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Electric Fluctuations and Ion Isotropy

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Abstract. In a recent paper observations of electric field fluctuations in the range .5 to 25 Hz were reported, observations by the RPWS experiment on Cassini. We have found that the data presented in that paper are affected by broadband interference which appears to be generated in the spacecraft wake. Evidence for a wake instability will be presented. We present a new spectrum for electric fluctuations in the solar wind taken when the antennas are outside the wake. In earlier papers we have tried to understand why the solar wind behaves as a collisional plasma although collisions are very rare. Whether these electric fluctuations might replace the effects of collisions will be discussed.

INTRODUCTION

In an earlier paper, observations were reported of electrostatic fluctuations in the frequency range below 25 Hz, from the RPWS experiment on the Cassini spacecraft. We now have found that the interpretation was wrong, and that the fluctuations are due to an instability on the wake of the spacecraft, specifically on the wake of the 4 m diameter high gain antenna. The evidence for this wake turbulence is presented, and then a new spectrum, taken with antennas outside the wake, is presented, and evidence is given that this represents waves in the free solar wind

The solar wind behaves as a collisional plasma although collisions are very rare. MHD seems to work, and the ions are relatively isotropic [1,2,3]. The ions, through conservation of magnetic moment, ought to have $T_{\|} / T_{\perp}$ of a few hundred, whereas it is observed to be within a factor of 2 of unity. It is probable that fluctuations of the fields replace collisions. To be most effective, electric fluctuations should be nearly resonant with the ions, and with the Doppler shift of reasonable candidate wave modes, would, at 1 AU, then appear in the range around and below 1 Hz. This range of electric fields has not been well explored experimentally. Because of photoelectric variations of the potential of a cylindrical antenna, this frequency range cannot be measured on a spacecraft spinning in the usual direction, i.e., around an axis nearly perpendicular to the sun direction Cassini is the first 3 axis stabilized spacecraft with a measurement channel devoted to this frequency range [4]. Kellogg et al., [3], reported such measurements while Cassini was in the range of 1 to 1.2 AU from the sun. However, on 1 Oct 2000 when a series of maneuvers was begun to allow various of the instruments to observe Jupiter, it was seen that the signal level in the frequency range .2 to 25 Hz depended strongly on spacecraft attitude in a way that did not seem consistent with natural signals.

EXPERIMENT DESCRIPTION

The measurements reported here are from the RPWS experiment on Cassini. [4]. Cassini is a large spacecraft, 6 m long, carrying a fixed 4 m diameter telemetry antenna at one end. RPWS measures electric fields using 3 orthogonal monopole antennas 10 m long and 2.86 cm diameter, made of beryllium-copper and magnetic fields using three mutually orthogonal search coils. Normally two of the electric monopoles are connected as a dipole, Ex, whose electric axis is approximately in the spacecraft X direction, and the third monopole, called Ew, is operated alone. Cassini must be oriented with the parabolic (high gain) antenna pointing toward the earth when downlink is required from distant positions. A crude sketch of the aspect of Cassini with respect to the sun in this case is shown in the lower two panels of Fig. 1. In this only the main structure of the spacecraft and the high gain antenna are shown together with the electric field monopoles. The bases of the antennas actually issue from a mechanism

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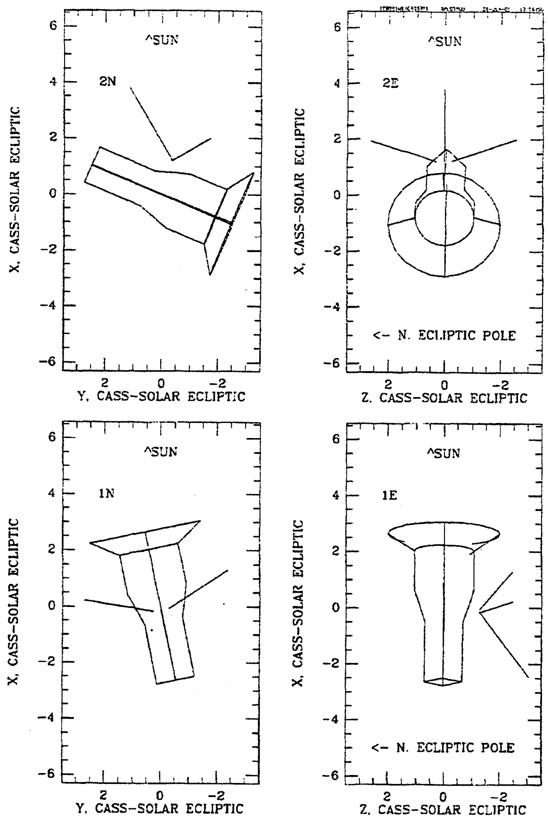

