Ion Isotropy and Ion Resonant Waves in the Solar Wind: Cassini Observations

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Abstract. Electric fields in the solar wind, in the range of one Hertz, are reported for the first time from a 3-axis stabilized spacecraft. The measurements are made with the Radio and Plasma Wave System (RPWS) experiment on the Cassini spacecraft [Gurnett et al., 2000]. Kellogg [2000] suggested that such waves could be important in maintaining the near-isotropy of solar wind ions and the validity of MHD for the description of the solar wind. The amplitudes found are larger than those estimated by Kellogg from other measurements, and are due to quasi-electrostatic waves. These amplitudes are quite sufficient to maintain isotropy of the solar wind ions.

1. Introduction

In many respects, the solar wind behaves as a collision-dominated fluid. MHD theory seems valid for the description of heliospheric process—the pressure is roughly isotropic, etc. Often, in plasma, fluctuating fields due to some instability can have the effect of collisions to randomize the particle distributions. This idea was elaborated theoretically a long time ago [Kennel and Engelmann, 1966], but has not been experimentally verified. Kellogg [2000] considered these questions, and particularly the question of why the ions of the solar wind are nearly isotropic, whereas conservation of magnetic moment in the outwardly decreasing magnetic field of this collisionless plasma would imply a ratio of $T_\parallel$ to $T_\perp$ of several hundred at 1 A.U. [Lemaire and Scherer, 1973]. Lemaire and Scherer's conclusions are somewhat modified by recent discoveries of large perpendicular energies near the sun [Kohl et al., 1998], but the problem remains. Kellogg concluded that fluctuating electric fields in the range of 1 Hz, which have never been adequately observed (An exception is Ulysses, whose spin axis pointed at the sun for brief periods, minimizing photoelectric variations [Lin et al. 1998]. Still Ulysses did not permit the level of detailed analysis of which this is a preliminary report.), but which were inferred from measurements of density and magnetic field fluctuations, were marginally able to maintain the observed isotropy. He noted, however, that several wave modes are known theoretically in this unexplored frequency regime, and that such waves ought to be investigated experimentally. Such waves cannot be measured on a spinning spacecraft, as the photoelectric variation of antenna potential [Kellogg, 1980; Lai et al. 1986] completely masks signals in a wide range around the spacecraft spin rate

The RPWS experiment [Gurnett et al., 2000] on the three-axis-stabilized Cassini has made electric field measurements in this frequency range for the first time from a 3-axis stabilized spacecraft, and preliminary results are reported here.

2. Experiment Description

Electric fields on Cassini are measured with three approximately orthogonal monopole antennas 10 m long and 2.86 cm in diameter. Normally, two of them are connected as a dipole, called EX, and the third, Ew, is operated as a monopole nearly orthogonal to EX. The antennas were made of beryllium-copper, without other coating, and were not voltage-biased, as is sometimes done to reduce the effect of density fluctuations. The two monopoles of the EX dipole made equal angles of 107 degrees with the Z axis of the spacecraft, which points away from the earth. At the beginning and end of the interval analyzed here, the Z axis also pointed away from the sun, thus minimizing photoelectric differences. Conversion of the measured voltage differences to electric fields requires knowledge of the effective length. In this preliminary report, the effective length of EX is taken to be the distance between midpoints, and for Ew is half the physical length. These are certain to be overestimates of the effective lengths; hence the electric fields will be underestimated, but probably not by more than a factor of two (in amplitude). The floating potential of an antenna in the solar wind is sensitive to the density and temperature of the ambient plasma, and the frequency range of interest here includes responses to changes in these. A more detailed analysis of the contributions of these changes to the measured antenna potential variations will be presented in a subsequent publication, but preliminary estimates are that the contributions also would probably not change the electric fields by more than a factor of 2 for the EX dipole. Cassini also carried a 3-axis search coil for the measurement of magnetic fluctuations.

