Cassini RPWS Findings at Jupiter

From the Radio and Plasma Wave Science portion of Volume 1 of the *Cassini Final Mission Report*

Jupiter

Cassini flew by Jupiter on December 30, 2000, on its way to Saturn. Arriving from the pre-noon sector, closest approach occurred in the afternoon sector at 138 Jovian radii (~10^7 km) from the planet, and was followed by an exploration of the dusk flank of the Jovian magnetosphere. In spite of the large distance of the flyby, several Cassini- Magnetospheres and Plasma Science (MAPS) instruments including RPWS recorded high-quality data for about 6 months around closest approach. These observations benefited from the simultaneous presence of Galileo in orbit around Jupiter, enabling two-point measurements, and were complemented by remote observations by HST, Chandra, and ground-based radio observations (e.g., with the Nançay decameter array, France). This resulted in a very rich data set that was the basis of many publications and will be further exploited in the coming years.

The distant observations were well adapted to the study of the complex zoo of Jupiter's magnetospheric radio emissions, nicely covered by the Kronos receiver of RPWS, an example of which is given in Figure RPWS-22. An early overview is given in [Lecacheux 2001]. The intensity spectrum of all Jovian radio components was accurately measured [Zarka et al. 2004a] through calibration on the Galactic background and Nançay observations, demonstrating in particular the absence of peak at 10 MHz in the decameter spectrum. The beaming of the decametric (DAM) and hectometric (HOM) components (a widely opened hollow cone of a few degrees thickness) were measured via two point Cassini-Wind measurements [Kaiser et al. 2000] as well as frequency-longitude statistics and modelling [Imai et al. 2008, 2011a,b]. The HOM low-frequency cutoff measured by Ulysses and Cassini provided constraints of its source location, in the outer regions of the Io plasma torus [Zarka et al. 2001a].

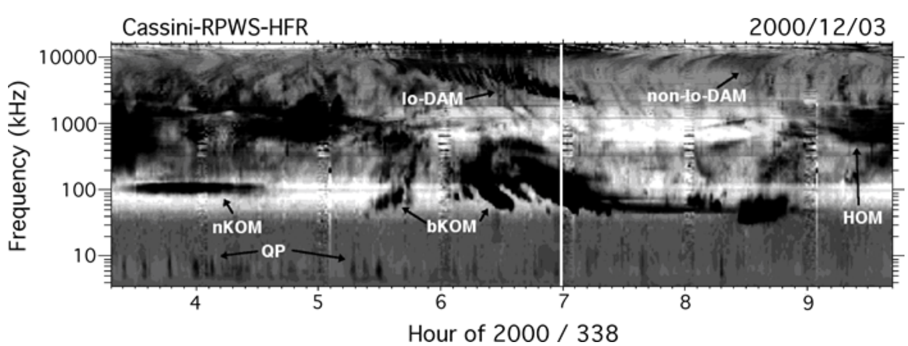

Figure RPWS-22. Jovian low-frequency radio emissions detected on December 3, 2000, by the RPWS experiment onboard Cassini approaching Jupiter. Frequency range is 3.5 kHz to 16.1 MHz. The Io-induced decameter emission (Io-DAM) appears here down to about 2 MHz, while weaker Io-independent (non-Io-DAM) arcs merge with the HOM component detected down to ~400 kHz. The auroral broadband kilometer (bKOM) component is detected down to ~40 kHz. The narrowband emission (nKOM) about 100 kHz is generated at or near the plasma frequency f_{pe} in Io's torus. The QP bursts, spaced by 5 to >15 min, are detected in the ~5 to 20 kHz range. Distance to Jupiter was 383 R_J (2.7 × 10^7 km) at the time of this observation.

The six month series of continuous homogeneous measurements provided unique measurements of time variations of the radio emission. Burst of auroral (non-Io) DAM emission were found to reoccur at a period slightly longer than the system III rotation period [Panchenko et al. 2010, 2013; Panchenko and Rucker 2011]. Gurnett et al. [2002] found from Cassini and Galileo observations that Jupiter's auroral radio and UV emissions were triggered by interplanetary shocks inducing magnetospheric compressions, in disagreement with theoretical predictions [Southwood and Kivelson 2001]. Hess et al. [2014] reconciled these views by a finer analysis of dawn and dusk radio emissions seen by Cassini, Galileo and Nançay, only dusk emissions being driven by both compressions and dilatations of the magnetosphere. They also used radio observations to deduce the subcorotation velocity of the magnetospheric plasma. Clarke et al. [2009] compared the effect of solar wind compressions on radio and UV aurora at Jupiter and Saturn, and found a weaker effect at Jupiter. Radio (non-Io-DAM, HOM, and bKOM) and UV comparisons are used quite systematically in the study of Jupiter's aurora [Clarke et al. 2004, 2005; Pryor et al. 2005]. Comparison of Galileo/Jupiter and Cassini/Saturn observations also revealed similar energetic events where auroral radio intensifications are related to centrifugal plasma ejections, from the Io torus at Jupiter and from the equatorial plasma sheet at Saturn [Louarn et al. 2007].