FIGURE 1. A rough sketch of the Cassini spacecraft, showing the positions of the high gain antenna and the RPWS antennas (heavy lines) in earth pointing attitude (lower two panels) and out of the wake (upper panels). N and E refer to a view from the North ecliptic pole and from the East, and 1 and 2 refer to different periods of Fig. 2.

which is not shown. One important appendage which is not shown is the magnetometer boom, which nearly bisects the Ex monopoles but is perpendicular to the spacecraft axis.

It will be seen, assuming that the solar wind is flowing in a radial direction, that the bases and lower parts of the RPWS antennas are in the plasma wake of the high gain antenna, and that they protrude through the wake surface. As Cassini traveled toward Jupiter, the sun-earth angle was never large enough to bring the RPWS antennas out of the wake until 1 Oct 2000.

WAKE INTERFERENCE

The first indications that something did not fit the interpretation of waves in the freely streaming solar wind came from comparing the signal intensities in the Ex and Ew antennas. The signal on the Ew monopole was several times more intense than the signal on the

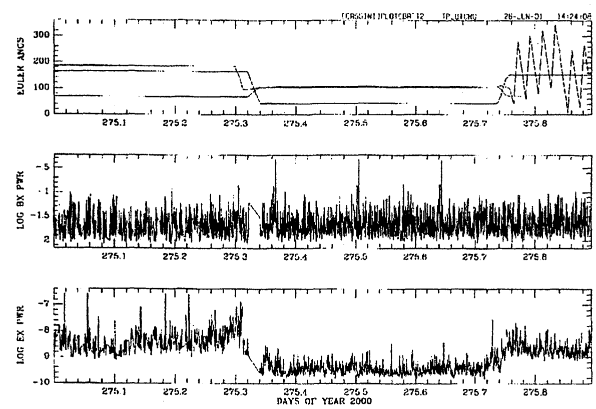

FIGURE 2. RPWS observations on 1 Oct, 2000 showing electric and magnetic fields and how they change as the orientation of Cassini is changed. The upper panel shows the Euler angles of the attitude without designation to show when the attitude changed.

Ex dipole. An explanation came on 1 Oct 2000 when Cassini was rotated so that some experiments could view Jupiter for the first time. The relative power observed in the Ex and Bx channels is plotted for the day in the lower two panels of Fig. 2, and the Euler angles of the spacecraft attitude are plotted without identification in the topmost panel, just to show times when the attitude changes. Relative power is power from the spectrum multiplied by freq $^{1.67}$, to make all frequencies equally important—otherwise the power is mainly just the power at the lowest frequency.

The attitude of Cassini at day 275.11 is shown in the lower panels of Fig. 1, while the attitude at day 275.55, (when the signal is Ex is considerable reduced) is shown in the upper panels of the figure. The changes were too large to be explained as response to an anisotropic signal, and furthermore show complete correlation with antenna position on following days.

The Ew-Ex difference was found to decrease as Cassini traveled outward. We now interpret this Ew-Ex difference as mainly due to an instability which is larger on the Ew antenna as it is farther downstream in the wake, and the decrease as due to a slowing of the growth rate as the plasma becomes less dense. Some Ew-Ex difference may be due to the different response of a monopole antenna to density fluctuations however, which are largely cancelled out by a dipole.

In summary, then, the observations lead to the belief that the signals are contaminated by an instability which is most intense on the surface of the wake of the high gain antenna, and which grows in the downstream direction. To investigate an instability on the surface of the wake, plots of signal vs. angle of the X antenna which was closest to the antisolar direction, were made.

