Plasma Wave Observations at Earth, Jupiter, and Saturn

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Plasma wave emissions have been detected at all of the planets that have been visited by spacecraft equipped with plasma wave instruments. (Mercury will be explored by the plasma wave instrument on BepiColombo Mercury Magnetospheric Orbiter in 2022.) Many of these emissions are believed to play a role in the acceleration of energetic particles, especially those observed in association with the radiation belts of Earth, Jupiter, and Saturn. Wave-particle interactions involving whistler mode chorus, hiss, equatorial noise, and electron cyclotron harmonics participate in both the acceleration and loss of these radiation belt particles and play a major role in radiation belt dynamics throughout the solar system. The effects of these wave modes, their occurrence probabilities, their amplitudes, and their relationships to solar wind properties and geomagnetic storm conditions have been investigated using a variety of spacecraft observations. This paper summarizes these studies and discusses the similarities and differences of the plasma waves detected at Earth, Jupiter, and Saturn.

1. INTRODUCTION

Plasma waves play an important role in radiation belt particle dynamics at Earth [*Horne and Thorne*, 1998; *Summers et al.*, 1998, 2007; *Thorne*, 2010], Jupiter [*Horne et al.*, 2008], and possibly Saturn [*Hospodarsky et al.*, 2008; *Mauk et al.*, 2009]. Wave-particle interactions are involved in both the acceleration and loss of radiation belt particles [*Kennel and Petschek*, 1966; *Omura and Summers*, 2006; *Mauk and Fox*, 2010; *Tang and Summers*, 2012]. In the next sections, we will briefly discuss the status of the current research for some of these emissions at Earth, Jupiter, and Saturn.

Dynamics of the Earth's Radiation Belts and Inner Magnetosphere
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2. EARTH OBSERVATIONS

The first spacecraft observations of plasma waves in Earth's magnetosphere were obtained from Alouette I [*Barrington and Belrose*, 1963] and Injun III [*Gurnett and O'Brien*, 1964] in 1962. Since these early space-based observations, a number of spacecraft have provided ongoing observations of the relationships between the many plasma waves detected in Earth's inner magnetosphere and the Van Allen radiation belts. Figure 1 is a spectrogram showing plasma waves observed on the CRRES spacecraft, including whistler mode chorus, plasmaspheric hiss, electrostatic cyclotron harmonic (ECH) emissions, and equatorial noise emission, all of which are believed to play a role in radiation belt dynamics. The importance of these wave modes and their occurrence probabilities, intensities, and relationships to solar wind properties and geomagnetic storm conditions have been investigated using a variety of spacecraft observations

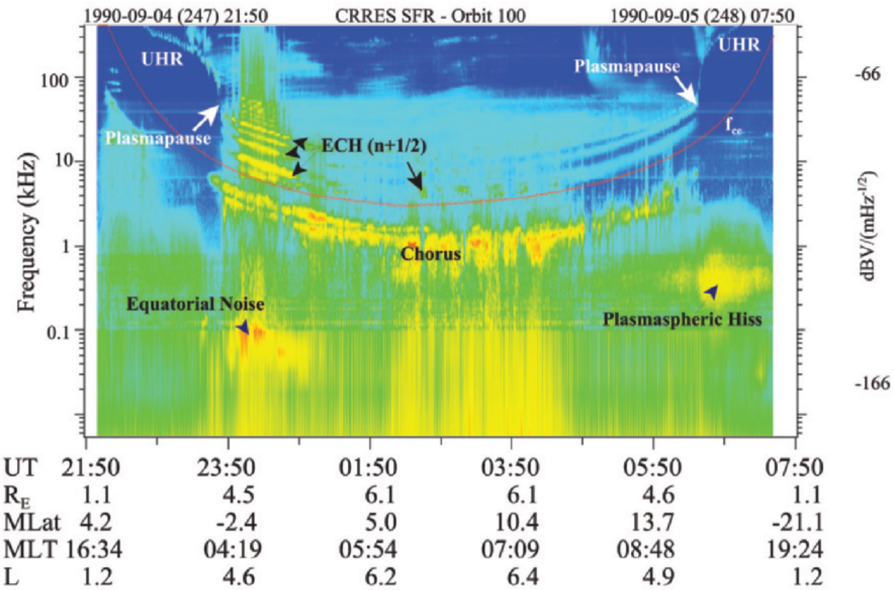

Figure 1. A spectrogram showing plasma waves that are believed to be important for radiation belt dynamics at the Earth observed on the CRRES spacecraft.

[*Meredith et al.*, 2001, 2003, 2004, 2006, 2007, 2008, 2009a; *Santolík et al.*, 2003, 2004, 2005, 2010; *Horne et al.*, 2007; *Breneman et al.*, 2009; *Sigsbee et al.*, 2010; *Li et al.*, 2011; *Bunch et al.*, 2011, 2012].

2.1. Whistler Mode Chorus Emissions

Chorus is an intense electromagnetic wave emission that propagates in the right-hand polarized whistler mode and is believed to be generated by nonlinear interactions of whistler mode waves with energetic electrons [*Storey*, 1953; *Allcock*, 1957; *Helliwell*, 1969; *Summers et al.*, 2007; *Katoh and Omura*, 2007; *Tao et al.*, 2012, and references therein]. Chorus observed in Earth's magnetosphere ranges in frequency from a few hundred Hz to a few kHz and typically occurs in two distinct frequency bands separated by a gap at one-half the electron cyclotron frequency, f_{ce} [*Tsurutani and Smith*, 1974]. The lower band starts at about 0.1 f_{ce}, and the upper band extends up to about 0.8 f_{ce} [*Meredith et al.*, 2001].

