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Ion cyclotron waves in the Saturnian magnetosphere associated with Cassini's engine exhaust

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[1] Five hours after the orbit insertion maneuver that placed Cassini into orbit about Saturn, a long (90 minute) burst of ion cyclotron waves were seen, very different than any waves on the inbound leg of the orbit or on succeeding orbits. The ion cyclotron waves were left-hand elliptically polarized and propagating at a moderately large angle to the local magnetic field. The waves had a noticeable compressional component consistent with their off angle propagation. The frequency band of the signals was moderately broad and consistent with the singly ionized components of the engine exhaust gases: CO₂, N₂, CO, and H₂O. While H₂O waves are seen elsewhere, and associated with the E ring, these waves were stronger and propagated at a much larger angle to the magnetic field. It appears that the engine exhaust products became ionized by solar EUV and electron impact and then accelerated by the magnetospheric electric field associated with co-rotation. This acceleration produced a ring-beam in velocity space much like that produced by Io pickup ions in the jovian magnetosphere. **Citation:** Russell, C. T., J. S. Leisner, K. K. Khurana, M. K. Dougherty, X. Blanco-Cano, and J. L. Fox (2005), Ion cyclotron waves in the Saturnian magnetosphere associated with Cassini's engine exhaust, *Geophys. Res. Lett.*, 32, L14S01, doi:10.1029/2005GL022672.

1. Introduction

[2] Early on July 1, 2004 the Cassini spacecraft fired its engines as it passed Saturn just above the rings. The engine firing was completely successful and Cassini orbiter and Huygens probe settled into their nominal orbit. The magnetometer [Dougherty *et al.*, 2004] was operated for this entire period recording the planetary magnetic field, the effects of current systems within the magnetosphere, and the waves arising from instabilities within the Saturnian plasma. Some waves had been seen inbound but around closest approach to Saturn few waves above the sensitivity of the magnetometer were seen. Then about 0600 UT almost 5 hours after the engine firing, a moderately strong oscillation began in the magnetic field. This oscillation was quite unlike any seen prior to perikron (periapsis at Saturn). In many respects the waves resembled those seen near Io [e.g.,

Russell *et al.*, 2001] where heavy ions are produced from Io's sulfur dioxide atmosphere. However, here the central frequency was closer to that of singly ionized N₂ than SO₂.

[3] Waves at Io are produced when newly created ions are accelerated perpendicular to the magnetic field by the magnetospheric electric field associated with the corotation of the magnetospheric plasma which in turn is maintained by the corotating ionosphere. This acceleration makes a ring beam, a distribution of ions orbiting the magnetic field with a narrow range of perpendicular energy or velocity and with little velocity along the magnetic field. This particle distribution is unstable to the generation of left-hand, circularly polarized waves propagating along the magnetic field [Huddleston *et al.*, 1998; Blanco-Cano *et al.*, 2001]. These are known as ion cyclotron waves. The waves seen in the Saturnian magnetosphere after the engine firing have the same characteristics but Cassini was not close to any of the Saturnian moons at the time. The engine was fired from 0112:00 to 0249:54 on July 1, 2004, as the spacecraft moved from 2.27 Rs to 1.20 Rs, changing latitude from 2.6° to 16.7° and moving from 1234 to 1910 LT. The waves were seen much later from 0600 to 0745 UT. During this latter period the spacecraft was moving outward from 3.90 Rs to 5.33 Rs, changing latitude from -5.7° to -8.8°, and moving from 0112 to 0205 LT.

2. Wave Observations

[4] The Cassini magnetic field investigation carries two vector magnetometers, a vector helium magnetometer and a fluxgate magnetometer [Dougherty *et al.*, 2004]. We use the fluxgate magnetometer during this pass because the strength of the field exceeded the range of the VHM during part of the period of interest. Figure 1 shows time series of the magnetic field during the wave event. We have fit a quadratic curve to the magnetic field for each component for the entire interval and removed the background magnetic field. The background magnetic field at the beginning of the wave event was (-83, 336, 2) nT in radial, theta and azimuthal coordinates. At the end of the wave event the field was (-52, 121, 2) nT in these coordinates. Figure 2 shows a shorter interval of the wave activity so that the individual wave packets can be resolved. There appears to be a beat period consistent with the presence of two or more waves of similar period.

