Radio and Plasma Wave Observations at Saturn from Cassini’s Approach and First Orbit

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We report data from the Cassini radio and plasma wave instrument during the approach and first orbit at Saturn. During the approach, radio emissions from Saturn showed that the radio rotation period is now 10 hours 45 minutes 45 ± 36 seconds, about 6 minutes longer than measured by Voyager in 1980 to 1981. In addition, many intense impulsive radio signals were detected from Saturn lightning during the approach and first orbit. Some of these have been linked to storm systems observed by the Cassini imaging instrument. Within the magnetosphere, whistler-mode auroral hiss emissions were observed near the rings, suggesting that a strong electrodynamic interaction is occurring in or near the rings.

Magnetized planets such as Saturn have many complicated radio and plasma wave phenomena. Here we present the first results from the Cassini Radio and Plasma Wave Science (RPWS) instrument (1) during the approach and first orbit around Saturn. The RPWS instrument is designed to measure the electric and magnetic fields of radio emissions and plasma waves across a broad range of frequencies, from 1 Hz to 16 MHz for electric fields and from 1 Hz to 12 kHz for magnetic fields. A Langmuir probe is also included to measure the density and temperature of the local plasma. Our observations are organized in the order in which the data were obtained, starting with radio emissions detected during the approach to Saturn, continuing through the region near the closest approach, and ending ~3 months after orbital insertion.

The Voyager 1 and 2 spacecraft first established that Saturn is an intense radio emitter. The primary component of this radiation is called Saturn kilometric radiation (SKR), because the peak intensities occur in the kilometer wavelength range (2), typically at frequencies from ~100 to 400 kHz. Just as with the other giant planets, the intensity of this radio emission is modulated by the rotation of the planet. During the Voyager flybys of Saturn in 1980 to 1981, the SKR modulation period was found to be 10 hours 39 min 24 ± 7 s (3). Because the charged particles responsible for the radio emission are controlled by the magnetic field, which is linked to the deep interior of the planet, and because the planet has no visible surface, this period has been widely adopted as the rotation period of Saturn (4). However, measurements by the Ulysses spacecraft (5) have shown that the radio rotation period is not constant.

This variability has now been confirmed by the Cassini observations. The RPWS first began to detect SKR in early April 2002, at a radial distance of ~2.5 astronomical units (AU) from Saturn. As the spacecraft approached Saturn, the signal strength gradually increased to the point that an accurate measurement of the SKR modulation period could be obtained. A normalized power spectrum of the fluctuations in the SKR intensity (Fig. 1) shows a sharp peak at a period of 10 hours 45 min 45 ± 36 s. Compared with the Voyager spectrum (Fig. 1), it
is clear that a substantial shift has occurred in the radio rotation period over the 23 years since the Voyager measurements were obtained. The reasons for this shift are poorly understood. Because the magnetic moment of Saturn is aligned almost exactly along the rotational axis (6), one possibility is that rotational wobble induced by the tilt in the magnetic axis is simply not enough to control the rotational modulation. Other second-order rotational effects (7, 8) can then become important, such as slippage of the magnetospheric plasma relative to the rotation of the upper atmosphere of Saturn, the period of which is known to vary with latitude and time (9). In sharp contrast, the radio rotation period of Jupiter, which has its magnetic axis tilted by 9.6° relative to its rotational axis, has been constant within a matter of seconds for more than 50 years. In addition to the radio rotation period, direction-finding measurement with the RPWS while viewing the southern polar regions confirmed that the SKR source is located over the southern auroral zone. This is consistent with constraints placed on the source location from the earlier Voyager measurements, which did not include a direction-finding capability.

During the Voyager 1 and 2 flybys of Saturn, numerous impulsive radio bursts, called Saturn electrostatic discharges (SEDs), were detected in the frequency range from 100 kHz to 40 MHz (10, 11). Subsequently, it was shown that these signals are produced by lightning in the atmosphere of Saturn (12, 13). Typical SED bursts had durations of ~40 ms and occurred in very regular episodes lasting several hours each, with a repetition period ranging from 10 hours 0 min to 10 hours 9 min (14). This period corresponded to the rotation period of clouds near the equator, which suggested that the lightning originated from a storm system that was being convected around the planet near the equator. A similar occurrence pattern was observed during both flybys, which were separated by ~9 months, suggesting the storm system was long-lived.

