector) x 3 R_J (radial extension), one gets 3.10^{12} W. These estimates suggest that the magnetic fluctuations are certainly not negligible in the energization process. Both their associated Poynting flux (assuming that they are Alfvén waves) and their intrinsic energy are of the order of reasonable estimates of the power and the total energy associated with the observed particle energization.

6. Discussion and conclusion

6.1. Towards a Spatial-Temporal Model of the Magnetospheric Event

Let us first discuss some of the implications of the observations reported in sections 2, 3, and 4. One of the crucial points appears to be the interpretation of the 18 min oscillations. This oscillation is indeed related to both remote sensing (radio waves) and in situ observations (magnetic field and particle count rates). As discussed now, the combination of the two types of measurements can help to solve some ambiguities on the spatial-temporal character of the phenomena. Is it purely temporal or does it result from the motion of a spatially organized region?

We already note that the weakly dispersed injections (as those observed around 28:00) are likely related to energization processes that were active a few hours before (4 hours from our estimates). These injections are not associated with a particular activity at their time of observation. For example, they do not correlate with magnetic fluctuations. It is reasonable to admit that their periodicity is not a purely temporal phenomenon, but rather results from the combined effects of their longitudinal organization and the corotation. The 18 min periodicity would then correspond to a typical 10° longitudinal separation of the injections.

The application of this simple spatial model to the explanation of the radio modulations presents difficulties. Let us indeed assume that the radio oscillations are mainly due to the rotation of a spatially organized region. From the observed correspondence between the dispersionless injections and the radio fluctuations, we deduce that the same type of organization would exist in the equatorial plane (where Galileo makes the in situ measurements) and in the auroral regions (where the auroral radio emissions come from). The radio fluctuations would then be explained by the motion of auroral "bright" radio spots separated by a few degrees in longitude. Such an explanation nevertheless requires that the PWS experiment detects the spots one after the other. A longitudinal separation of 10° in the region of generation of the auroral radio emissions (at a latitude of 75°