The data used here are power spectra from the Low Frequency Receiver (LFR) part of the Cassini RPWS experiment. In normal operation, the signals from EX, and from the parallel component of the magnetic field, BX, are analyzed and telemetered. The voltage differences are sampled at 100 samples per second and digitized by a 12 bit A/D converter. Normally strings of 512 samples are used, and they are normalized, windowed with a Hanning window, and Fourier

transformed. The resulting Fourier amplitudes are squared to give power, and summed to give a roughly logarithmic frequency scale, which normally runs from .195 Hz to 26 Hz. After reception on the Earth, the spectra are corrected for the frequency response of the instrument, and converted to physical units. The two lowest channels, however, rarely have signals above their noise thresholds, and so the analysis presented here will start at .5 Hz.

There some spikes in the data—very strong signals with a broad spectrum. These may merit further study, but for now we have attempted to remove them from our treatment in the belief that they are impulsive interference. Somewhat similar spikes have been seen with the Waves experiment on the Wind satellite, but none on Ulysses, which should have seen such spikes if they are natural.

3. Results

The data to be analyzed here are from the last Earth flyby of Cassini. Closest approach to Earth was at 0330 on 18 August. Data were obtained from August 15 to September 14, 1999.

Some representative power spectra of the electric field are shown in Fig. 1. Several spectra (4-10) have been averaged for each curve. The individual Fourier components seem to have a roughly log normal distribution with a very wide variance, so that single spectra have so much variability that trends are hard to recognize. Examples are shown of a very low power spectrum, (Day 245 = 2 September, 1700), and of a very high
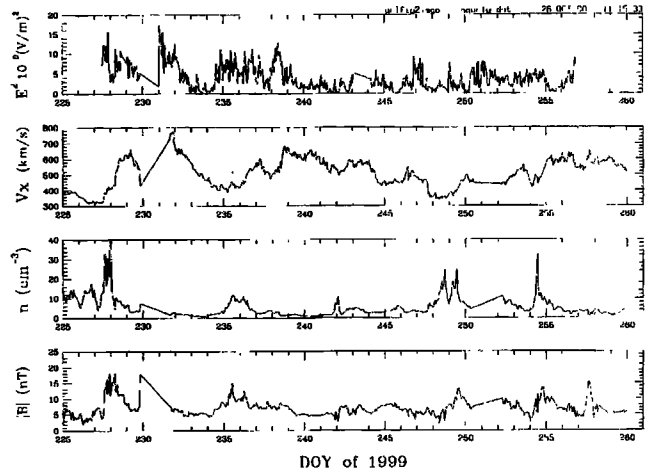
Figure 2. Hourly averages of wave power in units of 10^{-9} $(V/m)^2$, in the range .5 to 4 Hz over a solar rotation, together with solar wind data from Wind.

power (Day 237 = 24 August, 1800). Low power spectra are very rare, and a measurable signal is almost always present. In Fig. 1 the heavy line is a 24 day averaged spectrum from Days 233 to 257, which consists of nearly a complete solar rotation and is believed to be a period free of the Earth's influence. It will be seen that the average spectrum follows, very roughly, a power law in frequency,

$$P(f) = f^{-1.7}, \tag{1}$$

though the curve becomes steeper at the low frequency end.

In Fig. 2 are shown the hourly averages of the wave power, integrated over the range .5 Hz to 3.8 Hz. It will be seen that the wave power consistently exceeds 10^{-11} $(V/m)^2$, a value which Kellogg [2000] showed was sufficient to maintain isotropy of the proton distribution. Closest approach was on Day 230, and no data are available from the LFR during that period. When data begin again, the power level is quite high, but falls rapidly as Cassini recedes from the Earth. Levels have fallen to low values by the beginning of Day 233, and this is taken to mean that Cassini is in the solar wind, without major perturbation from the Earth. At this time, Cassini is 570. R_E downstream in the solar wind, and 250. R_E in the GSE -Y direction, the direction of the Earth's motion.