During the Cassini approach to Saturn, SED bursts were first detected on 22 July 2003 at a radial distance of 1.08 AU from Saturn. This SED episode lasted a few hours and was extremely intense, with peak intensities 10 to 30 times greater than those observed by Voyager 1, after correcting for radial distance. On the basis of observations of terrestrial lightning obtained during the Cassini flyby of Earth (15), the SEDs in this episode are estimated to be a factor of 10^6 more intense than comparable radio emissions from terrestrial lightning. Although a few weak SEDs were observed after this first episode, strong and easily identified SEDs were not observed again for nearly a year, until 13 July 2004, well after the 1 July 2004 orbit insertion. Since that time, strong SEDs have been observed on an irregular basis over a period of several months, with highly varying intensities and rates. However, none of these have intensities comparable to the very intense episode that occurred on 22 July 2003.

The number of SED bursts detected per Saturn rotation (Fig. 2) in the several-month period after orbital insertion varies considerably. Typical episodes were several hours long, with burst rates varying from a few per hour during periods of low activity to more than 100 per hour during very active periods. When active, the episodes tend to reappear every 10 to 11 hours as the planet repeatedly carries the storm system back around into view. Three different storm intervals have been identified, labeled A, B, and C (Fig. 2). Each is characterized by a distinctly different period that is thought to correspond to the atmospheric rotation period at the latitude where the storm system was located.

Previous evidence that SEDs are due to storm systems in Saturn’s atmosphere has been indirect (13). However, comparisons of the SEDs detected by the RPWS and images of Saturn obtained by the Imaging Science Subsystem have resulted in visual evidence for a link between SEDs and storm systems in Saturn’s atmosphere (16). In particular, the period and phase of the SEDs in intervals A and C match closely with distinctive cloud features seen in southern midlatitudes. The timing of the SED episodes always precedes the passage of the cloud feature across the central meridian with respect to Cassini. These observations suggest that the SED bursts are observed preferentially when the storm system is on the night side of Saturn, because the spacecraft was approximately over the dawn terminator during the system C observations. This relationship is expected, because radio signals from lightning can propagate through the ionosphere with less attenuation on the night side.

Previous studies of planetary magnetospheres, including Saturn (17, 18), have shown that a variety of plasma waves are produced in the solar wind upstream of the planet. During the Cassini approach to Saturn, the first evidence of plasma waves associated with the planet occurred on 22 March 2004, when a burst of electron plasma oscillations was observed at a radial distance of 825 Saturn radii (1 R_S = 60,268 km). This large distance was possible because the dawn-side approach trajectory of Cassini provided a favorable geometry for electrons to stream along the solar wind magnetic field from the bow shock to the spacecraft. At Saturn’s orbit, the solar wind magnetic field tends to lie in the ecliptic plane at an angle nearly perpendicular to the direction of the Sun.

Over the next few months, the electron plasma oscillations became more common and intense. Finally, at 0945 UT (Universal Time) on 28 June 2004, the spacecraft crossed the bow shock at a radial distance of 49.2 R_S. The bow shock crossing was identified in the RPWS data by an abrupt broadband burst of electrostatic noise. Subsequently, six more shock crossings were observed as the shock alternately moved back and forth over the spacecraft. These occurred at 1030, 1800, and 2000 UT on 28 June and on 0018, 0255, and 0535 UT on 29 June. The first crossing of the magnetopause
occurred at 1843 UT on 28 June, at a radial distance of 34.4 $R_S$. Numerous magneto-pause crossings were then observed as the spacecraft approached Saturn. The last and final crossing into the magnetosphere was at 0244 UT on 29 June, at a radial distance of 30.6 $R_S$. The locations of these crossings are similar to those observed in 1979 during the outbound pass of the Pioneer 11 spacecraft (19), which occurred on the morning side of Saturn at a local time similar to the Cassini inbound trajectory.