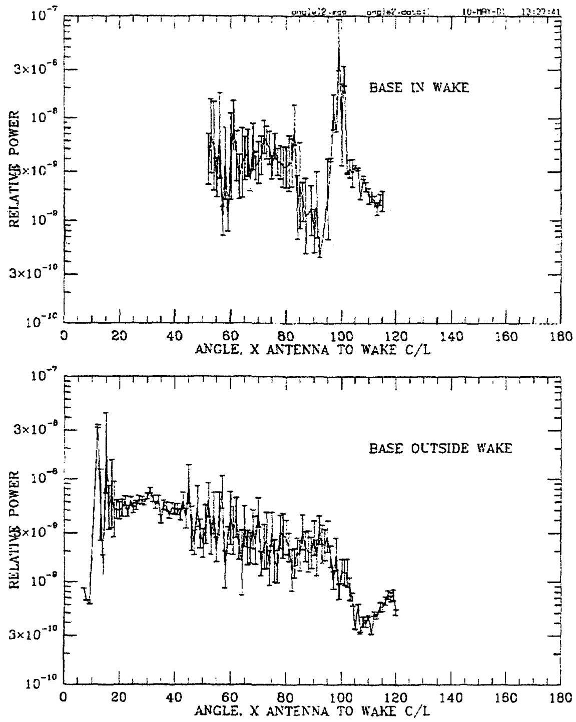

FIGURE 3. Relative wave power as a function of RPWS antenna position with respect to the anti-sun direction, taken as being the wake center line.

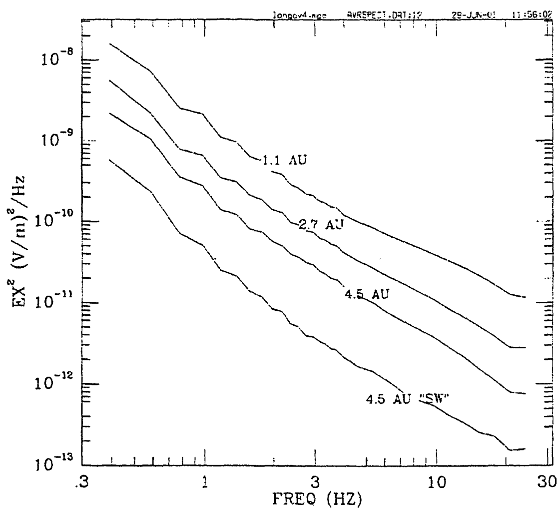

FIGURE 4. Observed electric field power spectrum in the spacecraft frame at various distances from the sun. The upper three curves are probably from wake turbulence. The lowest curve may be a true representation of the spectrum in the undisturbed solar wind at 4.5 AU.

In Fig. 3 plots of relative power in the .5-25 Hz band vs. the angle between the anti-sun direction (called the wake), and whichever X monopole is closest to the anti-sun direction, are shown.

The signals have been averaged in 3° bins, and the error bars shown are the expected standard deviation of the means. It will be seen that there is a sharp drop in the signal amplitude when the nearest X antenna is at an angle of more than 103° with the antisolar direction, which we interpret as meaning that the wake turbulence is radiated outward at a large angle. For base out of wake, there is a peak at about 10°, which we suppose means that the antenna is lying right in the turbulent layer around the wake, and the relative power also drops substantially at 100-105°.

Fluctuations in spacecraft wakes in the magnetosphere have been reported by several investigators and some theoretical work has been done [5,6,7,8]. However, the plasma regime here is quite different from the Earth's magnetosphere, both ions and electrons being unmagnetized. The Debye length is much larger than the spacecraft dimensions so that electrons can freely enter the wake even though ions are absent, and so only small electron density gradients are expected, conditions which argue against lower hybrid waves for this case. The electrons in the wake should be streaming toward the spacecraft and antenna, whereas the ions of the solar wind are streaming away and this suggests a Kelvin-Helmholtz instability on the wake-solar wind boundary due to this velocity difference. Note that the configuration of the wake of the Cassini high-gain antenna is quite different from most spacecraft wakes, in that the body of the spacecraft, presumed to be electrically positive with respect to the plasma, occupies much of the wake, while in most situations the wake is negatively charged.

Fig. 4 shows electric field spectra averaged over a solar rotation of the signals measured at three different solar distances. Three of the spectra are those when Cassini's attitude was like that shown in the lower panels of Fig. 1 so that they are spectra of the wake turbulence. At 3 Hz, the turbulence power varies as $r^{-1.3}$, more slowly than the plasma density. The lowest spectrum, marked 4.5 AU "SW", is from data when the antennas are upstream from the spacecraft body. We believe that this spectrum represents waves in the free solar wind. Not only is this spectrum about 10 dB weaker than the corresponding wake spectrum, but also its slope is different.

As a working hypothesis, it is assumed that the "SW" data represent electric fields in the free solar wind. To try to justify this assumption, in Fig. 5 Cassini data are compared to STO experiment data from Ulysses at about the same distance from the sun and for a heliographic latitude near 0, but at a higher frequency.