Chorus at Earth often contains a variety of structures, including rising and falling tones, and short impulsive bursts (individual whistler wave packets, commonly called chorus elements) with timescales of much less than a second [*Gurnett and O'Brien*, 1964; *Burtis and Helliwell*, 1969; *Sazhin and Hayakawa*, 1992; *LeDocq et al.*, 1998; *Lauben et al.*, 2002; *Santolík et al.*, 2003, and references therein]. The origin of these structures and their relationships to the source region of chorus is an active area of research [*Inan et al.*, 2004; *Chum et al.*, 2007; *Breneman et al.*, 2007; *Katoh and Omura*, 2011; *Omura et al.*, 2008, 2009; *Omura and Nunn*, 2011, and references therein]. Chorus is often observed during periods of disturbed magnetospheric conditions [*Tsurutani and Smith*, 1974, 1977; *Inan et al.*, 1992; *Lauben et al.*, 1998; *Sigsbee et al.*, 2008], and the occurrence of chorus is associated with energetic (10 to 100 keV), anisotropic ($T_\perp/T_\parallel > 1$) electron distributions [*Burton*, 1976; *Anderson and Maeda*, 1977; *Tsurutani et al.*, 1979; *Isenberg et al.*, 1982]. This association between energetic particles and chorus is consistent with a cyclotron resonance interaction [*Kennel and Petschek*, 1966; *Curtis*, 1978; *Sazhin and Hayakawa*, 1992].

A variety of studies have examined the propagation characteristics of chorus emissions at Earth [*Burtis and Helliwell*, 1969; *Burton and Holzer*, 1974; *Goldstein and Tsurutani*, 1984; *Hayakawa et al.*, 1984, 1990; *Nagano et al.*, 1996; *LeDocq et al.*, 1998; *Hospodarsky et al.*, 2001; *Lauben et al.*, 2002; *Santolík et al.*, 2005, 2009, 2010] and have suggested that chorus is generated very close to the magnetic equator. More recent work utilizing the Polar and the Cluster spacecraft [*Parrot et al.*, 2003; *Santolík and Gurnett*, 2003; *Santolík et al.*, 2005] have shown that the chorus source region for individual elements (measured along the magnetic field lines) is a few thousand km in size, and about 100 km transverse to the magnetic field.

The amplitudes of chorus emissions are important in understanding the possible wave-particle interactions. For example, at Earth, typical chorus amplitudes measured by

Cluster were <1 mV m^{-1}, but could reach ~30 mV m^{-1} during disturbed periods [*Santolík et al.*, 2003]. Magnetic wave amplitudes of chorus are typically a few pT to ~100 pT, with the largest fields detected by Cluster being a few nT (B_{wave}/B_o = ~0.01) (O. Santolík, personal communication, 2012). Using results from the STEREO spacecraft flybys of Earth, *Cattell et al.* [2008] reported even larger-amplitude electric field signals (240 mV m^{-1}) associated with high time resolution measurements of monochromatic whistler mode emissions in the Van Allen radiation belts. Similar large-amplitude emissions (~100 mV m^{-1}) have been reported in Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations [*Cully et al.*, 2008; *Li et al.*, 2011] and WIND observations [*Kellogg et al.*, 2010; *Wilson et al.*, 2011]. These observations suggest that strong nonlinear wave-particle processes may be more important than previously thought in accelerating electrons to populate the radiation belts [*Bortnik et al.*, 2008a; *Yoon*, 2011].

2.2. Plasmaspheric Hiss

Plasmaspheric hiss is a broadband, structureless whistler mode emission found in Earth's plasmasphere with typical wave amplitudes of ~1 to 100 pT. Hiss is believed to be responsible for generating the slot region between the inner and outer radiation belts, by removing high-energy particles from the radiation belts after geomagnetic storms [*Lyons et al.*, 1972; *Lyons and Thorne*, 1973; *Spjeldvik and Thorne*, 1975; *Albert*, 1994; *Abel and Thorne*, 1998]. The characteristics of hiss detected by the CRRES spacecraft and the relationship of hiss to electron loss timescales within the plasmasphere have been examined in a series of studies [*Meredith et al.*, 2004, 2006, 2007, 2009b]. Intense hiss observed in plasmaspheric plumes has also been shown to be important in scattering outer zone electrons [*Summers et al.*, 2007, 2008].

The exact origin of the plasmaspheric hiss has been debated for many years. Three basic theories have been proposed: (1) growth from preexisting "weak" waves from free energy of unstable electron populations [*Thorne et al.*, 1973; *Church and Thorne*, 1983], (2) accumulation of whistler waves from lightning in Earth's atmosphere [*Draganov et al.*, 1992; *Green et al.*, 2005, 2006; *Thorne et al.*, 2006; *Meredith et al.*, 2006], and (3) inward propagation of chorus into the plasmasphere from a source near the magnetic equator and outside the plasmasphere [*Church and Thorne*, 1983; *Chum and Santolík*, 2005; *Santolík et al.*, 2006; *Bortnik et al.*, 2008b, 2009a, 2009b]. Recent ray-tracing studies [*Bortnik et al.*, 2008b, 2009a] and simultaneous observations of chorus and hiss from two THEMIS spacecraft [*Bortnik et al.*, 2009b] have made a strong case for chorus producing the plasmaspheric hiss.

2.3. Equatorial Noise Emissions

Low-frequency electromagnetic emissions near Earth's geomagnetic equator were first reported by *Russell et al.* [1970], using the OGO 3 search coil magnetometer, and have been studied by more recent spacecraft [*Gurnett*, 1976; *Perraut et al.*, 1982; *Olsen et al.*, 1987; *Laakso et al.*, 1990; *Kasahara et al.*, 1992, 1994; *Boardsen et al.*, 1992; *Santolík et al.*, 2004]. The emissions propagate in the fast magnetosonic mode perpendicular to the ambient magnetic field, $\mathbf{B_o}$, and are usually observed within a few degrees of the geomagnetic equator between the local proton gyrofrequency (f_{cH}) and the lower hybrid frequency (f_{LHR}).

Gurnett [1976] used IMP 6 and Hawkeye high-resolution wideband electric and magnetic field wave data to show that the equatorial noise emissions contain a great deal of small-scale structures consisting of a complex superposition of bands with frequency spacings from a few Hz to several tens of Hz. A similar structure was reported in the data from the GEOS spacecraft [*Perraut et al.*, 1982]. These spacings were shown to be similar to the proton and ion gyrofrequencies, suggesting that the waves play a role in controlling the distribution of energetic ions through ion gyrofrequency resonances with energetic ring current protons, alpha particles, and heavy ions.

