SUB–SECOND TIME SCALES IN JOVIAN RADIO EMISSIONS AS MEASURED BY CASSINI/RPWS; COMPARISON WITH GROUND–BASED OBSERVATIONS

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Abstract

In regular operation since February 2000, the RPWS experiment aboard the Cassini spacecraft was able to measure various characteristics of Jupiter's radio emissions in the frequency range from a few Hz up to 16 MHz. This observing phase culminated with the closest approach to Jupiter on December 30, 2000, at a distance of 137 Jovian radii. Among other unprecedented capabilities, the RPWS science investigation was able to make high temporal and spectral observations of incoming electromagnetic radiation by coupling the High Frequency Receiver (HFR, which is tunable from 125 kHz to 16 MHz, with a bandwidth of 25 kHz and return gain settings once per millisecond) and the Wide Band Receiver (WBR, which can analyze the given bandwidth with a spectral resolution of about 100 Hz). This special mode was regularly activated, starting on February, 2000 (when Cassini was still at 2.1 AU from Jupiter), at intervals of several days for observing sessions lasting a few minutes using several representative frequency channels free from any on board interference, and selected over a two decades frequency range (namely between 125 and 15 MHz). The achieved time resolution (down to 1 millisecond, over continuous, 2 second–long snapshots) is well above the capability of most of the previous space borne radio experiments (aboard Voyager, Ulysses, Galileo) and is comparable to measurements obtained from the ground, but so far limited to the DAM highest frequency component. As a result a wealth of fine structures were revealed or re–observed throughout the whole Jovian radio spectrum. Some typical examples are presented and compared with ground–based observations. The characteristic time scales intrinsically present in DAM radiation and other radio components are estimated from a spectral analysis of the corresponding intensity fluctuations. Very short time structures down to the millisecond, known from ground observations at DAM frequencies as the "S–burst" phenomenon, were observed at nearly all frequencies, as well as longer time scales corresponding to much slower amplitude fluctuations. The latter kind of intensity fluctuations is remarkably organized in short, coherent trains of quasi–sinusoidal waves and rapidly changing periods. The relationship between these modulations and the observing geometry is discussed, as well as their possible origin.

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1 Introduction

Multiple scales in time and frequency are a striking feature of the phenomenology of non–thermal radio emissions from the magnetized planets (for a detailed review, see Zarka [1998] and references therein). In particular, ground–based measurements of Jovian decameter (DAM) radiation (observed from 40 MHz - the maximum frequency of the observable emission -, down to about 3 MHz in some occasions allowed by exceptional transparency of the earth's ionosphere [Ellis, 1982]) exhibit quite a large variety of time structures ranging from hours to less than one millisecond, often associated to more or less curved spectral features, drifting in the time–frequency plane. However, as recognized from the earliest ground–based observations, the DAM visibility is strongly affected by scattering along the radiation paths through the interplanetary medium and the terrestrial ionosphere: associated time scales are of the order of 0.1 to 1 s and 1 to 100 s, respectively. When observing DAM from the ground, one therefore cannot easily disentangle those scintillation effects from the modulations which would be intrinsic to Jupiter radiation. On the other hand, among the space borne radio astronomy experiments having flown so far inside the Jovian magnetosphere none had a sufficient time resolution to study DAM at time scales much shorter than a few 10 s. Indeed, while the PRA instrument (aboard Voyager 1 and 2 spacecraft) could explore the DAM spectrum with a sampling time of 6 s, the PWS instrument (aboard Galileo) and the URAP radio receiver (aboard Ulysses) had sampling times of 35 and 144 s respectively. As a result, only two kinds of time structures, occurring at time scales shorter than 10 seconds in DAM, could unambiguously be identified as originating in Jupiter environment: the so called "modulation lanes" phenomenon (at time scale of a few seconds) and the "S–bursts" phenomenon (at the millisecond time scale). Their identification came from clear relationships between observed spectral properties and geometry of the observer relative to Jupiter's magnetic field and Io's orbital position. The "modulation lanes" phenomenon is now thought to be also caused by scintillation occurring in some part of the Jovian inner magnetosphere [Imai et al., 2001]. Hence a simple DAM picture has emerged in the literature – with strong theoretical implications – opposing two forms of DAM radiation at short and long time scales, respectively, as for instance in Zarka et al. [1997]: "About 10% of Jupiter's decameter radio emission is detected under the form of very short and intense bursts... called S–bursts..., by contrast with the more usual Jovian emissions which exhibit variations at the minute–to–hour time scale and have been qualified L–bursts". In this work, we have used unprecedented capabilities of the RPWS instrument aboard Cassini spacecraft to analyze DAM radiation at high time resolution (down to 1 millisecond) and distances from Jupiter between 2.1 AU and 137 Jovian radii. After a short description of the relevant instrumentation (section 2) we present a preliminary data analysis of the observations (section 3), which shows that DAM is intrinsically modulated at various sub–second time scales, from which the shortest corresponds to the known "S–burst" phenomenon. Section 4 compares ground–based results with the observations and discusses their implications.

