

Ion isotropy and ion resonant waves in the solar wind: Corrected Cassini observations

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[1] In an earlier paper [Kellogg *et al.*, 2001], observations of electric field fluctuations in the range 0.5 to 25 Hz were reported. We have recently found that the data presented in that paper are seriously contaminated by broadband interference which appears to be generated in the spacecraft wake. Wake instabilities have been found by others, but the plasma conditions are quite different from those of any other observations of wake instabilities of which we are aware. In this paper, some characteristics of the wake interference are investigated, and an attempt is made to find conditions when it is not present. We believe that we have done this successfully and present a new spectrum and characteristics for electric field fluctuations in the solar wind. However, essentially no uncontaminated data were obtained nearer the Sun than 4.5 AU, and so the new results pertain only to the outer region. In the outer heliosphere the conditions are expected to be sufficiently different (large plasma beta) that the results may not pertain to the inner heliosphere. *INDEX TERMS:* 2159

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1. Introduction

[2] In earlier papers [Kellogg and Lin, 1997; Kellogg, 2000; Kellogg *et al.*, 2001] we have tried to understand why the solar wind behaves as a collisional plasma although collisions are very rare and, in particular, have searched for electric field fluctuations which might replace the effects of collisions. A particular feature of collisional plasma is the isotropy of pressure. Although Coulomb collisions may sometimes be significant for the electrons of the solar wind, the ions, through conservation of magnetic moment, ought to have T_{\parallel}/T_{\perp} of a few hundred, whereas it is observed to be within a factor of 2 of unity. 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. Although much work has been done, especially by Marsch, Tu, Hollweg, and coworkers [e.g., Marsch and Tu, 2001 and references therein] on the effect of fluctuations on ion distributions, 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. A three-axis stabilized spacecraft presents the best opportunity for such measurements, and Cassini is the first three-axis stabilized spacecraft with a measurement channel devoted to this frequency range [Gurnett *et al.*, 2003]. Kellogg *et al.* [2001] reported such measurements, while Cassini was in the range of 1 to 1.2 AU from the Sun. However, on 1 October 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 0.2 to 25 Hz depended strongly on spacecraft attitude in a way that did not seem consistent with natural signals. In this paper, evidence is presented that turbulence or an instability on the wake of the spacecraft generates interfering signals. 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.

2. Experiment Description

[3] The measurements reported here are from the RPWS experiment on Cassini. [Gurnett *et al.*, 2003]. Cassini is a large spacecraft, 6 meters long, carrying a fixed 4-meter

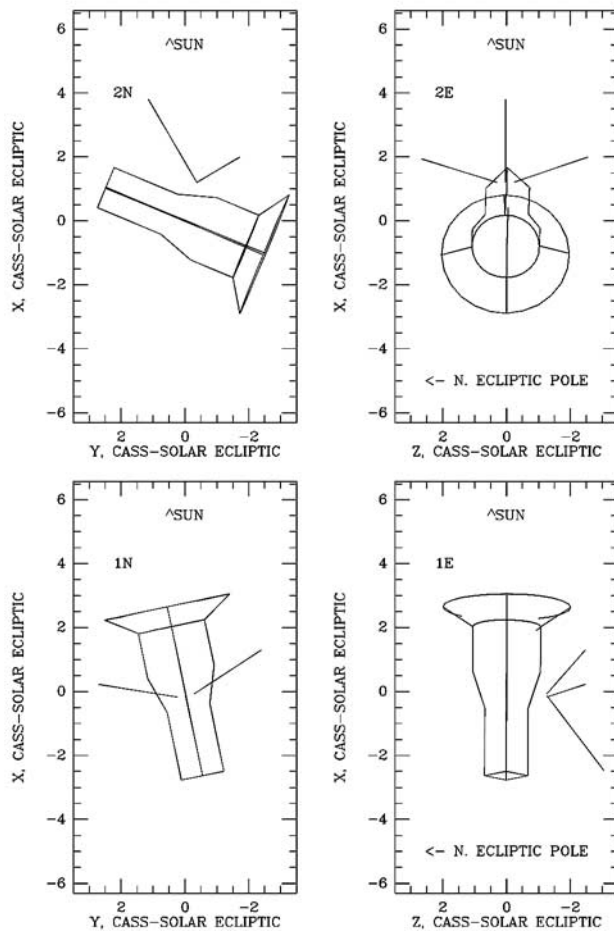


Figure 1. A rough sketch of the Cassini spacecraft, showing the positions of the high-gain antenna and the RPWS antennas (heavy lines) in Earth pointing attitude (lower two panels) and RPWS antennas out of the wake (upper panels).