Several recent studies have examined the properties of fast magnetosonic equatorial noise using modern instrumentation and analysis methods, as well as multispacecraft data. *Santolík et al.* [2004] performed a systematic analysis of equatorial noise from 781 perigees during the first 2 years of Cluster STAFF-SA data [*Cornilleau-Wehrlin et al.*, 1997]. Equatorial noise was found to have the most intense (typically ~1 to ~100 pT) wave magnetic fields of all natural emissions between f_{cH} and f_{LHR} and to occur about 60% of the time at radial distances between 3.9 and 5 R_E. *Němec et al.* [2005] examined the Cluster data in more detail and found that the most intense peaks in the power spectra occurred within 2° of the dipole magnetic equator and that the most likely emission frequency was between 4 and 5 times the local proton cyclotron frequency. Further analysis using a geomagnetic latitude based upon the location of the minimum-B equator [*Santolík et al.*, 2002] found that the most intense peaks occurred exactly at the magnetic equator [*Němec et al.*, 2006].

Meredith et al. [2008] presented a statistical survey of fast magnetosonic waves in the frequency range $0.5\,f_{LHR} < f < f_{LHR}$ and the occurrence of proton ring distributions using wave and particle data from the CRRES satellite. Fast magnetosonic waves were observed at most local times outside the plasmapause, but waves inside the plasmapause were restricted to the dusk sector. They found that the observed locations of the low-energy (E_R < 30 keV) proton ring distributions required for instability in the CRRES data closely matched the observed locations of magnetosonic waves on the duskside, both inside and outside the plasmapause. A statistical study of ion distributions thought to drive magnetosonic waves using 15 years of geosynchronous particle data found the peak occurrence of unstable ion distributions from midmorning to dusk for low geomagnetic activity periods. For high activity periods, the peak moved toward noon [*Thomsen et al.*, 2011].

The importance of these waves in radiation belt dynamics has been investigated by a number of authors [*Horne et al.*, 2000, 2007; *Chen et al.*, 2010; *Bortnik and Thorne*, 2010]. Using quasilinear theory, *Horne et al.* [2007] found that pitch angle and energy diffusion rates for equatorial noise were comparable to those for whistler mode chorus. Because of their importance, magnetosonic waves have been newly incorporated into ring current simulations using the Rice Convection Model and ring current-atmosphere interactions model [*Chen et al.*, 2010].

2.4. Electron Cyclotron Harmonics Emissions

ECH emissions are electrostatic emissions observed in bands between harmonics of the electron gyrofrequency, f_{ce}, and are sometimes known as $(n + 1/2)f_{ce}$ emissions [*Kennel et al.*, 1970; *Fredricks and Scarf*, 1973; *Shaw and Gurnett*, 1975; *Christiansen et al.*, 1978; *Horne and Thorne*, 2000; *Meredith et al.*, 2009a; *Thorne et al.*, 2010]. *Meredith et al.* [2009a] examined the ECH waves in CRRES data and showed that their intensity and occurrence rates were similar to chorus, and suggested that ECH emissions might be important in the production of the diffuse aurora. *Thorne et al.* [2010] examined these results in more detail and determined that the chorus emissions play a much larger role than the ECH waves in the auroral precipitation at lower L shells. However, at higher L shells, the ECH emissions may still dominate [*Liang et al.*, 2011; *Ni et al.*, 2012].

2.5. Upcoming Earth Missions

The Radiation Belt Storm Probes (RBSP) mission, to be launched late summer 2012, will consist of two identical spacecraft with a comprehensive suite of field and particle instruments. RBSP promises a rich new data set for studies of wave-particle interactions in Earth's radiation belts [*Staedter*, 2006; *Reeves*, 2007; *Kessel*, this volume]. In combination with other spacecraft assets and observational campaigns of the Balloon Array for RBSP Relativistic Electron Losses [*Millan et al.*, 2011], the RBSP mission will contribute to a significant increase in our understanding of Earth's Van Allen radiation belts.

3. JUPITER OBSERVATIONS

The Jovian magnetosphere is the largest and probably the most complex in the solar system. The Voyager flybys of Jupiter provided the first opportunities to directly measure the plasma waves in the Jovian magnetosphere [*Scarf et al.*, 1979a; *Gurnett et al.*, 1979; *Gurnett and Scarf*, 1983]. Figure 2 [*Kurth and Gurnett*, 1991] is a spectrogram obtained during the Voyager 1 flyby showing many of the plasma waves detected at Jupiter, including chorus, hiss, and ECH emissions. The orbiting Galileo mission provided additional opportunities to study plasma waves in the Jovian system [*Gurnett et al.*, 1996; J. D. Menietti et al., Chorus, ECH, and z-mode emissions observed at Jupiter and Saturn and a possible electron acceleration, submitted to the *Journal of Geophysical Research*, 2012, hereinafter referred to as Menietti et al., submitted manuscript, 2012]. Although many of the same plasma waves that are observed at Earth are also detected at Jupiter, the majority of studies have concentrated on the strong whistler mode chorus emission [*Scarf et al.*, 1979b; *Thorne and Tsurutani*, 1979; *Inan et al.*, 1983; *Thorne et al.*, 1997; *Bolton et al.*, 1997; *Xiao et al.*, 2003; *Katoh et al.*, 2011]. Chorus is detected primarily near the edge of the Io torus from L shells of about 6 to about 12 and has many of the characteristics of chorus observed at Earth, including two bands of chorus separated by a gap at 0.5 f_{ce} and small-scale structures (primarily rising tones) with timescales less than 1 s [*Coroniti et al.*, 1980, 1984]. Peak amplitudes of chorus detected by Voyager were found to be about 0.26 mV m^{-1} (10 pT assuming parallel propagation) and that the chorus scattered electrons with energy of a few keV [*Coroniti et al.*, 1980, 1984].