2 New capabilities of the Cassini/RPWS instrument

2.1 The RPWS instrument

The Radio and Plasma Wave Science experiment (RPWS) aboard the Cassini spacecraft is designed to study radio emissions, plasma waves, and thermal plasma in the vicinity of Saturn [Gurnett et al., 2001b]. The radio frequency part of the instrument was heavily used during the approach and the flyby of planet Jupiter by Cassini in the year 2000. It allows the analysis of incoming electromagnetic waves over a frequency range from 3.5 kHz to 16.1 MHz by combining output from three nearly orthogonal, 10 m long monopole antennas erected from the spacecraft body. The entire spectrum is analyzed by using four distinct band pass filters, namely of width 3.5–16 kHz, 16–71 kHz, 71–319 kHz and 50–75 kHz. The last filter can be tuned or swept by steps of 25 kHz everywhere in the spectrum. In each band, the spectral analysis is performed in two successive stages. The analogue stage includes amplification, filtering, frequency translation (if any) and automatic gain control (AGC, over a 80 dB dynamic range). In the second stage the filtered band, simultaneously measured from a pair of antennas, is further analyzed by a digital processor which computes auto– and cross–correlations of both input signals over a selectable number of sub–frequencies (1 to 32), with an additional dynamic range of about 40 dB. The time resolution of each fixed frequency band can be chosen between 0.125 and 1 s, while the tuneable band has a selectable resolution from 10 to 80 ms. The effective time resolution of one spectrum scan is defined by the chosen time resolutions and by the number of explored frequencies, mainly limited by the available data output bandwidth. This very flexible scheme allows one to adapt the analysis to various observing situations, going from low bit rate survey up to high speed reconstruction of direction of arrival and full polarization of incoming waves.

2.2 The ”millisecond mode”

To achieve an even faster time resolution, the data used in this work were obtained in a special configuration of the RPWS instrument, the so–called ”millisecond mode”. In this mode, the digital analysis is suppressed and the output of the tunable 25 kHz bandwidth filter is digitized and directly output to the telemetry, with a maximum time resolution of 1 ms per sample. In addition, the AGCed, analogue output of the 25 kHz bandwidth filter is down converted to 50 kHz and redirected to the input of an other RPWS sub–system, the Wide Band Receiver (WBR). The WBR is designed to perform waveform capture over a bandwidth of about 80 kHz, with a sampling rate of 4.5 μs (222 kHz clock). While not optimal in terms of sensitivity, since only a 25 kHz band of the available 111 kHz bandwidth is occupied by the signal, the configuration allows one to improve the time resolution down to the 40 μs theoretical limit and, in case of strong signal, to get frequency resolution as narrow as 100 Hz.

Table 1: Cassini "millisecond mode" observational parameters during Jupiter flyby.

HFR frequency (kHz)	Number of observing sessions	Number of 2 s packets	Sessions with DAM activity (%)
125	876	27344	NA
1025	906	28409	33
2075	50	884	46
6025	93	1591	54
8025	947	30719	31
10025	60	970	78
15025	89	1586	29

3 Observations

This special mode was regularly activated, starting on February 2000 when Cassini was still at 2.1 AU from Jupiter, while the closest approach to Jupiter occurred on December 30, 2000, at a distance of 137 Jovian radii from Jupiter. These measurements will continue beyond Jupiter, but much less frequently, until Jovian signals disappear. To accommodate telemetry constraints, the "millisecond mode" was operated at intervals of several days, for observing sessions lasting a few minutes, using several representative frequency channels, free from any on board interference, and selected over a two decades frequency range. Each session is made of a number of HFR data packets, containing 2048 consecutive signal samples at the time resolution of one millisecond, and of the synchronized WBR waveform capture. Analyzed frequencies and relevant observation parameters are displayed in Table 1.