3. Dynamic Spectra

[5] We can demonstrate the evolution of the waves by use of a dynamic spectrum in which we display successive Fourier analyses of the records with color-coded power-

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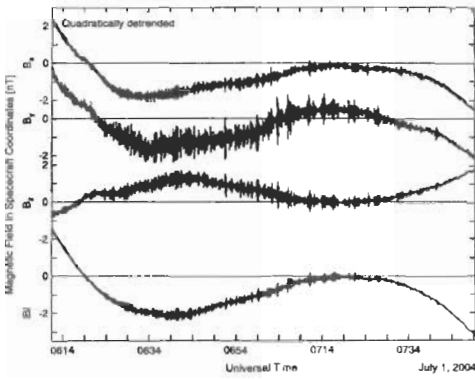


Figure 1. Magnetic field vector components and the total field with a quadratic fit removed to show the small waves seen in the larger background field.

spectral densities versus time and frequency. To emphasize the higher frequencies at the expense of the lower frequencies we take the derivative of the signals before calculating the Fourier Spectrum. We then sum the powers from the three sensors and subtract the power in the total field strength. This produces the transverse power that we expect to be largest for an ion cyclotron wave. This is shown in Figure 3 (top). Also shown are lines corresponding to the local gyrofrequency of singly ionized molecules of mass 18, 28 and 44 corresponding to water, molecular nitrogen (and carbon monoxide) and finally carbon dioxide. As can be seen these local gyrofrequencies order the wave frequencies quite well. We expect the maximum growth rate of such ring-beam instabilities to be about 90 to 95% of the gyrofrequency as calculated from the total field strength at the point of origin of the waves [Blanco-Cano et al., 2001].

[6] Figure 3 (bottom) shows the compressional power in the same format calculated from the total field strength. The compressional power is smaller than the transverse power but still significant. The waves are left-hand elliptically polarized. The compressional power and elliptical polarization are to be expected for propagation at a significant angle to the magnetic field. Studies of the direction of propagation of these waves using minimum variance analysis show that they are propagating about 30° to 50° to the magnetic field.

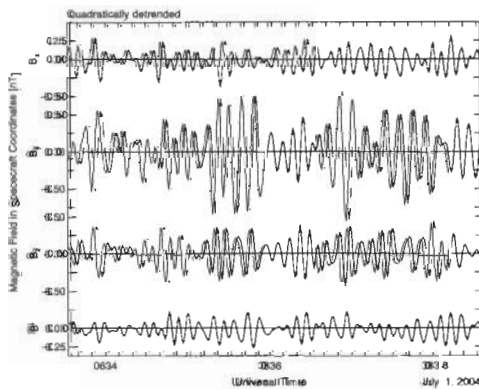


Figure 2. Magnetic field vector components and the total field with the quadratic fit removal for a short section of the wave activity shown in Figure 2 to illustrate the temporal behavior of the waves.

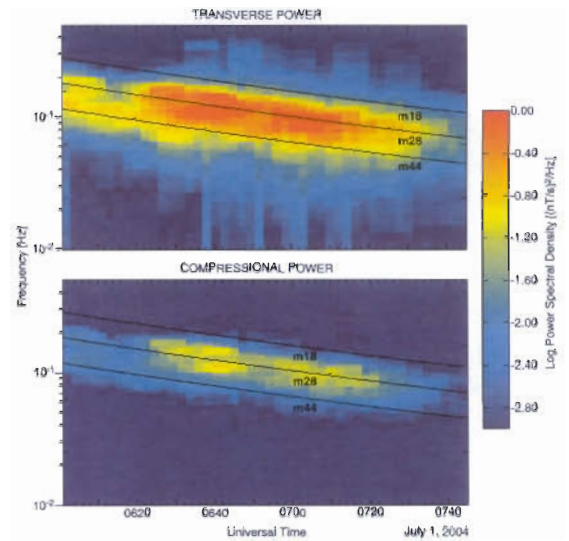


Figure 3. (top) Dynamic spectrum of the derivative of the magnetic field from 0612 to 0750 UT on July 1, 2004. Power from all three sensors has been summed and the compressional power subtracted. Lines show the local gyrofrequency of singly charged molecules of carbon dioxide, carbon monoxide or nitrogen and water. (bottom) Dynamic spectrum of compressional power in the derivative of the magnetic field.

It is possible that the source region of these waves is such that access to the spacecraft from the region of growth requires them to propagate at some large angle to the magnetic field.

4. Power Spectral Densities

[7] If we examine the magnetic field (and not its derivative), we obtain a power spectrum such as that in Figure 4 for the period 0634–0639 UT where the waves were strong (see also the time series for this period in Figure 2). Again

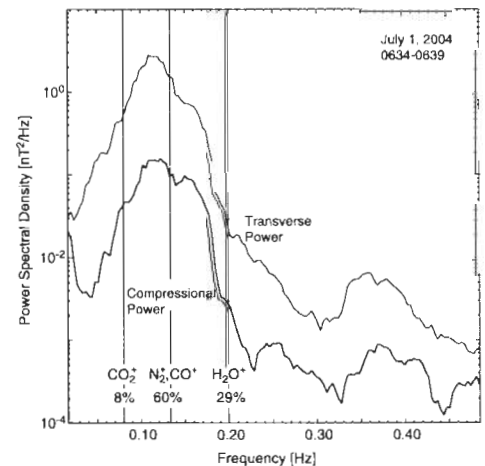


Figure 4. Power spectral density of the waves seen in Figure 2. The percentages show the relative amount of molecules of different mass in the engine exhaust. The lines show the local gyrofrequencies of the singly ionized components of these molecules.