Statistical surveys of the occurrence and strength of the Jovian chorus detected by Galileo have been performed by *Horne et al.* [2008] and *Menietti et al.* [2008a]. These studies showed that chorus typically occurred between 400 and 8 kHz with peak amplitudes ~10^{-10} V^2 m^{-2} Hz^{-1} (~0.1 mV m^{-1} and ~3 pT). The maximum power and occurrence frequency was observed a few degrees above the magnetic equator with the amplitude and frequency decreasing rapidly as the spacecraft went to higher latitudes. *Horne et al.* [2008] demonstrated that interactions between electrons and whistler mode waves in the Jovian magnetosphere cause significant acceleration of MeV electrons. The volcanoes on the moon Io provide a source of particles that are ionized and form the Io plasma torus. Outward transport of cold dense plasma and inward transport of 1 to 100 keV plasma occur due to magnetic flux interchange instabilities. This transport develops temperature anisotropies that produce whistler mode chorus. Using wave power spectral density from the Galileo measurements, *Horne et al.* [2008] calculated

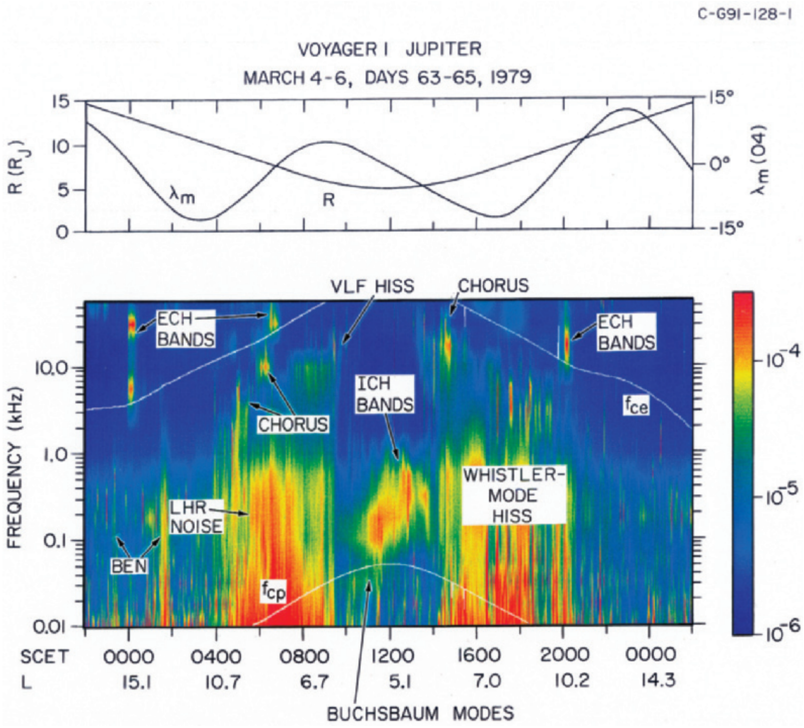

Figure 2. A spectrogram obtained during the Voyager 1 flyby showing many of the plasma waves detected at Jupiter. From *Kurth and Gurnett* [1991].

quasilinear pitch angle and energy diffusion coefficients and solved a 2-D diffusion equation over the region of 5 to 20 R_J. Fluxes of 1 to 6 MeV electrons were found to increase by more than an order of magnitude within 30 days. These electrons are then transported toward the planet via radial diffusion and accelerated to even higher (~50 MeV) energies by betatron and Fermi processes, resulting in the intense radiation belts detected close to the planet.

Tao et al. [2011] expanded on the work of *Horne et al.* [2008] using the intensity distribution of the chorus as determined by *Menietti et al.* [2008a] to examine the effect of different density models for the injection events and the effects of latitude-dependent wave normal angles for the chorus. They found that if the density inside the injection event is half that of the density outside, there is a negligible effect on the timescale of electron energization, but if the density inside the injection is one fourth of the density outside, the timescales of energization are significantly changed (1 and 3 MeV particle fluxes are decreased, 10 MeV electron fluxes is increased). The latitude-dependent wave normal angle distribution has no obvious effect on 10 MeV electron fluxes, but it reduces the fluxes of 1 and 3 MeV electrons by about a factor of 3. Thus, realistic density models of the injection events and the change of wave normal angle of chorus waves during propagation should be taken into account in future studies to more accurately model electron flux evolution of Jovian electrons.

The next mission to visit Jupiter with a plasma wave instrument is the Juno mission, scheduled to arrive at Jupiter in July 2016. Although it is primarily an auroral physics mission (polar orbit), it will likely measure chorus and other plasma waves during its trajectory at lower magnetic latitudes, providing new insight on the plasma wave properties of emissions found at the inner edge of the Jovian radiation belts. Furthermore, the recently announced European Space Agency Jupiter Icy moon Explorer (JUICE) mission will carry sophisticated field and particle instruments that will provide additional plasma wave measurements in the region of interest at Jupiter.

4. SATURN OBSERVATIONS

A variety of plasma and radio waves detected by the Voyager spacecraft during their flybys of Saturn [*Gurnett et al.*, 1981; *Scarf et al.*, 1982, 1983] included whistler mode chorus and hiss [*Scarf et al.*, 1984], and ECH and upper hybrid resonance (UHR) emissions [*Kurth et al.*, 1983]. The Cassini mission to Saturn, with its many orbits and the opportunity to sample many different regions of the magnetosphere and a more capable Radio and Plasma Wave

Science (RPWS) instrument [*Gurnett et al.*, 2004], has allowed a much more detailed study of plasma waves to be accomplished. Many of these emissions have similar characteristics to emissions detected at Earth and Jupiter, but important differences have also been reported.

4.1. Whistler Mode Chorus

The Voyager spacecraft detected only a few short periods of chorus during their flybys of Saturn due primarily to the geometry of the flybys. Also, the lack of a search coil magnetometer and the Voyager plasma wave instrument response to dust impacts on the spacecraft in the equatorial region complicates the identification of chorus and other whistler mode waves in the low-resolution, low-rate data. Unfortunately, the amount of high-resolution wideband data obtained during the flybys was greatly limited due to telemetry constraints (see the work of *Scarf et al.* [1983] for a discussion of these issues). However, a wideband frame was obtained when chorus was present during the Voyager 1 flyby [*Scarf et al.*, 1983]. This high-resolution data showed a band of chorus present below 0.5 f_{ce} (from about 0.2 to 0.4 f_{ce}). The chorus was primarily hiss-like (diffuse) with some rising structures, but the temporal variations were "unusually slow" [*Scarf et al.*, 1983]. No chorus above 0.5 f_{ce} was detected by Voyager at Saturn. *Scarf et al.* [1983, 1984] examined the possibility of wave-particle interaction and pitch angle scattering of the electrons in Saturn's inner magnetosphere from the detected chorus, but the amplitudes were too small to play a significant role. However, during the period of the Voyager flybys, the Saturnian magnetosphere was not very active, and it is possible that the chorus emission could play a more significant role during more active periods [*Kurth and Gurnett*, 1991].