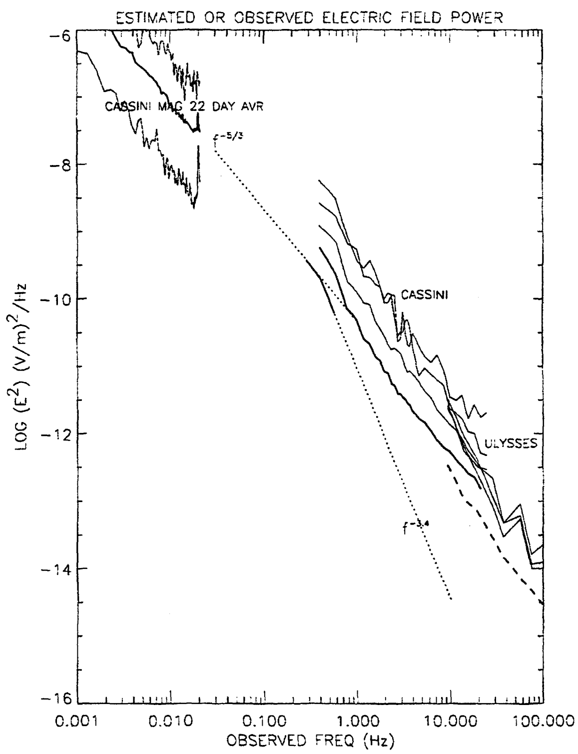

FIGURE 5. Estimation and observation of electric fields at 4.5 AU plotted against observed (Doppler-shifted) frequency. In the upper left are shown expected electric fields from the Lorentz transformation of magnetic fluctuations. The heavy line running between .4 z and 25 Hz is the averaged observed "SW" spectrum. See text.

In the region near 4.5 AU, the noise threshold of the STO experiment in the 9-448 Hz range is near the average signals from Cassini RPWS so that comparison of averages is not meaningful. Rather, we have selected a few periods of strongest signals. These are shown as lighter lines in Fig. 5. The dashed line near the ULYSSES data is the noise threshold for the instrument. Now they agree perfectly, though in our earlier paper [3] the Cassini spectrum was out of line with Ulysses. Hence, these direct measurements of electric fields give some confirmation that the "SW" electric field is actually the electric field in the undisturbed solar wind. Unfortunately, except for a very short period, the high gain antenna was pointed either at Earth or at the sun until Cassini had reached 4.5 AU on 1 Oct. 2000, aspects which put the antennas in the wake, so that no uncontaminated data are available closer to the sun.

ELECTRIC FIELDS IN THE SOLAR WIND

A contribution to observed electric field fluctuations in the solar wind comes from the Lorentz transform of the magnetic fluctuations. It is essential to determine whether the observed fields are from this Lorentz transform or from either electrostatic waves or the longitudinal component of the wave modes of the magnetic fluctuations, because the ions are not affected by Lorentz transform fields. The Lorentz transform of magnetic fluctuations gives a field of the order of $E(f) = V_{sw}B(f)$. Since, in the region considered a typical Alfven speed V_A is only about 15 km/s while the typical solar wind speed, V_{sw}, is about 500 km/s, the intrinsic electric field which the ions see might be much smaller than the field measured here if the observed fields are the Lorentz transform of the magnetic fluctuations.

However, at 4.5 AU, the Cassini search coil is not sufficiently sensitive to be used to measure the magnetic component of these waves. Therefore, we have to use some indirect arguments which, however, will not lead to a definite conclusion.

It is well known that magnetic power spectra follow the Kolmogorov power law, -5/3, for the inertial range. Magnetic fluctuations are well known to be intermittent, with power which varies from one period to another by orders of magnitude. However, during any interval of 10 minutes or more, the spectrum seems always to be roughly a power spectrum with index near -5/3. We therefore consider the spectra at lower frequencies obtained from the Cassini MAG experiment of Imperial College and extrapolate them to the desired frequency range. Some magnetic fluctuations are shown in Fig. 5 in the upper left corner.

What is shown is an average spectrum of the transverse (to the antisolar direction) magnetic field, averaged over the same period as the electric field spectrum multiplied by V_{sw} to give the electric field of the expected Lorentz transform (heavy line). Also shown are two spectra (light lines) representing large and small daily averages, to give an idea of the variation encountered. A dashed line has been drawn from the high frequency limit of the magnetic power spectrum at the –5/3 power law. It is also well known [9,10] that this power law ceases to be valid (beginning of the "dissipation" range) at a frequency of the order of the ion cyclotron frequency. At the frequency given by Neugebauer, i.e, at a Doppler shifted frequency whose wavenumber is equal to the inverse proton cyclotron radius we have continued it at a typical power law found by Beinroth and Neubauer [11], namely $f^{-3.4}$. This is our attempt to use what is known of magnetic field fluctuations to extrapolate the magnetic measurements to a higher frequency range and to calculate the electric field which would result from the Lorentz transformation.