The achieved time resolution (down to 1 millisecond, over continuous, 2 second–long snapshots), is well above the capability of most of the previous space borne radio experiments (aboard Voyager, Ulysses, Galileo) and is comparable to measurements obtained from the ground, but so far limited to the DAM highest frequency component.

3.1 Data processing

After proper intensity calibration (in V^2/Hz at the antenna output), HFR data have been plotted as time series, each 2 second long, continuous data packets being displayed individually. In order to characterize the intensity fluctuation spectrum of these time series, the average power spectrum over each observing sessions has been computed, relative to the theoretical, white noise power spectrum within a 25 kHz bandwidth. The range of available fluctuation frequencies extends from about 0.5 Hz (i.e. 1/2.048 s.) up to 500 Hz (the Nyquist frequency for 1 ms sampling). When needed, high resolution dynamic spectra were extracted from the synchronized WBR data. Examples of both original time series and intensity fluctuation average spectra are displayed in Figure 1 and 3. Each X–axis of the time series plot represents 15 s of elapsed time, while the Y–axis logarithmically displays the intensity over a range of five decades. The fluctuation power spectra

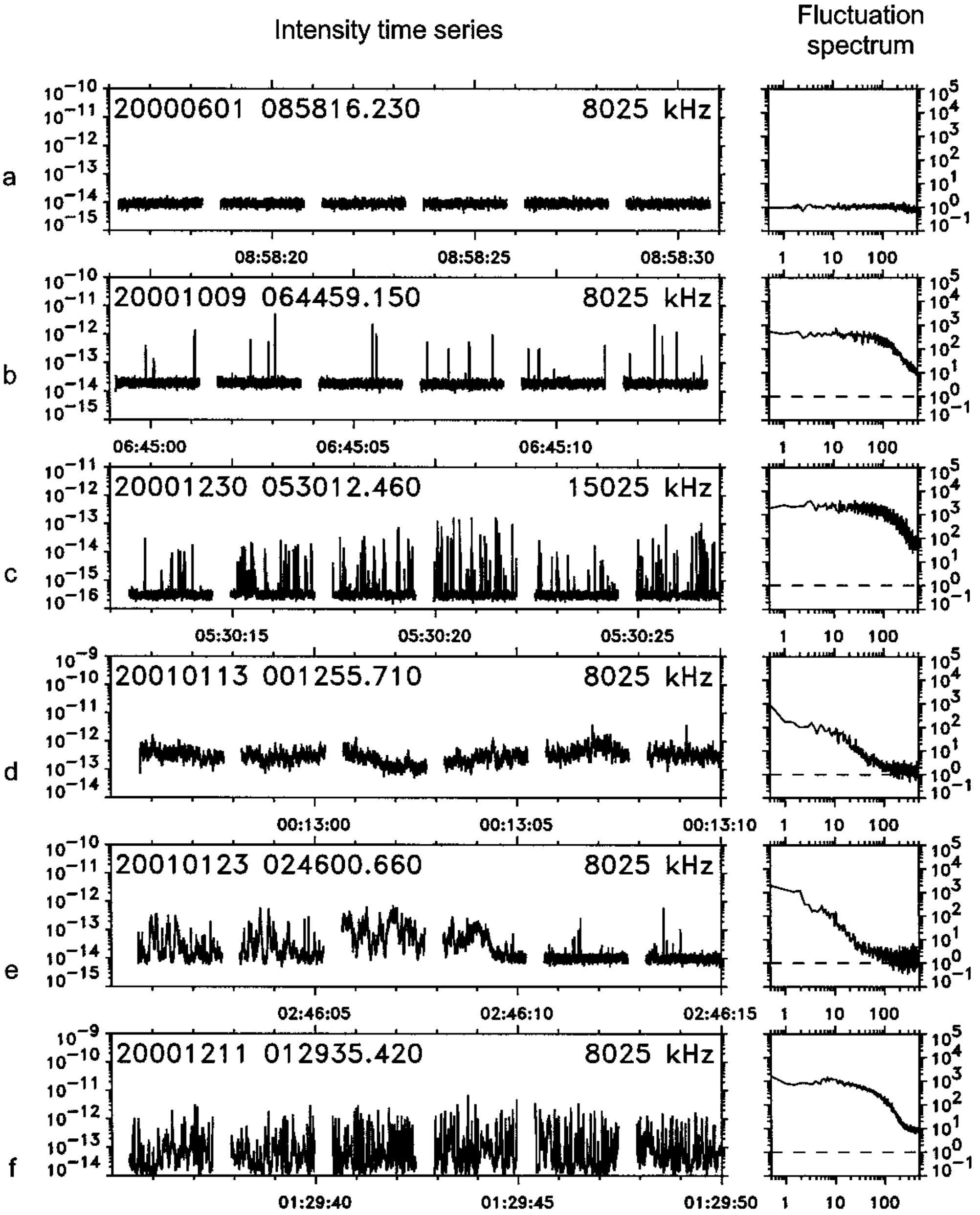

Figure 1: Examples of impulsive emissions. The left panels display time series recorded over 15 s, by packets of 2.048 s. The amplitude has a logarithmic scale over five decades. The right panels display power spectra of intensity fluctuations, computed over the corresponding time series, in the frequency range from 0.5 to 500 Hz. The fluctuation power is normalized to white noise power within a 25 kHz bandwidth.

have also a fixed amplitude range of 50 dB with respect to the white noise power level over 25 kHz.

3.2 Results