The Cassini spacecraft has detected a variety of wave emissions at Saturn [*Gurnett et al.*, 2005; *Hospodarsky et al.*, 2008; *Menietti et al.*, 2008b, 2008c; *Mauk et al.*, 2009; *Kurth et al.*, 2009; Menietti et al., submitted manuscript, 2012]. Figure 3 shows typical spectrograms of the electric and magnetic field intensities of the plasma wave emissions measured by RPWS during a pass through Saturn's inner magnetosphere. The intensities are plotted as decibels (dB) above background, and the white line shows f_{ce} derived from the magnetometer instrument [*Dougherty et al.*, 2004]. During this orbit, whistler mode emission is observed both during the inbound and the outbound trajectory. Following the definition of *Hospodarsky et al.* [2008], we will call this emission chorus, although at times, the emission may appear hiss-like. Electrostatic ECH and UHR waves are also present, and the Saturn kilometric radio (SKR) emission is observed above about 20 kHz throughout most of this period. The whistler

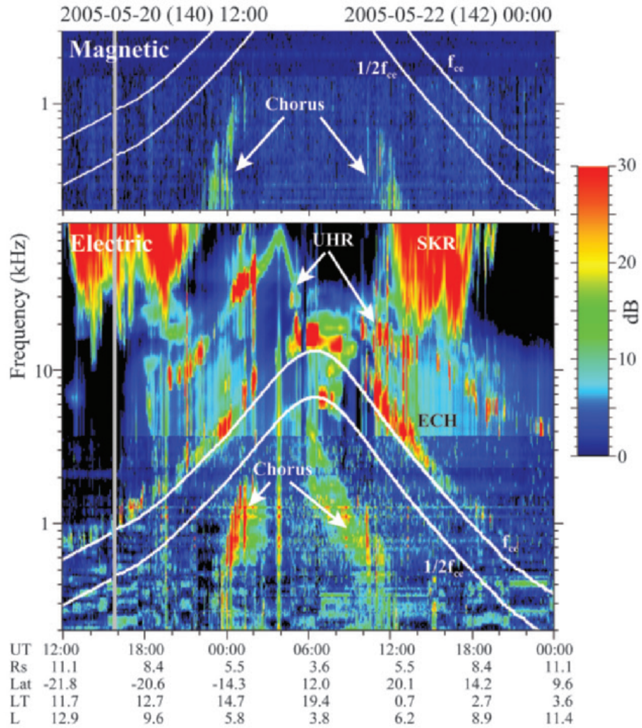

Figure 3. (top) Magnetic and (bottom) electric field frequency-time spectrograms from the Cassini Radio and Plasma Wave Science instrument. The white lines are f_{ce} and 0.5 f_{ce} determined from the magnetometer data.

mode chorus emissions shown in Figure 3 are similar to the chorus detected by the Voyager spacecraft with frequencies only below 0.5 f_{ce}. The majority of the chorus detected at Saturn has this characteristic and was called "magnetospheric" chorus by *Hospodarsky et al.* [2008]. "Magnetospheric" chorus is detected by the RPWS instrument during most orbits of Saturn when Cassini is within about 30° of the magnetic equator and between L shells of about 4 and 8.

Figure 4 shows two "magnetospheric" chorus spectrograms using the higher-resolution wideband receiver (WBR) data. A variety of small-scale structures, from hiss-like emission to rising tones, is detected but with larger timescales than observed at Earth or Jupiter (many seconds to many minutes). The emissions that have rising tones with periods on the order of 5 min (Figure 4, bottom) have been investigated in more detail (J. S. Leisner et al., manuscript in preparation, 2012). Although *Hospodarsky et al.* [2008] called the whistler mode emissions with ~5 min period rising tones "chorus," it is likely that they have a different origin than chorus at Earth. These whistler mode emissions with ~5 min periods, referred to as "rising whistler mode emission" and sometimes as "worms" (J. S. Leisner et al., manuscript in preparation) are detected about 5% of the time when Cassini is within 5.5 R_S,

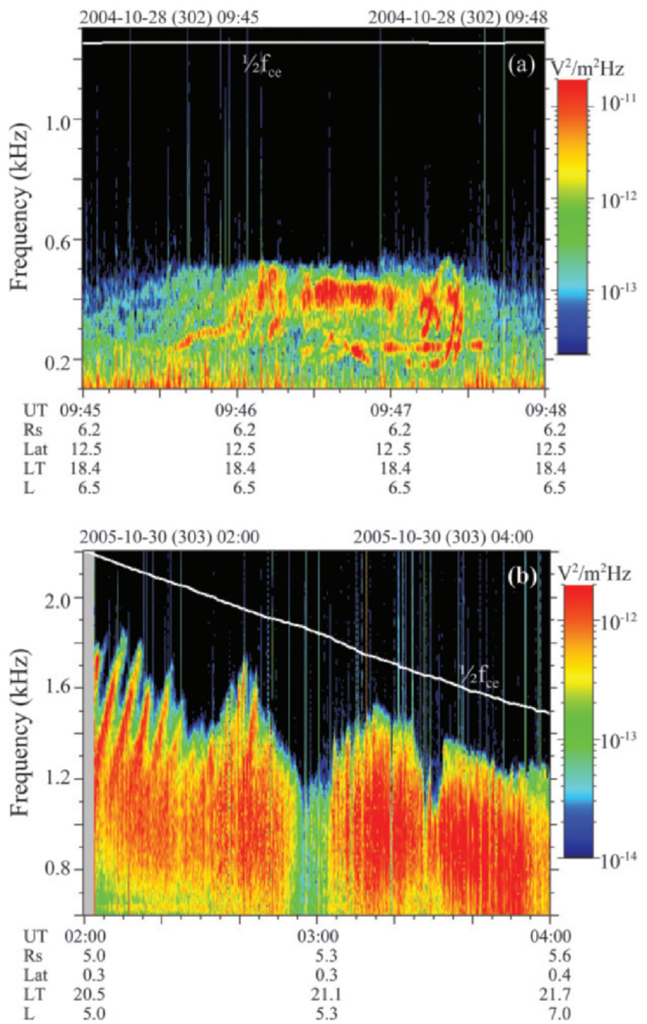

Figure 4. High-resolution wideband frequency-time spectrograms of "magnetospheric" chorus emissions measured by Cassini showing selected small-scale structure of the emissions. The white line is 0.5 f_{ce} determined from the magnetometer data. After *Hospodarsky et al.* [2008].