Although several types of plasma waves were observed in the outer magnetosphere, as with the Voyager flybys (17, 18), the strongest and most complex plasma wave emissions were in the inner region of the magnetosphere, inside of $\sim 10 R_S$. A frequency-time spectrogram of the electric field intensities detected by the RPWS in this region (Fig. 3) shows intense SKR from $\sim$100 to 400 kHz. Narrowband emissions at slightly lower frequencies, such as the one starting at $\sim$25 kHz at 2000 UT on 30 June, gradually drifting upward in frequency, and ending at $\sim$100 kHz at 0100 UT on 1 July, are commonly observed in planetary magnetospheres (20) and are due to an electrostatic oscillation at the upper hybrid resonance (UHR) frequency. The UHR frequency is given by $f_{\text{UHR}} = \sqrt{f_c^2 + f_p^2}$, where $f_c$ is the electron cyclotron frequency and $f_p$ is the electron plasma frequency. The electron cyclotron frequency is given by $f_c = 28 B$ Hz, where $B$ is the magnetic field strength in nT. The electron plasma frequency is given by $f_p = 8980 \sqrt{N_e}$ Hz, where $N_e$ is the electron number density in cm$^{-3}$. The termination of the strong upper hybrid band at 0100 UT occurs near the inbound crossing of the outer edge of the A ring. After the closest approach to the planet, the upper hybrid band reappears at 0405 UT at a frequency of $\sim$110 kHz, again near the outer edge of the A ring, and gradually drifts downward in frequency until it disappears at a frequency of $\sim$30 kHz at 0900 UT. Because the UHR depends on $f_c$, it is useful to compare the frequency of the upper hybrid band with $f_c$. The $f_c$ computed from the measured magnetic field strength (21) is well below the UHR frequency. This means that, except for a small correction, the upper hybrid band is essentially at the local $f_c$. A second, somewhat similar, narrowband emission can be seen at a frequency slightly above $f_c$ on both the inbound pass, from $\sim$0000 to 0100 UT, and on the outbound pass, from $\sim$0405 to 0530 UT. This type of emission is also a common feature of planetary magnetospheres (19) and is an electrostatic electron cyclotron harmonic (ECH) wave. ECH waves occur near half-integral harmonics of $f_c$, i.e., near $(n + 1/2)f_c$, where $n$ is an integer. The UHR and ECH waves are both driven by a loss-cone anisotropy in the trapped electron distribution and play an important role in the pitch-angle scattering and loss of energetic radiation-belt electrons. At even lower frequencies, after $\sim$0400 UT on 1 July, several diffuse emissions were seen at frequencies below $f_c$. These are all whistler-mode emissions, because this is the only mode that can propagate at these frequencies. Whistler-mode emissions also play an important role in the pitch-angle scattering and loss of trapped radiation-belt electrons (22).

The electric field spectrum in the region where the spacecraft is passing over the rings, from $\sim$0110 to 0409 UT, is complicated and not fully resolved (Fig. 3). The intense broadband noise, extending up to several tens of kHz from 0112 to 0248 UT, was produced by the firing of the rocket engine used to put the spacecraft into orbit around Saturn. A high-resolution frequency-time spectrogram (Fig. 4) of electric field waveforms obtained during the outbound pass over the rings from $\sim$0309 to 0348 UT shows a broad V-shaped emission centered on $\sim$0330 UT, with well-defined low- and high-frequency cutoffs that range from $\sim$1 to 8 kHz.

The V-shaped frequency-time shape of this emission is similar to a commonly occurring terrestrial whistler-mode emission called auroral hiss. At Earth, auroral hiss is known to be generated by magnetic field-aligned beams of low-energy (a few eV to several keV) electrons (23) associated with the current system responsible for the aurora. The V-shaped spectral feature arises from propagation along the whistler-mode resonance cone, which directs the radiation along a cone, the axis of which is aligned along the magnetic field. The cone angle increases with frequency, which accounts for the V-shaped frequency-time structure. If the electron plasma frequency is less than $f_c$, as is often the case in Earth’s auroral regions and is the case here, then the upper cutoff frequency of auroral hiss is at the local $f_c$ (24). Calculations using a ray path model show that the auroral hiss-like emissions detected by Cassini originate from a source close to the B ring, at a radial distance of $\sim 1.7 \pm 0.1 R_S$. The existence of such auroral hiss-like emissions near Saturn’s rings indicate that a low-energy beam of electrons is being accelerated outward away from the ring at a radial distance of

![Fig. 3. A color frequency-time spectrogram showing the electric field intensities detected by the RPWS during the Cassini pass through the inner region of the saturnian magnetosphere. The intensities are coded according to the color scale at the top of the spectrogram. The white line is the $f_c$ computed from Cassini magnetic field measurements (27). Lat., latitude; LT, local time.](image-url)
near the synchronous orbit point where the gravitational and centrifugal forces cancel. This electron beam is most likely associated with a current system induced by an electrodynamic interaction between the rings and the corotating magnetospheric plasma.