diameter telemetry antenna at one end. RPWS measures electric fields using three orthogonal monopole antennas 10 m long and 2.86 cm diameter made of beryllium-copper. Magnetic fields are measured 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. The two monopoles of the Ex dipole make angles of 107° with respect to the positive Z axis of the spacecraft, which points away from the high gain antenna. Ew, in the Y-Z plane, makes an angle of 37° with respect to +Z. 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 Figure 1. In this, only the main structure of the spacecraft and the high gain antenna are shown together with the electric field monopoles. No lines have been hidden, and a number of appendages have been omitted, but the relation of the antennas to the spacecraft body and to the high gain antenna is correct. Also the spacecraft body is shown as square to emphasize

the X and Y coordinate directions, which are at the corners of the square, though of course it is actually round. The bases of the antennas actually issue from a mechanism 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.

[4] 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 fact that the high gain antenna pointed at the earth and not at the Sun implies that the spacecraft Z axis is not always radially anti-Sunward, but the Sun-Earth angle was never large enough in this period to bring the RPWS antennas out of the wake.

3. Wake Interference

[5] 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 Ex dipole. An explanation came on 1 October 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 Figure 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 $\text{freq}^{1.67}$, 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 Figure 1, while the attitude at day 275.55, when the signal is Ex is considerably reduced, is shown in the upper panels of Figure 1. It will be seen that the signal is much reduced when the antennas are upstream from the spacecraft body and telemetry antenna. The changes were too large to be explained as response to an anisotropic signal and furthermore show complete correlation with antenna position.

[6] The Ew-Ex difference was found to decrease as Cassini traveled outward. Examples of the averaged power spectrum on the two antennas are shown at several distances from the Sun in Figure 3. These data have been selected for lack of spacecraft interference by excluding any time series with signal points more than six standard deviations from the average. This usually excludes a large fraction of the time series. We note that the sudden drop in apparent power at about 30 Hz is due to a low-pass (antialiasing) filter in the circuit and is not a physical effect.

[7] It appears from the overall data (see Figure 2) that the wake turbulence is extremely variable, responding probably to differences in ambient plasma. In Figure 3, the two spectra shown at 2.7 AU, taken from data on February 6 and February 8 2000, show that there is also variability in the ratio of Ew to Ex. This also shows that possibly this ratio might be used to identify times of reduced perturbation, but this idea has not yet been carried out. The reason for the difference in these two spectra is not known. It is

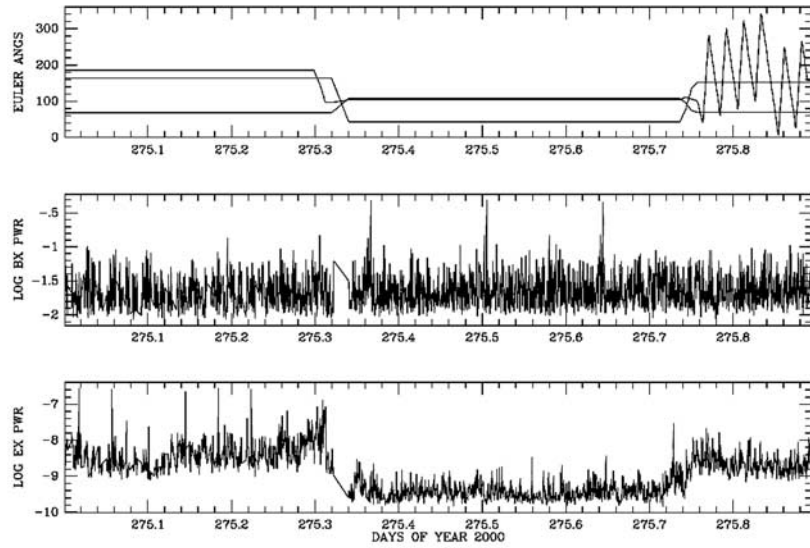


Figure 2. RPWS observations on 1 October 2000 showing electric and magnetic fields and how they change as the orientation of Cassini is changed. The upper panel shows the Euler angles of the attitude without designation to show when the attitude changed. N and E refer to a view from the north ecliptic pole and from the ecliptic east, and 1 and 2 refer to the different periods of Figure 2. See text.

possible that the solar wind direction changed to bring the antennas out of the wake, but the plasma instrument does not view the complete solar wind distribution functions in this orientation, so that this cannot be determined. The aberration of the apparent solar wind due to the spacecraft

velocity does not provide an explanation, as the antennas are on the south ecliptic side of the spacecraft as in the lower panels of Figure 1 and so cannot be brought out of the wake by changes of the solar wind velocity which are in the plane of the ecliptic.