are observed near the magnetic equator and appear to be related to electrons with energies of a few keV, though what causes the 5 min periodicity is still not well understood. Although quasiperiodic emissions with similar spectral structure to the "worms" have been detected at low L shells and high latitudes at Earth [*Sato and Fukunishi*, 1981; *Pasmanik et al.*, 2004], it is unlikely they are generated by the same source mechanism due to the difference in where they are detected (high latitudes at Earth, near the equator at Saturn).

Chorus is also detected at Saturn in association with local plasma injections (defined as "injection event" chorus by *Hospodarsky et al.* [2008]). Injection events are planetward injections of hot, tenuous plasma produced by the interchange instability as the colder, denser plasma from the inner magnetosphere flows outward in magnetospheres of rapidly rotating planets such as Saturn [*Mitchell et al.*, 2009b; *Mauk et al.*, 2009, and references therein]. Figure 5 shows two high-resolution examples of "injection event" chorus. For many plasma injection events, chorus emissions are detected both above and below 0.5 f_{ce} (white line), with a gap in the emission at ~0.5 f_{ce}. This chorus is usually detected for only the few minutes Cassini is in the injection event and is not observed outside of the injection event. These "injection event" chorus observations often contain structure (usually a series of rising tones) at a much smaller timescale (less than

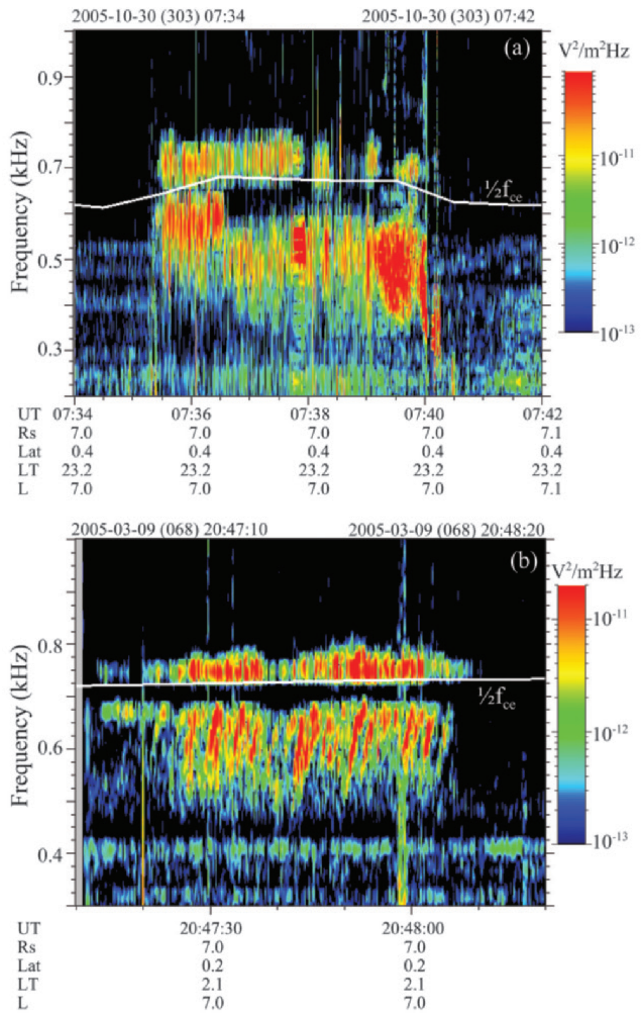

Figure 5. High-resolution wideband frequency-time spectrograms of "injection event" chorus emissions measured by Cassini showing selected small-scale structure of the emissions. The white line is 0.5 f_{ce} determined from the magnetometer data. After *Hospodarsky et al.* [2008].