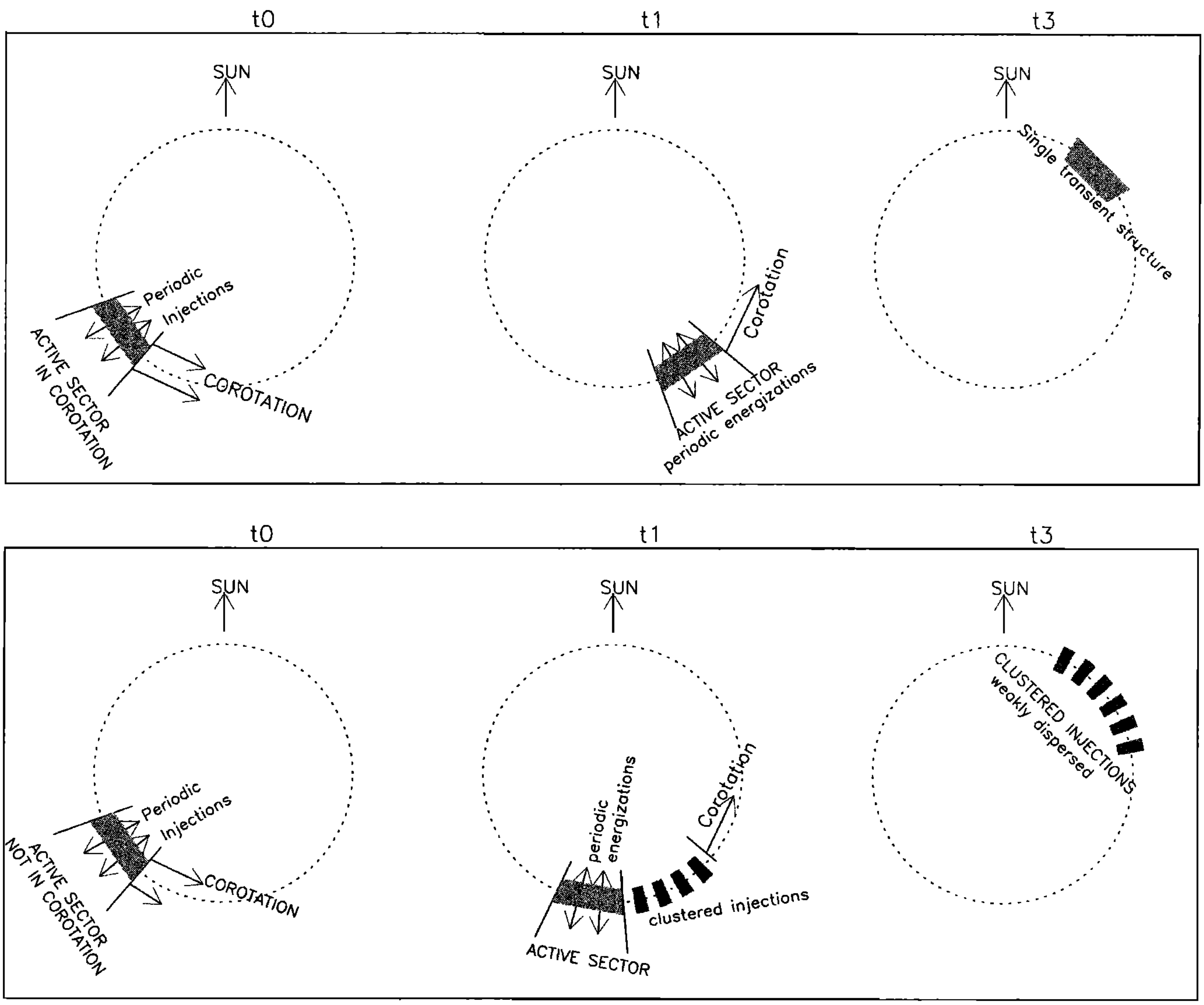

Figure 8. Possible models of the activity. The organization of the phenomena in the equatorial plane is presented for two cases: (top) case of an active zone in corotation; (bottom) active zone presenting a lag with respect to the corotation and formation of the clustered injections.

and a radial distance of 2 R_j for radiations at 5 MHz) leads to a typical separation of 5×10^3 km between spots. Seen from Galileo (at 12 R_j), the angular separation between such spots would be of the order of 2°. Even if the auroral radio emissions present a rather high directivity, the radiating diagram of a point source is certainly wider than a cone of 2° opening angle. The radio flux measured by Galileo then most probably comes from a region that covers several of these hypothetical "spots". Thus the corotation of "bright" spots alone cannot explain the observed radio fluctuations. We conclude that the radio flux modulations instead have a temporal origin. This would also be the case of the associated magnetic fluctuations and the dispersionless injections.

To reconcile the two interpretations, we propose a model sketched in Figure 8. The magnetospheric event is associated with the development of an instability in the external part of the Io torus. This leads to the generation of periodic fluctuations and defines an "active" zone of restricted longitudinal extension where the injections occur. Inside the active region, the periodic fluctuations regularly inject bunches of energetic particles. Then, as the particle dynamics is primarily organized by the corotation, each signature of the local energization processes is swept along by the corotation. Two scenarios have to be considered. If the active region corotates (as sketched in the upper panel of Figure 8), the temporal injections always take place exactly at the same system III longitude. Thus clustered injections would be observed in association with local energization processes only and would be systematically nondispersed. Once the activity stops, one expects to observe a global increase of the particle flux (a kind of long-duration injection) in the longitude sector corresponding to the active zone. As discussed before, the phenomenon is actually more complex since clustered weakly dispersed as well as dispersionless injections are observed. This may be explained by a motion of the active zone with respect to the corotation (as sketched in the bottom panel of Figure 8). Indeed, in such a case, beside the active region or once the activity stops, the phase space density presents a spatial periodicity that is the remnant of the initial temporal excitation. Weakly dispersed clustered injections may thus exist. They will persist for a while after the end of the activity. Later, as suggested before, they may mix to form a global increase of the flux in a large sector of longitude.