During the whole approach and flyby of Jupiter, the Jovian radio emissions could be detected in a large proportion of the "millisecond mode" RPWS data (at least one third), as figured in the last column of Table 1 (by assuming a conservative 3 dB detection over the sky background). As expected, this proportion was regularly increasing, as well as the signal level, as the Cassini distance from Jupiter decreased. However, the observed phenomenology did not show any obvious change, indicating that most of the observed features are intrinsic to DAM and not due to interplanetary scattering. Figures 1 and 3 summarize the typical kinds of DAM activity, recorded when Cassini was within about 500 Jovian radii (or 0.25 AU) from Jupiter. Figure 1-a displays the case of no emission and shows that the selected frequency channels were really free from any on board interference.

3.2.1 Burst time profiles:

Figures 1-b and c are two examples of impulsive emissions, made of very short, intense, isolated bursts radiated above a quiet (sky) background. The bursts occurrence can vary from a few events up to several tens per second. The corresponding fluctuation energy extends well beyond 100 Hz. The apparent low pass cut off at about 200 Hz is due to the minimum duration of the individual short bursts, which last a few milliseconds and, as demonstrated below, correspond to standard, drifting "S–bursts". In Figures 1-d and e, the background is no longer zero and the emission appears as an intense continuum, which fluctuates within the 1 to 10 Hz range. Case in Figure 1-e, with the fastest variations, also displays some S–bursts superimposed to the varying continuum. Figure 1-f exhibits an extreme case of very fast occurrence of those bursts, where they occur so densely that the signal level does not return to zero and can stay well above the sky background level for a while. Figure 2 displays a few examples of such fast bursts analyzed with the WBR in the 25 kHz bandwidth centered at 8025 kHz. The frequency resolution is 1.74 kHz and the time resolution 0.58 ms. The bursts exhibit a characteristic drift in the time–frequency plane, with a negative slope of -5 MHz/s. The instantaneous bandwidth and duration are smaller than 3 kHz and 2 ms, respectively. This demonstrates that they actually are "classical" S–bursts. The short burst activity was frequently found at all frequencies higher or equal to 2075 kHz, but was not seen at 1025 and 125 kHz.