The spectrogram (Fig. 4) also shows a large number of narrowband emissions in the frequency range from ~6 to 11 kHz. Similar narrowband emissions were observed by Voyager 1 and 2 at Saturn (17, 18) and are believed to be free-space (ordinary mode) electromagnetic waves generated by mode conversion from electron plasma oscillations, most likely in regions with steep density gradients. These narrowband emissions do not seem to penetrate into the region beyond the sharp upper cutoff of the auroral hiss-like emissions. Because free-space ordinary-mode electromagnetic waves cannot propagate at frequencies below \( f_p \), this observation is consistent with the interpretation that the upper cutoff of the auroral hiss-like emission is at the local \( f_p \).

Using the plasma wave resonances and cutoffs described above, we constructed an electron density profile through the inner region of Saturn’s magnetosphere (Fig. 5). During the inbound pass, from ~2000 UT on 30 June to ~0100 UT on 1 July, and during the outbound pass from ~0405 to 0900 UT, the electron density was computed from the UHR bands (Fig. 3). The electron densities increase systematically with decreasing radial distance and reach a peak of a little more than 100 cm\(^{-3}\) near the outer edge of the A ring. Although not discernable in the spectrogram, weak UHR emissions allow the electron density to be extended into the region where the density decreases rapidly inside the outer edge of the A ring. Because of the noise from the rocket engine firing, no electron densities could be obtained from 0112 to 0147 UT. However, starting immediately after the termination of the rocket-engine firing, the electron density could be determined almost continuously from a combination of three measurements: the upper cutoff frequency of the auroral hiss-like emissions, the frequency of electron plasma oscillations, and the cutoff of the narrowband electromagnetic emissions, all of which are at \( f_p \). The resulting profile shows that the electron density reaches a deep minimum of \( \sim 3 \times 10^{-2} \) cm\(^{-3}\) at ~1.7 \( R_S \), near the center of the V-shaped auroral hiss emission. Langmuir probe measurements, which give electron densities consistent with the plasma wave measurements, show that the electron temperature over the ring plane is low, only ~0.5 to 1.0 eV.

In order to fit the ion current portion of the voltage sweep, ion masses in the range of 20 to 40 atomic mass units are required. The minimum in the electron density profile is close to the synchronous orbit point where the gravitational and centrifugal forces that act on the corotating magnetospheric plasma are in balance (25). Plasma generated inside this radius tends to be gravitationally attracted toward Saturn, whereas plasma generated outside this radius tends to be carried outward away from Saturn by interchange instabilities. Such dynamical processes may be able to account for the deep minimum in the plasma density at this point.

During the Voyager 2 ring plane crossing at Saturn, it was discovered that the plasma wave and radio astronomy instruments could detect the impact of small micrometer-sized dust particles (18, 26). When a small particle strikes the spacecraft at a velocity exceeding a few kilometers per second, the particle is instantly vaporized and heated to a high temperature (\( 10^4 \) to \( 10^5 \) K), thereby ionizing a substantial amount of the gas. As the resulting ionized gas cloud sweeps over the electric field antenna, some of the charge is collected by the antenna, thereby producing a voltage pulse into the receiver. Laboratory measurements show that the charge released, and therefore the amplitude of the voltage pulse, is proportional to the mass of the impacting particle.

During the pass through the outer regions of the saturnian system, the Cassini RPWS detected a small but nearly continuous level of dust impacts at a rate of a few impacts per minute. As the spacecraft approached the inbound ring plane crossing, the impact rate began to increase markedly ~2 min before the ring plane crossing, reached a peak at ~0046:33 UT, almost exactly at the ring plane crossing, and then decreased back to the pre-existing levels ~2 min later. Waveforms of the voltages on the \( x \)-axis electric dipole antenna (Fig. 6) near the time of peak impact rate show many very short pulses due to dust impacts. The peak impact rate at the ring plane crossing ranges from ~500 to 2000 impacts per second, depending on the counting threshold used. Similar dust impact waveforms were observed again during the outbound ring plane crossing at 0433:54 UT. The pulse amplitudes vary over a wide range (Fig. 6), from very small pulses that can just barely be detected to very large pulses that...
The voltage waveform from the x-axis electric antenna during the inbound ring plane crossing. The short pulses with durations of a fraction of 1 ms are due to dust impacts on the spacecraft body.