Also shown are solar wind data from the Wind spacecraft. Data from times when Wind was inside the Earth's bow shock have been deleted. During the period shown, there may be as much as 40 hours offset between the two data sets due to the time for the solar wind to travel outward and for the Earth to catch up to the prograde position of Cassini. The times have been corrected for the time for the solar wind to travel outward (less than 24 hours), but not for the prograde position. As can be seen, there is no really striking correlation between the wave power level and solar wind conditions.

In Fig. 3 is shown the 24 day averaged power spectrum, together with the electric fields from magnetic fluctuations [Bavassano et al., 1982, Behannon, 1978, and Beinroth and Neubauer, 1986], and from density fluctuations (electron density fluctuations from Celnikier et al. [1987], ion density from Neugebauer [1976], converted to equivalent electric fields by Kellogg [2000]. This figure is modified from Kellogg [2000] which should be consulted for a detailed explanation of
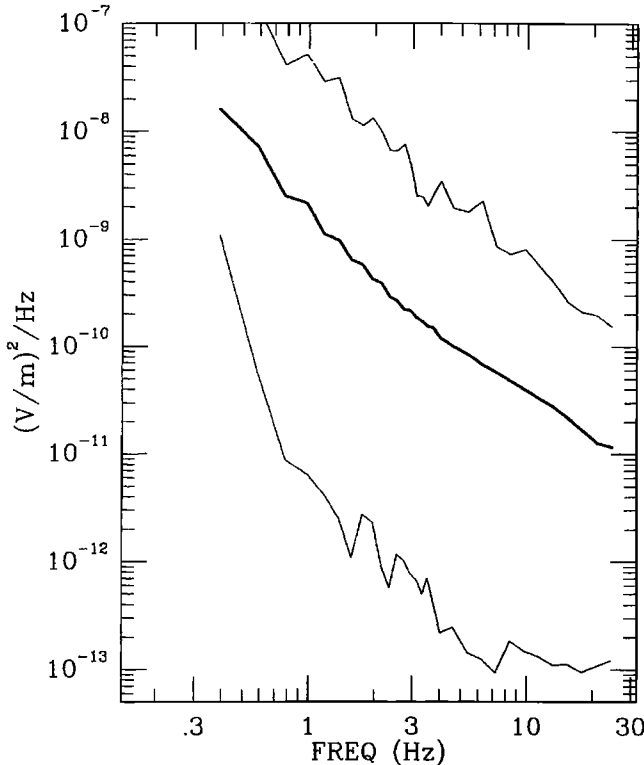

Figure 1. Several characteristic spectra in the range .5 to 25 Hz. The thick line is a spectrum averaged over nearly a complete solar rotation, and the thinner lines are chosen to show nearly the maximum and minimum spectra found. The minimum is close to the sum of noise level of the instrument and shot noise on the antenna.
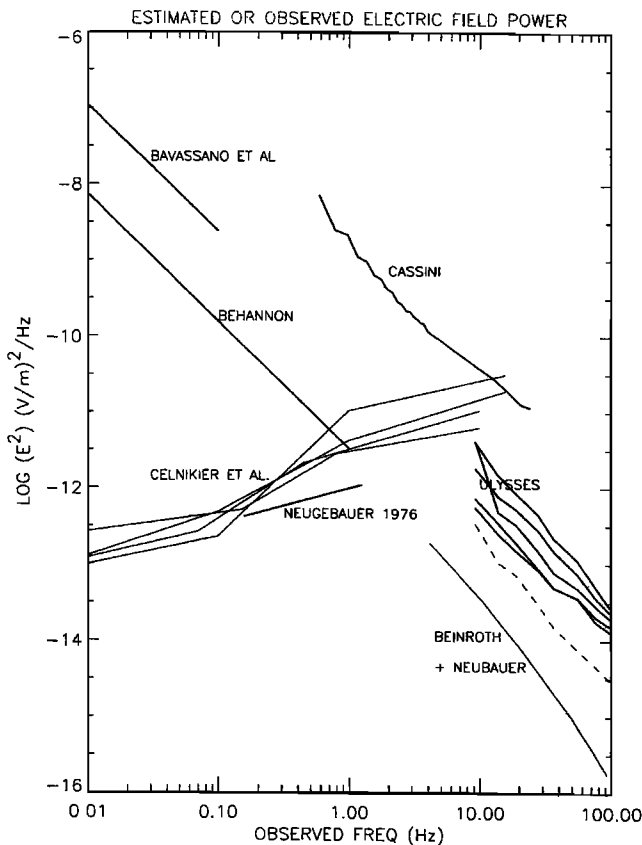
Figure 3. Comparison of the observed fields of this study with previous estimates [Kellogg 2000] and with previous observations of Ulysses.