3.2.2 Wave–like time profiles:

In Figure 3 are displayed some examples of an other kind of frequently observed modulations, occurring at all the studied frequencies, between 125 kHz and 15.025 MHz. The component of fluctuations faster than 10 Hz is very weak or absent. The intensity variations is made of more or less regular trains of smooth, wave–like oscillations, with chaotic (Figure 3-a) to quasi–periodic (Figure 3-b) behaviours. The amplitude of the observed modulation may reach or exceed 10 dB. The quasi–period of the modulation stays fixed for a few seconds, then changes progressively (Figure 3-b, middle). Figure 3-d displays an example where the modulation period had a well defined value of 2.5 Hz, stable over more

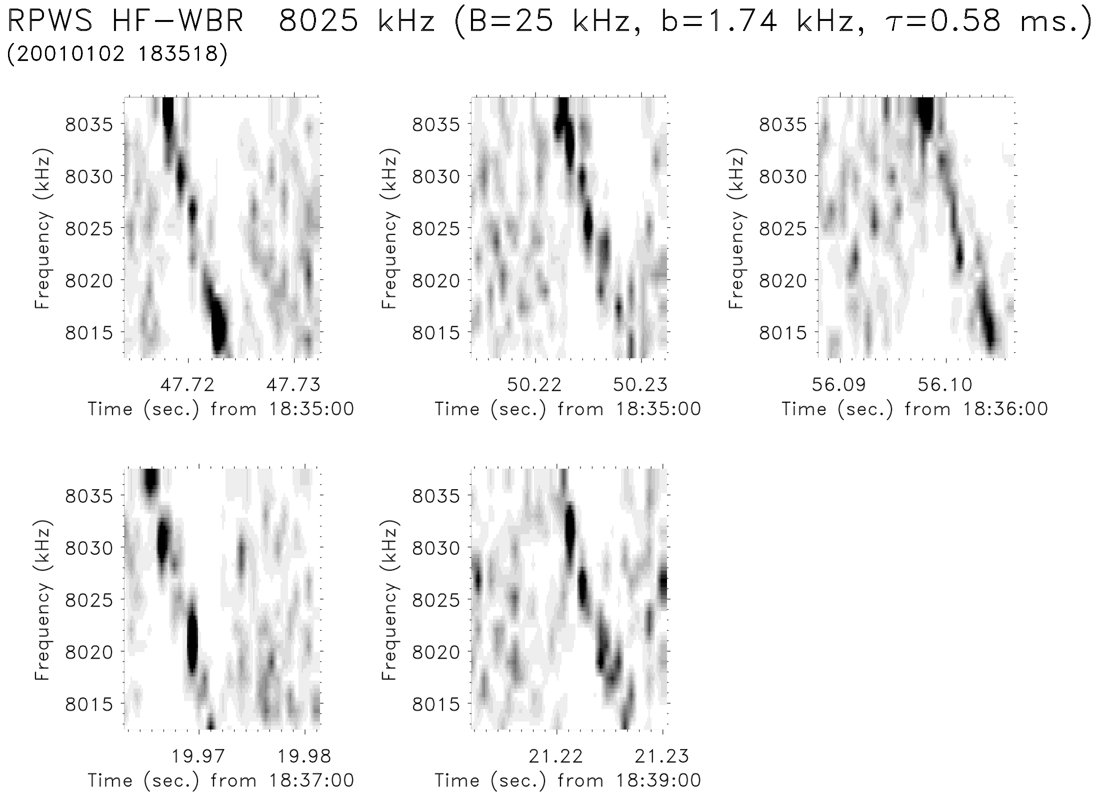

Figure 2: Examples of S–bursts analyzed in frequency with the WBR sub system. Time and frequency resolutions are 0.58 ms and 1.74 kHz respectively. The bursts exhibit a characteristic, negative drift of -5 MHz/s.

than 40 s. The observed quasi–periods may range from 1 to about 5 Hz and typically last for a few seconds. The WBR analysis does not show any frequency sub–structure within the 25 kHz frequency bandwidth.

4 Discussion

The first kind of activity (section 3.2.1) can be characterized by a large component of intensity fluctuation energy above 100 Hz. By using this criterion, the observing sessions at a given frequency were sorted in two distinct classes and plotted in function of the observing geometry with respect to Jupiter. Figure 4 shows the result for 8025 kHz: the CML–Io phase occurrence diagram, as well as the marginal occurrence histograms, are built for all the observed events (dots) and for the fast events (full circles). There is a clear dependence of bursts activity occurrence on the orbital phase of the satellite Io. The result has to be compared with Figure 3 by Alexander and Desch [1984], - who could perform a similar statistical analysis from Voyager/PRA data in the range 5 to 15 MHz -, and confirms our identification of the bursts activity, as observed by Cassini, with the Jovian S–bursts phenomenon. The narrow control of the S–bursts visibility by the apparent