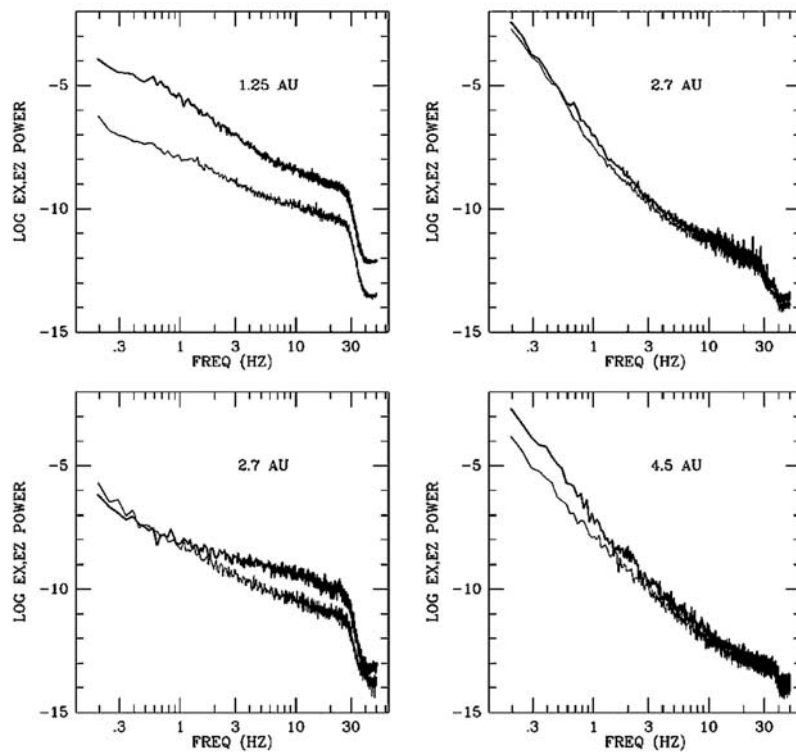


Figure 3. Averaged signal power on the Ex dipole (light line) and on the Ew monopole (dark line) for several distances from the Sun.

[8] It will be obvious that the spectra at 2.7 AU show much more variability than other spectra of this paper. The spectra of later figures are usually averaged over a solar rotation, to remove the effects of corotating interaction regions, fast and slow stream, etc. During most of the cruise from 1.2 AU to 4.5 AU, the experiment was in a mode which telemetered only the measurements from the channels Ex and Bx, so that the ratio of Ew to Ex cannot be determined. The experiment was in the proper mode to return Ew for only parts of 3 days at 2.7 AU, and no other such data are available between 1.2 and 4.5 AU. Hence these data are averaged over 10 or a few tens of spectra to reduce statistical fluctuation, but there is no averaging to remove the quite striking systematic variations which we attribute to ambient plasma variations. The spectra at 1.2 and 4.5 AU are typical of the whole period of a solar rotation which has been analyzed, but the spectra at 2.7 AU seem different and there is not sufficient data for further analysis.

[9] 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 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 canceled out by a dipole.

[10] In summary, then, the following 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. (1) The signal on Ew, a monopole which is in either Earth or Sun pointing attitude farther downstream than the Ex dipole, is more intense than that on Ex; (2) the signal on Ex becomes much weaker, but still not zero, when the Ex antennas are upstream of the spacecraft body and the high-gain antenna, and (3) the signals are also stronger when the antenna base is within the wake and the antennas protrude through the wake surface.

[11] With the working hypothesis that there was an instability, probably on the surface of the wake, plots of signal versus angle of the X antenna which was closest to the antisolar direction, assumed to be the direction of the solar wind, were made. Two plots, one when the bases of the antennas are inside the wake, and one when they are outside, are shown in Figure 4. These are taken from two channel LFR data (spectra) and are plots of relative power in the 0.5–25 Hz band versus the angle between the anti-Sun direction (called the wake), and whichever X antenna is closest to the anti-Sun direction. 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°.