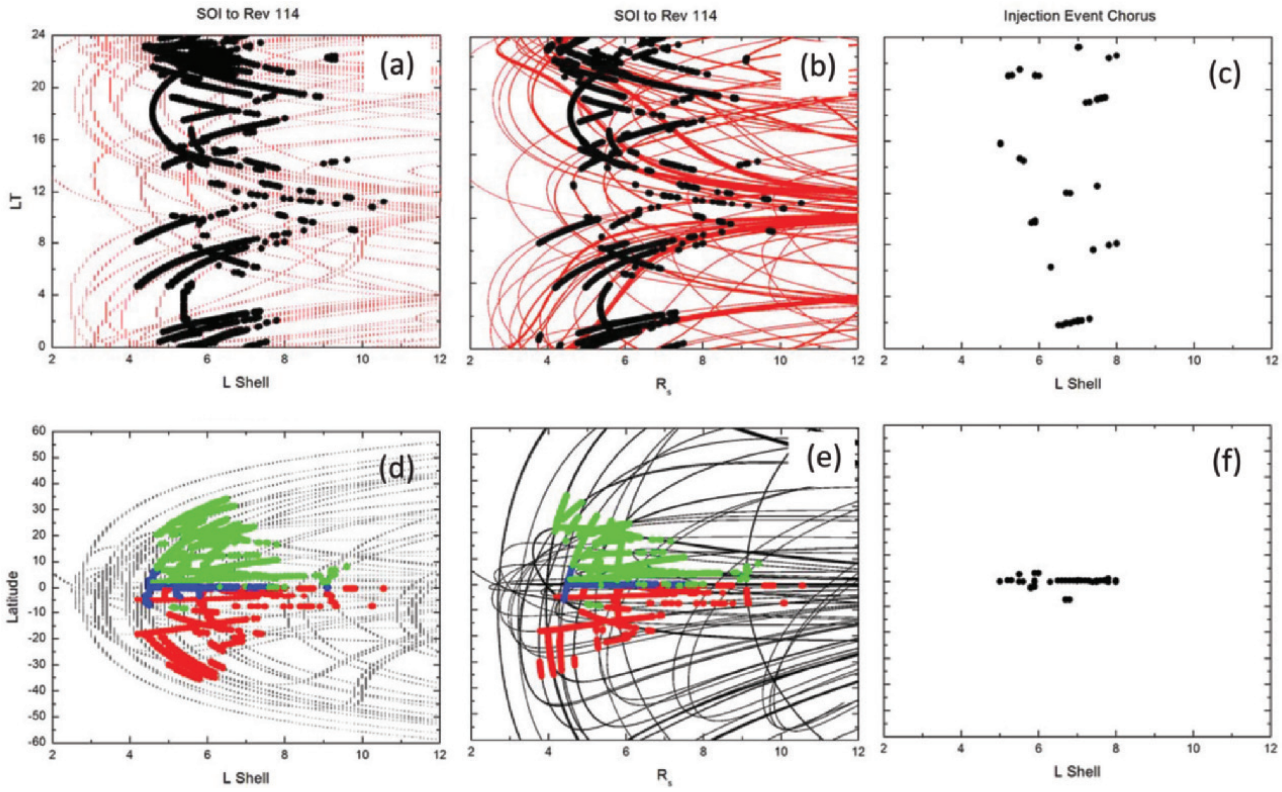

Figure 6. The position of Cassini during the periods that the (left and center) "magnetospheric" and (right) "injection event" chorus is detected. Figures 6a and 6c plot local time (LT) versus L shell and Figure 6b plots LT versus Saturn radius (R_s). Figures 6d and 6f plot magnetic latitude versus L shell, and Figure 6d plots magnetic latitude versus R_s. The propagation direction of the chorus emission detected at Saturn with respect to the magnetic field is shown by the color of the dots in Figures 6d and 6e, with green, propagating antiparallel to **B**, red, propagating parallel, and blue, a mixture of parallel and antiparallel.

a second to a few seconds) than the "magnetospheric" chorus and appear much more similar to chorus detected at Earth and Jupiter [*Hospodarsky et al.*, 2008].

Examination of the Cassini Plasma Spectrometer (CAPS) electron data [*Young et al.*, 2004] for the injection event shown in Figure 5a indicates that inside the injection, the low-energy (<100 eV) electron flux is reduced, while the high-energy component (>1 keV) is enhanced [*Rymer et al.*, 2008]. The higher-energy component forms pancake-like distributions while the lower-energy electrons are more field aligned [*Rymer et al.*, 2008, Figure 5]. *Menietti et al.* [2008c] examined this event and modeled the measured electron plasma distributions to conduct linear dispersion analysis of the plasma wave modes. They found that the higher-energy pancake-like distribution with temperature anisotropy can drive the observed whistler mode waves.

The relationships between the detection of whistler mode emission and the various orbital parameters of the Cassini spacecraft have also been examined for the first 115 orbits of Cassini (1 July 2004 to 15 July 2009). This analysis is similar to the technique *Hospodarsky et al.* [2008] used for the first 45 orbits of Cassini. Whistler mode emission is identified only when the five-channel waveform receiver detects electromagnetic waves, and valid wave normal and Poynting vector calculations can be performed (see the work of *Hospodarsky et al.* [2008] for more details on the criteria used). As discussed above, we have not tried to distinguish between hiss and chorus for these studies, so we have defined all whistler mode emissions that we detect at low-latitude "chorus." Whistler mode auroral hiss is also often detected by Cassini at higher latitudes (typically >30°) [*Mitchell et al.*, 2009a; *Kurth et al.*, 2009; *Kopf et al.*, 2010; *Gurnett et al.*, 2011]. We distinguish between the whistler mode chorus and auroral hiss by the location at which it is detected (higher latitude for auroral hiss, low latitude for chorus), the different spectral characteristics (funnel shape for auroral hiss, band of emission between about 0.1 and 0.5 f_{ce} for chorus), and the direction of propagation (auroral hiss has only been seen by

Cassini coming up from the planet propagating toward the equator, chorus propagates away from the equatorial region).

Figure 6 shows the occurrence of the Saturn "magnetospheric" chorus (solid dots) with respect to L shell versus LT (Figure 6a) and magnetic latitude (MLAT) (Figure 6d), and Saturn radius, R_s, versus LT (Figure 6b) and MLAT (Figure 6e) for Cassini's first 115 orbits (including Saturn orbit insertion). Figures 6c and 6f show the occurrence of "injection event" chorus with respect to L shell versus LT and MLAT, respectively. The dotted lines in the panels are the trajectory of Cassini during the orbits examined for chorus to show the orbital coverage for this period. As can be seen from Figure 6, both the "magnetospheric" and "injection event" chorus primarily occur between about 4 and 8 L shell (and about 4 to 8 R_s). There is no obvious correlation between the occurrence of the "magnetospheric" or "injection event" chorus and LT in this region. However, "magnetospheric" chorus that is detected at L shells above ~8 occurs primarily near local noon and near the magnetic equator.

Figures 6d, 6e, and 6f show that "magnetospheric" chorus can be detected at higher latitudes nearer the planet (inner cutoff is approximately at the Enceladus' L shell of ~4) and that "injection event" chorus is detected only near the magnetic equator. From the wave normal and Poynting vector analysis of these waves [*Hospodarsky et al.*, 2001, 2008], the propagation characteristics of the chorus at Saturn with respect to the Saturn magnetic field are also shown in Figure 6. Solid green dots on Figure 6 refer to wave propagation antiparallel to the magnetic field (northward propagation away from the magnetic equator), red refers to parallel propagation (southward propagation), and blue shows mixed propagation directions. As can be seen, the chorus at Saturn propagates away from the magnetic equator.