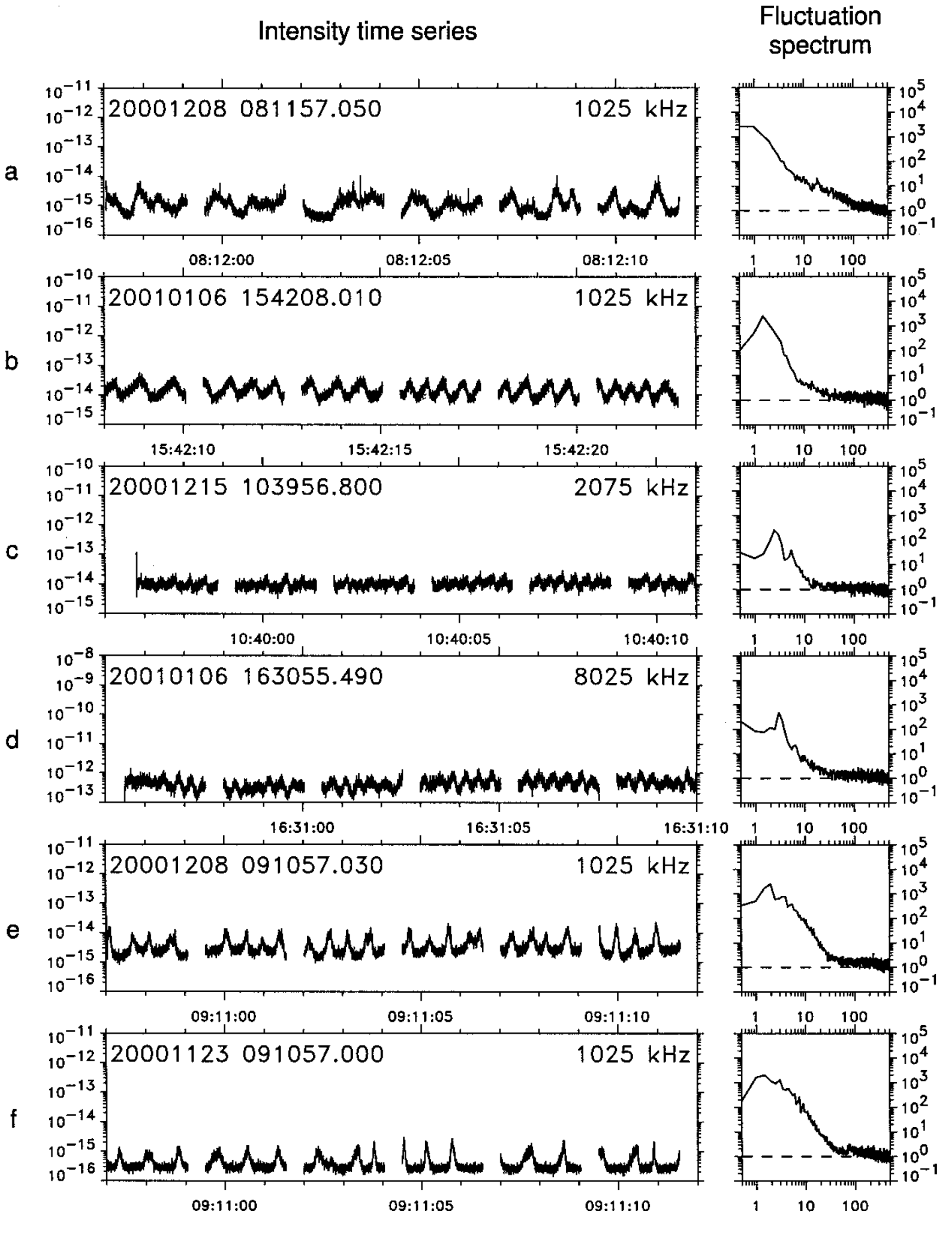

Figure 3: Same as Figure 1, but for examples of wave like intensity modulations.

position of Io leads to the following question, whose definitive answer is out of the scope of this paper: can the S–bursts phenomenon be explained as the result of the narrow angular beaming of a specific DAM radiation component (the standard hypothesis) or, alternatively, by fast scintillation of radiation through some turbulent plasma layers when DAM radiation is observed at grazing incidence on Jupiter limb ?