[12] Fluctuations in spacecraft wakes in the magnetosphere have been reported by several investigators and some theoretical work has been done [Gurnett *et al.*,

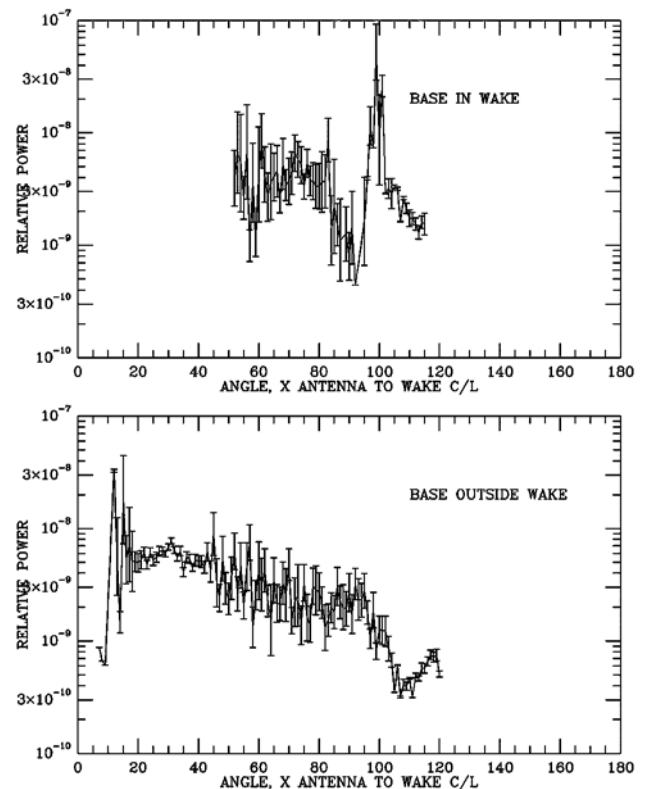


Figure 4. Relative wave power as a function of RPWS antenna position with respect to the anti-Sun direction, taken as being the wake centerline.

1988; Murphy *et al.*, 1989; Keller *et al.*, 1997; Samir *et al.*, 1989]. However, the plasma conditions here are quite different from those in 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, since they are presumably absorbed on its surface, 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. However, 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 and full of electrons but not ions.

[13] Figure 5 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 Figure 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

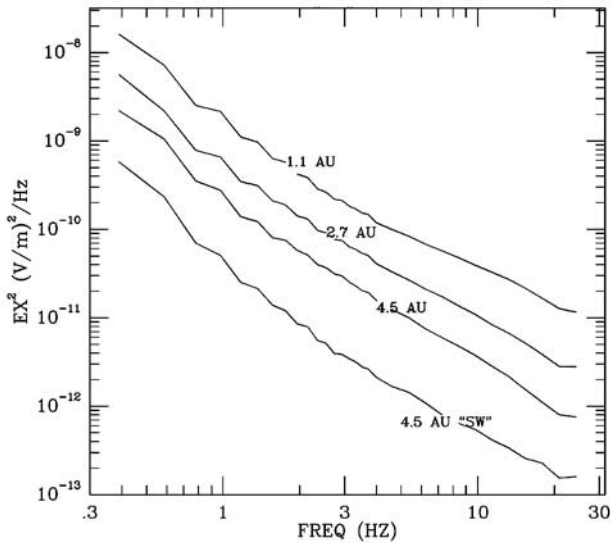


Figure 5. Observed electric field power spectrum in the spacecraft frame at various distances from the Sun. Each spectrum has been averaged over approximately one solar rotation to remove effects of streams and stream interfaces. The upper three curves are probably from wake turbulence. The lowest curve may be a true representation of the spectrum in the undisturbed solar wind at 4.5 AU.

about 10 dB weaker than the corresponding wake spectrum but also its slope is different. The three wake spectra all have an $F^{-2.3}$ slope at low frequencies and a roughly $F^{-1.74}$ slope at high frequencies, with a breakpoint between 1 and 2 Hz. The “SW” spectrum is steeper at low frequencies, with an $F^{-2.74}$ spectrum at low frequencies. At high frequencies it is flatter, $F^{-1.59}$.

[14] 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 Figure 6 Cassini data are compared with STO experiment data from Ulysses at about the same distance from the Sun and for a heliographic latitude near 0. 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 over a period of a solar rotation as seen by each spacecraft and have plotted the measured electric fields. These are shown as lighter lines in Figure 6. The dashed line near the ULYSSES data is the noise threshold for the instrument. Now they agree perfectly, though in our earlier paper [Kellogg *et al.*, 2001] 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.