An initial examination of the peak wave amplitudes by *Hospodarsky et al.* [2008] of the chorus emissions at Saturn found amplitudes (~1 mV m^{-1} and 0.04 nT) much smaller than the peak amplitudes that have been reported at Earth (~30 mV m^{-1} and 1 nT), but larger by at least an order of magnitude than the amplitudes detected at Saturn by Voyager. The detection of these larger amplitudes suggests that chorus may be responsible for some pitch angle and energy diffusion at Saturn, although this needs to be investigated in more detail.

4.2. ECH Emissions

Electrostatic emissions at Saturn include the ECH waves and the UHR emission (see Figure 3). The ECH emission typically occurs at multiple harmonics of f_{ce}, specifically $(n + 1/2)f_{ce}$, where n is an integer. The UHR emissions can be used to estimate the electron plasma density since the UHR frequency, f_{UHF}, is given by $f_{pe}^2 + f_{ce}^2 = f_{uhr}^2$. By measuring the UHR frequency and obtaining f_{ce} from the magnetic field strength, the electron plasma density, n_e, can be calculated from $f_{pe} = 8980\ n_e^{1/2}$. *Persoon et al.* [2005, 2006, 2009] have developed a plasma density model for the inner magnetosphere using UHR frequency observed by the Cassini spacecraft at Saturn.

ECH emissions show very different characteristics inside and outside of injection events at Saturn. Outside of injection events, the ECH emissions are primarily found in the first harmonic band centered near 1.5 f_{ce}, with weaker, more sporadic bands at the higher harmonics [*Menietti et al.*, 2008b]. During injection events, the characteristics of the ECH emissions change drastically with an increase in intensity and harmonic structure [*Menietti et al.*, 2008c; *Tao et al.*, 2010]. This change in the ECH emission inside of an injection event can easily be seen from about 17:35:20 to about 17:40:15 UT in Figure 7 (from *Menietti et al.* [2008c]). This event is the same as shown in Figure 5a, and the change in the ECH waves occurs during the local plasma injection event observed in the CAPS data [*Rymer et al.*, 2008].

4.3. Cassini Solstice Mission

The Cassini mission has been extended through September 2017, with the extended phase named for the Saturnian summer solstice, which occurs in May 2017. Since Cassini arrived at Saturn just after the northern winter solstice, the extension will allow for the first study of a complete seasonal

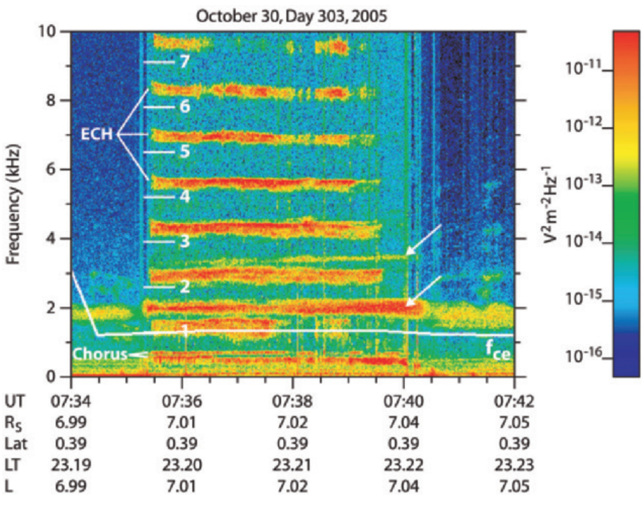

Figure 7. High-resolution wideband frequency-time spectrogram of the power spectra of the wave electric field during the injection event shown in Figure 5a. The enhanced electrostatic cyclotron harmonic wave spectra inside the injection event is easy to see starting at about 07:35:20 UT. From *Menietti et al.* [2008c].

Table 1. Summary of Wave Parameters

Emission	Earth	Jupiter	Saturn
Chorus	$0.1\ f_{ce}$ to $0.5\ f_{ce}$	$0.1\ f_{ce}$ to $0.5\ f_{ce}$	$0.1\ f_{ce}$ to $0.5\ f_{ce}$
	$0.5\ f_{ce}$ to $0.9\ f_{ce}$	$0.5\ f_{ce}$ to $0.9\ f_{ce}$	$0.5\ f_{ce}$ to $0.8\ f_{ce}$ (injections)
	~0.2 to ~5 kHz	~0.1 to 8 kHz	~0.1 to 2 kHz
	~1 pT to ~1 nT	~1 to 100 pT	~1 to 40 pT
Hiss	~100 to ~5 kHz	not distinguished from chorus	not distinguished from chorus
	~1 to ~100 pT		
Equatorial noise	$f_{cH} < f < f_{LHR}$	not observed	not observed
	~10 to ~200 Hz		
	~1 to ~100 pT		
Electrostatic cyclotron harmonic	$(n + 1/2)*f_{ce}$	$(n + 1/2)*f_{ce}$	$(n + 1/2)*f_{ce}$
	~5 to 50 kHz	~3 to 200 kHz	~1 to 20 kHz
	~1 mV m^{-1}	~0.6 mV m^{-1}	~0.3 mV m^{-1}

period of Saturn by an orbiting spacecraft. Late in 2016/early 2017, Cassini will go into a series of high-inclination, "Juno-like" orbits that cross the equatorial region between the inner edge of the rings and the upper atmosphere (altitudes of few thousand km). These orbits should provide a rich data set of fields and particles in the region of Saturn's newly discovered inner radiation belt.

5. CONCLUSION

The last few years have seen major advances in our understanding of the role of plasma waves in the dynamics of planetary radiation belts, especially of Earth's Van Allen belts. Observations at Jupiter and Saturn have added to our understanding of the interaction of plasma waves and radiation belt particles in environments that are both very similar and very different from Earth. Table 1 summarizes some of the parameters of these waves at each planet. It should be noted that the majority of studies at Jupiter and Saturn do not distinguish between whistler mode hiss and chorus. While chorus, hiss, equatorial noise, and ECH emissions all appear to play a role in radiation belt dynamics at Earth, only chorus has been examined in detail at Jupiter and Saturn. Further work is needed to determine the importance of each type of plasma wave emissions at the outer planets. The RBSP mission at Earth, the Juno and JUICE missions to Jupiter, and the continued Cassini mission at Saturn, all with advanced plasma wave and particle instruments, will continue to increase our understanding of the role of plasma waves on the dynamics and evolution of the radiation belts.

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