The second kind of activity, observed by Cassini at the sub–second time scale (section

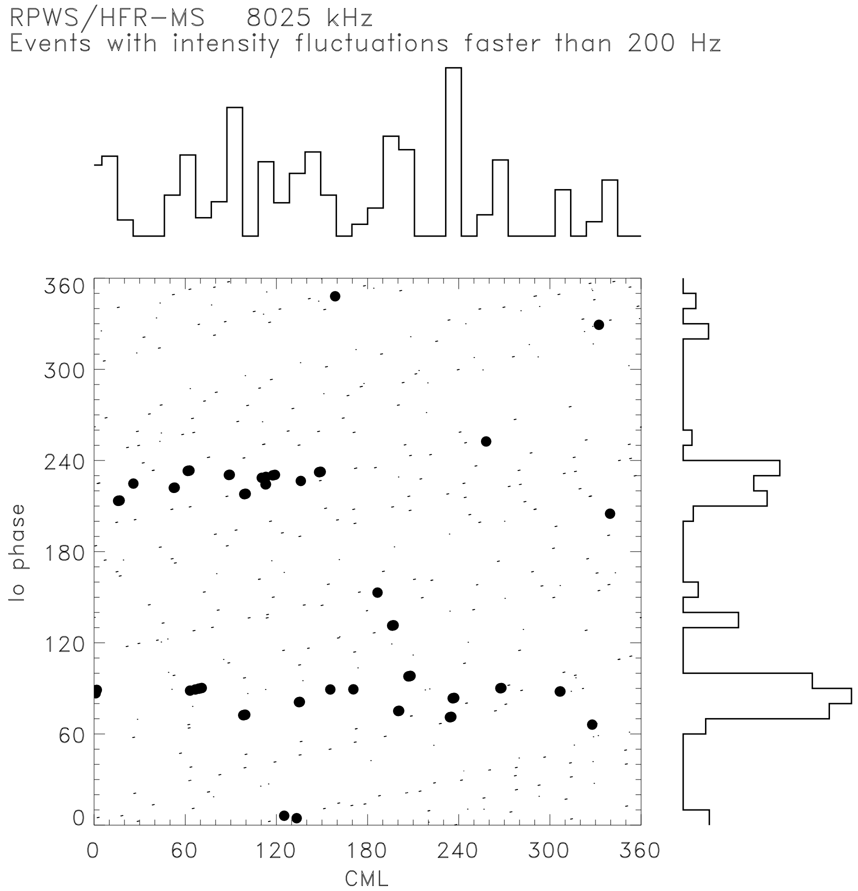

Figure 4: Occurrence of burst emissions at 8025 kHz, in function of observer CML and Io phase at the Cassini location. The marginal histograms, both in CML and Io phase are also displayed. Dots refer to observations, full circle to events of interest.

3.2.2), is more puzzling. Figure 5 displays, as in Figure 4, the CML–Io phase occurrence diagram of these events. No relationship with the observing geometry clearly appears. Instrumental causes, like linearity distortion due to input signal saturating at some stage of the electronics, cannot be totally excluded but are unlikely. Some fringe patterns - related to on board interference due to RTG grounding - were noticed during the instrument checkout in mid–1999, but at a much lower intensity level and much longer fluctuations period. However, since burst– and wave–like emissions are never observed at the same time, the latter cannot be readily explained by interference. Published ground–based observations describe the "modulation lanes" phenomenon [Imai et al., 2001], quite similar in terms of modulation amplitude and quasi–periodic character, but with time scales well above 1 s. Most likely, the wave–like modulation at the sub second time scale must also be present in high resolution ground–based observations, but are possibly obscured by interplanetary and ionospheric scintillations occurring at the same time scales. On the other hand, our Cassini observations might correspond to "Striated Spectral Activity" events, as reported by Thieman et al. [1988] from Voyager PRA data. This kind of activity (see for example the Figure 1-a from Thieman et al. [1988]) appeared as quasi–