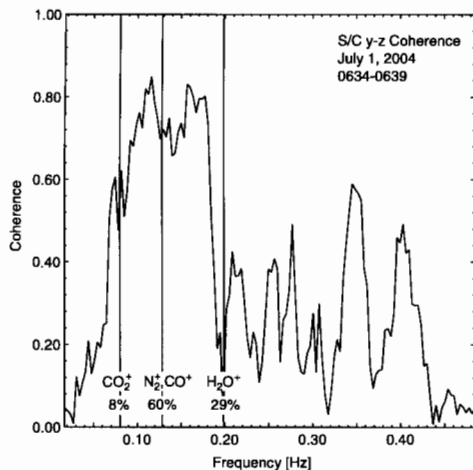


Figure 5. Coherency spectra of the waves seen in Figure 3. The far right peak corresponds to doubly ionized water group molecules. The second peak on the right could be singly ionized atomic nitrogen.

the waves are strong in the compressional component as expected for a transverse wave propagating at a finite angle to the magnetic field. The percentages on Figure 4 (8%, 60% and 29%) show the relative amount that each molecule or combination in the case of CO and N₂ was expected to be present in the engine exhaust. The relative number density of ions will depend on the ionization rate of each species and may be somewhat different than these percentages. However, it is clear that the peak power is just below the mass-28 gyrofrequency, where we expect the maximum growth of mass-28 waves.

[8] The last spectrum shown in Figure 5 is the coherence of the signal. It is a high number if there is a single coherent source of waves. Quite prominent in this display are waves that most probably correspond to singly ionized atomic nitrogen. On the right a strong coherent signal is seen at the expected frequency of doubly ionized water group ions.

5. Discussion and Conclusions

[9] No ion cyclotron waves in this band of frequencies has been seen inbound or on the four successive Cassini orbits. No waves have been seen that resemble such waves in other magnetospheres. The most analogous waves are the sulfur dioxide and sulfur monoxide waves seen at Io in the jovian magnetosphere [Russell *et al.*, 2001]. We did not expect waves to arise at Saturn at these frequencies because we do not know of any natural sources of these waves at this location in the saturnian magnetosphere. However, the expected products of the rocket exhaust match the spectrum well. Most of the exhaust is CO (18%) and N₂ (42%) and most of the waves appear around their common gyro frequency. How could this happen? When the engines fired they produced a plume of over 850 kg of neutral gas. It should have immediately begun to ionize in the solar extreme ultraviolet radiation at a rate of between about 4 to $10 \times 10^{-9} \text{ s}^{-1}$ depending on species and for moderate

solar activity conditions [e.g., Sittler *et al.*, 2004]. This would result in about 4 mg of ions per second from photoionization alone. Impact ionization would increase this total. Initially, any ions produced would have low energies because the magnetosphere was corotating at a speed close to the orbital speed of Cassini when the rocket fired. Only when the gas cloud reached distances close to 5 Rs did the energy of the picked up ions reach a value sufficient to generate strong waves. An ionization rate of 4 mg per second picked up at 50 km/s produces over 5 MW of power. Perhaps 10% of this power will appear as electromagnetic waves. At the amplitude seen (~ 0.25 nT) propagating at 100 km/s, then $4 \times 10^{-8} \text{ W/m}^2$ is propagating past Cassini. Thus these 4 mg/s could power a patch of the equatorial regions of dimension 15,000 km by 15,000 km. The velocity of the engine exhaust is 3 km/s initially slowing down as it and Cassini move away from closest approach. For an average separation velocity is 1.5 km/s the spacecraft and cloud should only be 27,000 km apart after 5 hours. Thus it is not unreasonable that Cassini can sense waves from the exhaust cloud. When the event ended near 0740 UT the gas cloud may have dissipated but it is more probable that the trajectory of the spacecraft and the cloud just separated sufficiently far that the waves no longer had access to the spacecraft.

[10] In short, it appears that Cassini observed ion cyclotron waves induced by its own exhaust gases, ionized and accelerated by the magnetospheric rotation. This is the first known artificial stimulation of electromagnetic waves in a magnetosphere by the creation of pickup ions.

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