Cassini, Galileo, and Voyager radio observations were used to try to demonstrate the influence of satellites other than Io on DAM emissions. Marginal results were obtained statistically [Hospodarsky et al. 2001a], whereas clear evidence was obtained for Europa and Ganymede by comparison of observations with modelled dynamic spectra [Louis et al. 2017a]. The ExPRES simulation tool developed in Meudon [Hess et al. 2008] and the experienced gained with Cassini on Jupiter's radio emissions were used to build simulations preparing the re-exploration of the Jovian magnetosphere by the electrostatic energy analyzer (ESA) Juice mission [Cecconi et al. 2012].

Fast recording modes of RPWS (spectral and waveform) allowed us to characterize the fine structure of Jovian radio emissions in the kilometer (bKOM) to decameter range [Kurth et al. 2001; Lecacheux et al. 2001], including zebra-like patterns in the bKOM emission. Those were tentatively interpreted by bubble-like plasma inhomogeneities [Farrell et al. 2004] or the double plasma resonance mechanism involving ion cyclotron waves [Zlotnik et al. 2016]. Similar patterns have been observed at decameter wavelengths [Panchenko et al. 2016, 2018].

At the very low-frequency end of the radio spectrum (below a few 10s of kHz), Cassini together with Ulysses and Galileo characterized the Jovian Quasi-Periodic bursts [Kaiser et al. 2001, 2004], stereoscopic observations demonstrated their strobe-like behavior and wide beaming [Hospodarsky et al. 2004], and direction-finding techniques localized their sources at high latitude regions of the magnetopause, implying complex propagation [Hospodarsky et al. 2004; Kimura et al. 2012]. QP bursts were tentatively related to the so-called Jovian anomalous continuum radiation [Ye et al. 2012]. Propagation of radio waves near the edges of the Io plasma torus were shown to generate the HOM attenuation lane, an intensity gap oscillating between $\sim$1 and $\sim$3 MHz, described by Boudjada et al. [2011] and modelled by Menietti et al. [2003] and Imai et al. [2015]. Occultations of Jovian radio emissions were used to probe the Io plasma torus [Boudjada et al. 2014a].

Analysis of local low-frequency plasma waves recorded by RPWS was used to study the Jovian dust flank magnetopause and bow shock [Kurth et al. 2002; Szego et al. 2003], magnetosheath [Bebesi et al. 2010, 2011] and pre-shock [Szego et al. 2006]. The magnetopause was found to be in the process of being compressed by a solar wind pressure increase at the time of the Cassini flyby [Kurth et al. 2002].

Langmuir waves were detected upstream of the bow shock, and their level compared with that at other planets: the ratio of the energy density of the waves electric field to the plasma was found to increase with distance from the Sun [Hospodarsky et al. 2006].

Z-mode radiation and electron cyclotron harmonics (at low latitudes) and whistler-mode chorus (at higher latitudes) were measured [Menietti et al. 2012, 2016a] and their effect on electron acceleration was evaluated [de Soria-Santacruz et al. 2017]. RPWS spectral and waveform measurements also permitted to detect nanodust particles in the interplanetary medium, of likely Jovian origin [Meyer-Vernet et al. 2009; Schippers et al. 2014, 2015].

Observations of Jupiter radio emissions were used to calibrate the Direction-Finding (actually Gonio-Polarimetric) capability of RPWS/Kronos [Vogl et al. 2001, 2004], which proved extremely successful at Saturn. Early use of this directional capability permitted to check the origin of lightning-like signals observed in Cassini's inbound leg to Saturn, which proved to be Jovian radio bursts [Fischer et al. 2006c].

Overall, the Cassini RPWS experiment was very successful at Jupiter. The obtained results were reported in several review papers about comparisons of radio waves [Zarka 2000, 2004; Zarka and Kurth 2005; de Pater and Kurth 2007; Rucker et al. 2014] and plasma waves [Hospodarsky et al. 2012) at the magnetized planets, as well as in reviews about auroras [Badman et al. 2014], magnetospheric processes [Blanc et al. 2002; Seki et al. 2015], or dust detection [Meyer-Vernet et al. 2017]. They greatly helped to prepare the magnetospheric measurements of the Juno mission in Jovian polar orbit [Bagenal et al. 2017]. Two PhD theses were largely based on Cassini RPWS measurements at Jupiter [Cecconi 2004; Imai 2016].

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