wave vector, k. The first two modes have a magnetic component, and the electric field in the plasma rest frame would be of the order of B V_A, where V_A is the Alfven speed. In the solar wind the electric field would then be primarily due to the special relativity transformation of B into E, and so E would be of the order of B V_{sw}, about an order of magnitude larger. In fact, in the higher part of the available range, clear signatures of whistlers are seen, with a ratio E/B of the order of c/100. Their occurrence in the search coil data is fairly rare, but due to the lower sensitivity of the search coil to these waves, their contribution to the overall wave power is still uncertain.

In this low frequency range, the search coils are less sensitive to waves in these modes than the electric antennas, so we look for the largest electric fields. In Fig. 4 are shown scatter plots of EX and BX for 24 August 1999 = Day 236, a fairly active day, as can be seen from the hourly averages in Fig 2. This period includes the high power spectrum shown in Fig. 1. About 25% of the points, selected to have the largest electric fields, are plotted. In each panel the relationship E/B = V_{sw} is shown as a dotted line. The electric fields are almost always much stronger and the observed waves are electrostatic to a reasonable approximation. There is, however, a small magnetic component, which varies from one spectrum to another.

Since E is much larger than $V_{sw}B$ (and conversely, smaller than c^2/V_{sw}), it can be concluded that the measured values of both E and B are close to those in the plasma rest frame; i.e., the relativity transformation does not change either by a large amount. The E/B ratio in the plasma rest frame can then be estimated by sketching lines through the trends in Fig. 4. The very rough results for the various frequency bands are as follows:
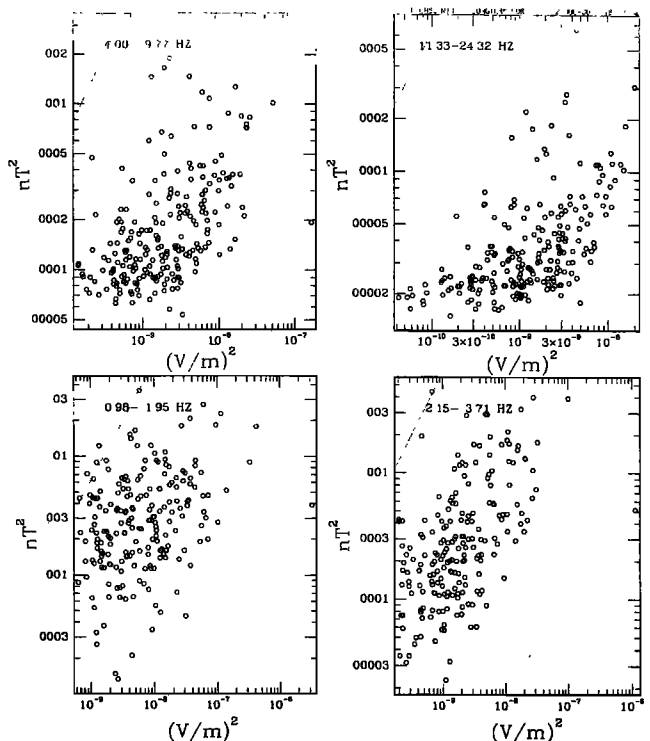
the estimations involved. Also shown are electric field measurements from the URAP experiment on Ulysses [Stone et al. 1992]. The URAP noise threshold is shown as a dashed line. The 24 day averaged Cassini spectrum is also shown in Fig. 2. It will be seen that the spectrum forms a reasonable extension of the Ulysses observations which are shown. However, the Ulysses spectra are more intense than the average observed, which would be close to the threshold, as the signals observed in Ulysses are often not above threshold. It appears also to be roughly consistent with the values derived from the Bavassano data, but this, as will be shown, must be fortuitous.