[15] 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 October 2000, aspects which put the antennas in the wake so that no uncontaminated data are available closer to the Sun. Our particular interest was in studying fluctuation fields which might be responsible for maintaining near-isotropy of the

solar wind ion distributions. At 4.5 AU, it may be that the firehose instability is responsible for maintaining this near-isotropy [Kellogg, 2000], a mechanism which can rarely work at 1 AU and not at all nearer the Sun. It appears, therefore, that Cassini will not be able to contribute data relevant to solar wind ion isotropy inside 1 AU.

4. Electric Fields in the Solar Wind

[16] 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 $E(f) = V_{sw}B(f)$, while the intrinsic electric field of, for example, waves with a phase speed of the Alfvén speed would have only $E(f) = V_A B(f)$. Since, in the region considered, a typical Alfvén 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 would be more than an order of magnitude smaller than the field measured

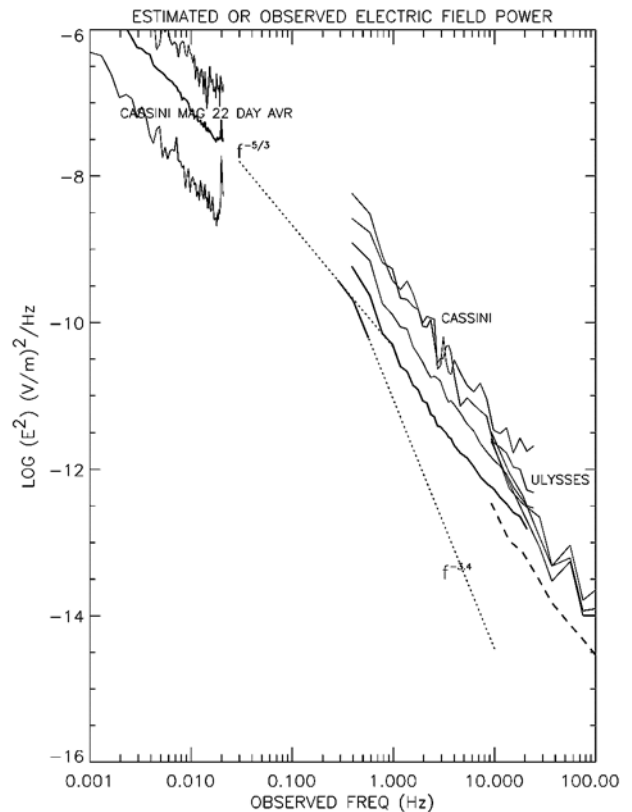


Figure 6. Estimation and observation of electric fields at 4.5 AU plotted against observed (Doppler-shifted) frequency. In the upper left is shown expected electric fields from the Lorentz transformation of magnetic fluctuations. The heavy line running between 0.4 z and 25 Hz is the averaged observed “SW” spectrum. See text for more details.

here if the observed fields are due to the Lorentz transform of the magnetic fluctuations.

[17] However, at 4.5 AU, the Cassini search coil is not sufficiently sensitive to be used to measure the magnetic component of the waves seen in electric field in the same frequency range. Therefore we have to use some indirect arguments, which, however, will not lead to a definite conclusion.

[18] It is well known that magnetic power spectra in this frequency range follow the Kolmogorov power law for the inertial range, namely

$$B^2(f) \propto f^{-5/3}. \quad (1)$$

Magnetic fluctuations are well known to be intermittent, with power that varies from one period to another by orders of magnitude. However, during any interval of an hour or more, the spectrum seems always to be roughly a power spectrum at the usual index near $-5/3$. We therefore consider the magnetic spectra at much lower frequencies obtained from the Cassini MAG experiment of Imperial College and extrapolate them to the desired frequency range. Some measured magnetic fluctuations are shown in Figure 6 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 (heavy line) multiplied by V_{sw} to give the electric field of the expected Lorentz transform. Also shown are two spectra (light lines) representing large and small daily averages, to give an idea of the variation encountered. The data used, obtained from more rapid sampling, have been averaged to give 24 s measurements. One hundred twenty-eight sample FFTs have been performed on the resulting strings. The data have not been windowed, and no prewhitening has been used, as has sometimes been done. Neither has any correction been made for aliasing, other than the boxcar averaging. A dashed line has been drawn from the high-frequency limit of the magnetic power spectrum at this power law. It is also well known [Neugebauer, 1975; Leamon *et al.*, 1998] 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, namely, at a Doppler shifted frequency whose wave number is equal to the inverse proton cyclotron radius:

$$k = \frac{\sqrt{2Mk_B T}}{eB} \quad (2)$$

we have continued it at a typical power law found by Beinroth and Neubauer [1981], 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.