Using this model, one can reconstruct the spatial-temporal development of the event. From 25:00 to 26:30, in the longitudinal sector [35°, 75°], Galileo is inside an active region characterized by an 18 min oscillation. Since similar modulations in the radio flux are observed before 25:00, this region was already active before Galileo entered it. The weakly dispersed injection observed from 24:00 to 25:00 could come from this region. A quiet region with an extension of 25° is then crossed before the observation of clustered weakly dispersed injections (from 27:00 to 28:15, in the longitude sector 95°-135°). These injections are the result of an activation that has occurred a few hours before (4 hours from our estimates). The radio signature of this activation could thus be the significant radio flux increase observed from 23:00 to 24:00. The magnetospheric event itself (the whole disturbed period lasting from 22:30 to 28:00) would then correspond to the succession of two individual dissipation processes, one active before 24:00, the other still active at 26:00. Each of them creates its own system of spatially organized injections. Both processes operate in well-defined longitudinal sectors during typically 1-3 hours (as estimated from the duration of the strong auroral radio events). These sectors will later correspond to distinct sources of n-KOM. In the framework of this model, it is interesting to note that the observation of a similar periodicity for both dispersionless and weakly dispersed injections (as is observed here) would imply that the active zone is almost fixed in local time.

6.2. Summary and Comments

In conclusion, this multi-instrument analysis of a Jovian magnetospheric event leads to the following results:

1. The "C3 magnetic storm" described by *Mauk et al.* [1999] is a temporal event that precisely corresponds to an "energetic event" similar to those described by *Louarn et al.* [1998, 2000]. Then, there is a relationship among (1) strong injections of energetic particles in the external part of the Io torus, (2) sudden increase in the flux of the auroral radio emissions, and (3) creation of new sources of n-KOM radio emissions in the Io torus.

2. Two types of clustered injections are observed, dispersionless and weakly dispersed ones. Both types present a clear periodic organization (with a periodicity of the order of 18 min in the present case). Dispersionless injections are correlated with magnetic fluctuations which is not the case for the weakly dispersed injections. Strong modulations in the auroral radio flux, still with an 18 min periodicity, are also observed. This correspondence demonstrates the role of large-scale oscillations in the chain of processes that lead to the auroral particle acceleration and radio generation in the Jovian magnetosphere. It is also interesting to note that this generation of strong magnetic fluctuations during a large-scale magnetospheric disturbance is quite analogous to the generation of Pi fluctuations during terrestrial substorms.

3. The clustered injections occur in well-defined system III longitudinal sectors (active regions). Their effects persist for several Jovian rotations. They finally define longitude sectors where the density of high-energy particles is larger than elsewhere. These regions correspond to the sources of n-KOM. Thus we relate the formation of the n-KOM sources to particular magnetospheric perturbations and to increases in the density of energetic particles in specific longitude sectors. This result leads to a reconsideration of the usual explanation of the drift in longitude of the n-KOM sources. This drift is classically interpreted as an effect of the corotation lag of the plasma in the external part of the Io torus. The present observations suggest that the drift of the energetic particles also has to be taken into account. The contribution of the particle drift to the observed drift of the source (15° per rotation) is of the order of 10° per rotation. The remaining 5°per rotation can be attributed to the corotation lag (at 10 R_j). This is less than the estimates of the corotation lag found in the literature.

4. We get direct evidence of the energy release associated with the magnetospheric event. At distances ranging from 10 to 15 R_j and over longitudinal domains of a few tens of degrees, the event leads to a 100% increase in the energetic electron density (at energies larger than 10 keV) over a timescale of a few hours. The typical power associated with this phenomenon is of the order of 10^{12} W. Compared to

potential sources of power in the magnetosphere, this corresponds to the dissipation of the rotational energy of some 200 kg/s of matter in the Io torus. Considering the individual injections, we also conclude that the low frequency magnetic fluctuations (18 min period) play a significant role in the energy budget of the transient processes. This stresses the importance of the oscillations with period close to the Alfvèn transit time or to the electron bounce period in this large-scale magnetospheric disturbance.

Following the study of *Louarn et al.* [2000] suggesting that the magnetospheric events redistribute the plasma between the Io torus and more external regions of the magnetosphere, it is tempting to interpret the active region as the longitudinal sector where the matter is extracted from the Io torus and evacuated radially. Along this line, we propose that the sequence of phenomena described here characterizes the process by which a part of the rotational energy is sporadically dissipated in the Jovian magnetosphere. It corresponds to the development of an instability in the external part of the Io torus, in an active region of limited longitudinal extension. This active region probably presents a significant proper motion with respect to the corotation. On the basis of the present observations, it could even be almost fixed in local time. These observations give new insight on the activity of the Jovian magnetosphere and on the problem of radial plasma transport. One of the important unknowns remains the origin of the disturbance (purely internal or partly driven by the solar wind). The recent combined Cassini-Galileo observations of the jovian magnetosphere would certainly help to solve parts of this issue.

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