4. Mode Identification

It is beyond the scope of this preliminary report to attempt a complete identification of the observed modes. In particular, the measured components of E and B only allow tendencies to be discerned, and do not allow full description of the waves. However, the simplest considerations are in order. Possible modes in this frequency range are (1) Whistlers, including oblique whistlers, (2) electromagnetic ion cyclotron waves, (3) ion acoustic waves, (4) electrostatic ion cyclotron waves, and (5) ion Bernstein modes. We use the warm plasma designations, as MHD is not accurate for waves in the solar wind. For these modes, which have phase speeds small compared to the solar wind speed (except for whistlers at the high end of the band), the observed frequency is almost entirely due to Doppler shift, and is therefore a measure of the

Figure 4. Scatter plots of BX vs. EX for 24 August 1999 (1800-2000 Z) in four frequency bands.

Freq. Band	E/B
.98 - 1.95 Hz	c/160
2.15 - 3.71 Hz	c/120
4.00 - 9.77 Hz	c/100
11.33 - 24.32 Hz	c/30 to c/100

These can be contrasted with $E/B = V_A = c/400$ to $c/1000$ for quasi-parallel whistlers and electromagnetic ion cyclotron waves in this wave vector range. However, there is still uncertainty in calibration, i.e., in the effective lengths and in the effects of density fluctuations, so that it would be premature to rule these out.

5. Summary and Discussion

Electric fields in the range of one Hertz have been observed in the solar wind on a 3-axis stabilized spacecraft for the first time. In this frequency range, 3-axis stabilization greatly improves the accuracy of such measurements over what has been available heretofore. This frequency range cannot be observed on a spacecraft spinning around an axis making an appreciable angle to the direction of the sun, and the RPWS experiment on Cassini was the first to have sufficient sensitivity near this frequency to make these observations. Some conclusions and corrections to previous work can be made.

First, it is easy to see that these electrostatic waves are seriously inconsistent with the Kellogg [2000] estimates of electric field derived from the measurements of density, although those estimates are supposed to be of the electrostatic part of any waves. It must be that the Boltzmann relation,

$$\delta n = n_0 (e/k_B T_e) \delta \phi, \qquad (2)$$

used by Kellogg to estimate the electric field, is seriously wrong. More careful analysis of the dispersion relation for a warm plasma shows that Kellogg was too optimistic about the range of validity of this relation, and that while it holds reasonably well for ion acoustic waves propagating within about 45° of the magnetic field direction, it, to give the worst example for the first three modes above, is wrong by factor of 200 for electromagnetic ion cyclotron waves with k at more than 75° from B. For the whistler and ion acoustic modes, however, eq (2) is sufficiently accurate that these modes are apparently ruled out by the disagreement between the estimates from density fluctuations and the observations, unless there were improbable changes in the nearly 30 years between the density fluctuation and the Cassini measurements.

However, the considerations that led Kellogg [2000] to think that electric fields in the range of one Hertz might account for the observed near isotropy of the solar wind seem to be borne out. The electric fields are observed to be nearly two orders of magnitude (in power) larger than those estimated to be necessary to maintain isotropy. Other than that observation, identification of the modes of these waves will be left to future work.

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