[19] 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 0.4 Hz, the electric field is larger than the extrapolation only by an amount not large compared with the variation of the magnetic spectra (as shown by the

spectra in light lines in Figure 6), 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 [Kellogg *et al.*, 1999] provides the best way to measure electrostatic waves in the relevant frequency range.

[20] 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 0.02 Hz and the amplitudes of electric field fluctuations in the Cassini range above 0.4 Hz. No such correlation was found, and in fact the calculated correlation is slightly negative, even though both quantities are positive. This provides some slight evidence in favor of electrostatic waves.

5. Discussion

[21] 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 [Kellogg and Lin, 1997 (but there is a typographical error); Kellogg, 2000], a rough estimate of the diffusion of the velocity perpendicular (to the magnetic field) in time τ in a fluctuating electric field was obtained as

$$\frac{\langle \delta v_{\perp}^2 \rangle}{\tau} = \frac{1}{4\pi} \int \left(\frac{qE_{\perp}(\omega)}{m} \right)^2 \frac{d\omega}{\omega}, \quad (3)$$

while the conservation of magnetic moment, v_{\perp}^2/B , would lead to decrease of the perpendicular component according to

$$\frac{d}{dt} (v_{\perp}^2) = \frac{d}{dt} \left(\frac{v_{\perp 0}^2}{B_0} B \right) = -\frac{nv_{\perp 0}^2}{R} V_{sw}, \quad (4)$$

In these, q is the charge of the particle, $E_{\perp}(\omega)$ is the spectrum of the perpendicular component of electric field, v_{sw} is the solar wind speed, and B is assumed to decrease as $1/r^n$. At 4.5 AU, for a solar wind speed of 500 km/sec, a proton temperature of 2 eV and $|B|$ decreasing as $1/r$, we have, from equation (4):

$$\frac{d}{dt} (v_{\perp}^2) = -250 \frac{m^2}{\text{sec}^3}.$$

A form of equation (3) involving cyclotron resonance may easily be obtained, but we take resonance into account simply by integrating equation (3) in the vicinity of the cyclotron frequency. A typical proton cyclotron frequency at 4.5 AU, corresponding to a magnetic field of 1 nT, is 0.015 Hz. This would be observed at about 0.4 Hz due to Doppler shift. The spectrum given by Kellogg [2000] was erroneously calculated from density fluctuations and was

relatively flat compared with what we now think is correct. Hence the diffusion in equation (3) is very sensitive to the lower frequency limit. Again, we use the octave around 0.4 Hz. In this region, the average electric field spectrum, the heavy line in Figure 6, is represented by

$$E^2(f) = 1.2 \times 10^{-10} f^{-5/3} \left(\frac{V}{m}\right)^2 \text{ Hz}^{-1},$$

with F in Hz.

[22] First, it is assumed that the observed electric fields are actually those of electrostatic waves. Performing the integral in equation (3) from 0.28 Hz to 0.56 Hz, (which represents an extrapolation below the lowest measured point at 0.39 Hz) we obtain

$$\frac{\langle \delta v_{\perp}^2 \rangle}{\tau} = 1.1 \times 10^5 \frac{\text{m}^2}{\text{s}^3}.$$

At 4.5 AU, there are qualitative differences with the situation at 1 AU and nearer the Sun. As discussed by Kellogg [2000], 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 Alfvén 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 Alfvén speed, and so magnetic fluctuations provide the dominant diffusive force, (unless there are electrostatic fluctuations). In this case, the $E(\omega)^2$ in equation (3) is to be replaced by $(V_{\text{th}} B(\omega))^2$. Assuming that $B^2(\omega) = E_{\perp}^2(\omega)/V_{\text{sw}}^2$,

$$\frac{\langle \delta v_{\perp}^2 \rangle}{\tau} = 180 \frac{\text{m}^2}{\text{sec}^3},$$

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.

6. Summary and Conclusions

[23] 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 is 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 trans-

form of the magnetic fluctuations, then they are perhaps marginally large enough.

[24] 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. In the case that 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 [Tu, 1988].

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