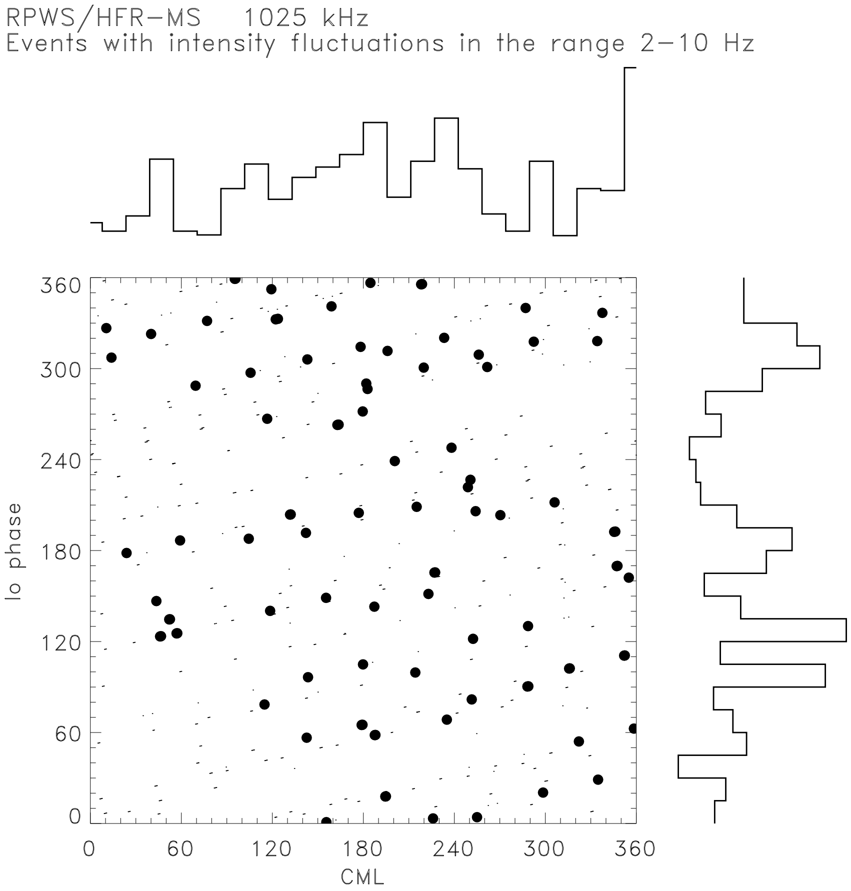

Figure 5: Same as Figure 4, but for wave–like modulations at 1025 kHz.

periodic structures in frequency and time, more or less under–sampled by the PRA swept frequency analysis, leading to "banded" and "chaotic" classes of SSA events. The latter class might correspond to our observations. What is the origin of the Jovian, wave–like modulated activity, as observed by Cassini at the sub–second time scale? An explanation in terms of maser cyclotron amplification mechanism is hard to find. More appealing would be to invoke pulsation of bunches of electrons in underlying acceleration processes of auroral particles. Alternatively, the solution might be found, once more, by taking into account expected strong scattering effects in or near the Jovian, small size, coherent radio source.

5 Summary

Thanks to its new unprecedented spectral analysis capabilities the Cassini/RPWS radio astronomy instrument could demonstrate that the Jovian DAM radiation is intrinsically highly time structured at the sub–second time scale. With respect to the previous data obtained from the ground, these observations, done at several representative frequency channels of 25 kHz bandwidth, ranging from 125 kHz to 15 MHz, disentangle Jovian intrinsic phenomena from various propagation effects and extend the ground–based data base, mostly obtained above about 10 MHz. In addition to the known S–bursts phenomenon, which disappears at frequencies between 1 and 2 MHz and is strongly correlated with the apparent orbital position of Io, the Cassini data reveal a wealth of fast intensity modulations, more or less organized in time. In particular, at all explored frequencies and in a noticeable proportion of the time, the Jovian signal exhibits intensity fluctuations in remarkably organized, short, coherent trains of quasi–sinusoidal waves and rapidly changing periods. The existence in Jovian DAM radiation of a quasi continuous spectrum of intrinsic fluctuations from the minute to the millisecond scales deserves a more thorough analysis and, in any case, suggests that isolated, S–bursts phenomenon, might be nothing else than one particular case of temporal DAM fluctuations.

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