It will be seen that the averaged Cassini electric field spectrum (heavy line) lies slightly above the estimates from these extrapolations, especially at frequencies above about 1 Hz. However, in the region expected to be resonant with the ions, namely around .4 Hz marked with a heavier line, the electric field is larger than the extrapolation only by an amount not large compared to the variation of the magnetic spectra (as shown by the spectra in light lines in Fig. 5), and so we consider that it is uncertain whether the averaged Cassini electric field is larger than the Lorentz transform of the magnetic field or not. Note that if electrostatic waves were actually to be measurable above the Lorentz transform of B, then their electric fields would have to be quite large in the plasma frame, larger by a factor of $V_{sw}/V_A \approx 30$ than the electric fields of order $V_A B$ due to electromagnetic modes. Measurement of density fluctuations [12] provides the best way to measure electrostatic waves in the relevant frequency range.

If, as is true at frequencies below one cycle per minute, the spectra remain $f^{-5/3}$ power laws even though their amplitudes vary, then it might be expected that there is a correlation between the amplitudes of the magnetic spectra from MAG at frequencies below .02 Hz and the amplitudes of electric field fluctuations in the Cassini range above .4 Hz. No such correlation was found and, in fact, the calculated correlation is slightly negative, even though both quantities are positive. This provides some evidence in favor of electrostatic waves.

DISCUSSION

Since the evidence for electrostatic waves is inconclusive, the question of whether the observed fluctuations are sufficient to isotropize the ions will be discussed according to each of the possibilities. In earlier papers [1] (but there is a typographical error) and [2], a rough estimate of the diffusion of the velocity perpendicular (to the magnetic field) in time τ in a fluctuating electric field was obtained and compared to the decrease of the perpendicular component due to the conservation of magnetic moment, $v_\perp^2/B$. The order of magnitude calculations in those papers will not be repeated here for lack of space. The spectrum used in [2] was erroneously calculated from density fluctuations, and was relatively flat compared to what we now think is correct. Hence the diffusion, proportional to the electric power, is very sensitive to the lower frequency limit. We integrate the electric power under the heavy line in the octave around .4 Hz in Fig 5. If it is assumed that the observed electric fields are actually those of electrostatic waves, then the electric fields are more than sufficient to maintain isotropy.

At 4.5 AU, there are qualitative differences with the situation at 1 AU and nearer the Sun. As discussed by [2], the dominant contribution to diffusion of ions inside 1 AU is electric fluctuations, even if these are only from electromagnetic fluctuations (ion cyclotron waves and whistlers), since the ratio of E to B in these fluctuations is of order Alfven speed, v_A, while the ratio of forces is the thermal speed. At 4.5 AU however, the thermal speed is expected to be larger than the Alfven speed, and so magnetic fluctuations provide the dominant diffusive force (unless there are electrostatic fluctuations). In this case, the fluctuations appear only marginally able to maintain isotropy. However, the calculation is only correct to an order of magnitude so that the fluctuations might be sufficient. Unfortunately, the parameters of the plasma and the solar wind are such that it is difficult to decide this question at 4.5 AU.

SUMMARY AND CONCLUSIONS

Our main purpose is to identify fluctuating fields which might replace collisions to validate MHD and to maintain the isotropy of the ion distributions. It turns out that it is difficult to do this at 4.5 AU, given the parameters of the solar wind and the thresholds of the Cassini RPWS instrument complement. Significant electric fields have been observed but it is difficult to know for sure that these are electrostatic waves since the magnetic fluctuations in the same frequency range are too small to be observed. If these electric fields are electrostatic, then they are plenty large enough to account for the isotropy of the ions. If they are the Lorentz transform of the magnetic fluctuations, then they are perhaps marginally large enough.

The evidence leans toward electrostatic waves in that (1) the electric fields are slightly larger than extrapolations of Lorentz transformed magnetic fields, and (2) there is no correlation with the amplitude of magnetic field spectra. However, if the waves are not electrostatic and the magnetic fluctuations are dominant, then the picture is that isotropy is just due to the heating of the perpendicular component of the ion velocity by absorption of the magnetic fluctuations, a picture which was suggested long ago [13].

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