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DETECTION OF ELECTRIC-FIELD TURBULENCE IN THE EARTH'S BOW SHOCK*

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We present the first account of observation of low-frequency fluctuating electric fields generated in the earth's bow shock. We find that the wave amplitude is not a smooth function of space through the shock, but rather that it is strongly correlated with magnetic-field structures within the shock.

OGO-5 was launched 4 March 1968 into a highly eccentric earth orbit with an apogee of 24 earth radii (≈148 000 km) geocentric. The TRW plasma-wave experiment on board OGO-5 includes five electric-dipole and three magnetic-loop (search coil) sensors mounted on a 22-ft boom. Three short electric-dipole sensors are mounted orthogonally, so that all three electric-field vector components can be measured in time sequence. The output is fed into narrow-band (15%) filters with center frequencies at 0.56, 1.3, 3.0, 7.35, 14.5, 30.0, and 70.0 kHz. The circuits have rise times of 30 msec and decay times of 300 msec. In a given frequency band, each directional component is sampled for 9.2 sec sequentially; after 27.6 sec the center frequency is advanced to the next channel. A complete axis and frequency scan sequence requires 3.2 min. In addition, the wave form on one axis is continuously monitored by a separate broadband (1-22 kHz) analog telemetry system, permitting reconstruction of the power spectrum for this one axis. The remaining two boom-mounted dipoles are collinear. Their output is monitored through a 200-Hz center-frequency filter for about 2 sec every 9.2 sec. The five electric dipoles do not operate as resistively coupled Langmuir probes, but rather are capacitively coupled to the plasma[1] since the dipole dimensions (50 cm) are much smaller than the Debye length, and the current collecting area is small. The dipoles measure potential gradients induced across them by ambient electric fields. The three electrostatically shielded magnetic loops are boom-mounted orthogonal to the main electric dipoles, and they are sequentially sampled by axis and by frequency through 0.56- and 70-kHz filters. The 0.56-kHz magnetic output is phase-shifted, mixed with the 0.56-kHz electric output, and monitored through a zero-crossing correlator, so that electrostatic and electromagnetic waves may be separated.

Figure 1 presents a sequence of approximate electric-field power spectra assembled from the band-pass channel outputs for an outbound shock crossing on 12 March 1968. The abscissa is the frequency from 0.56 to 70 kHz; the ordinate, the maximum power spectral density (regardless of axis) in $(\mu V/m)^2/Hz$ observed in each 27.6-sec channel sample. The time axis is orthogonal to these two, and is shown in perspective along the 45° axis. Each spectrum requires 3.2 min; the initiation of a new spectral sequence is indicated by tick marks along the time axis. Near the origin, OGO-5 was downstream in the post-shock magnetosheath; as time proceeded, the outbound satellite traversed the shock. At the top of Fig. 1, OGO-5 was upstream. Shown in small insets are simultaneous measurements of one component of the magnetic field detected by the University of California at Los Angeles (UCLA) fluxgate magnetometer (sensitive from 0-2.5 Hz at the 8-kbit/sec rate). Upstream (top of Fig. 1) in the solar wind, the magnetic field is quiet, and the electric-field spectrum contains a significant high-frequency component (indicated by shading) which may be near the local electron plasma frequency. Nearer the shock, where the magnetic

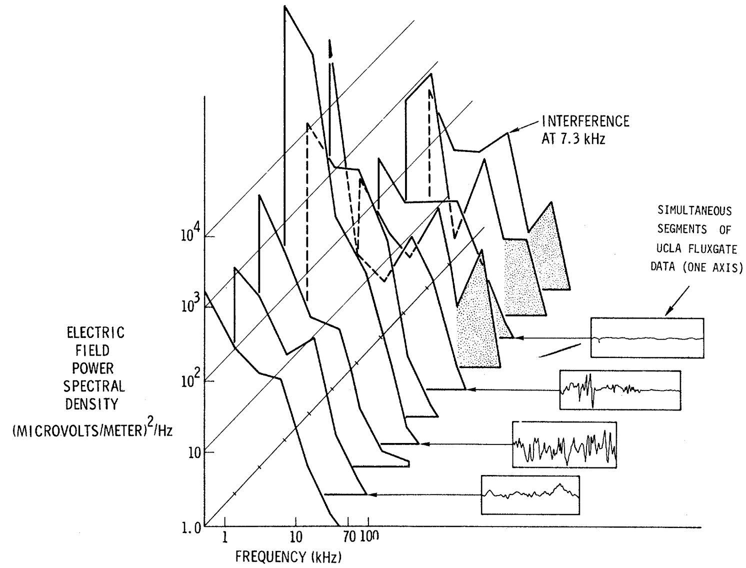

FIG. 1. Approximate ac electric-field power spectra and simultaneous dc magnetometer data for the OGO-5 outbound bow shock crossing of 12 March 1968. Each individual spectrum is made up from readings taken over a 3.23-min sequence, and the final shock crossing (fifth spectrum down from the top) occurred at 2042 UT, with the spacecraft at a radial distance from the earth of approximately 112 000 km.

field is more disturbed, the high-frequency amplitude is significantly reduced. The shock was probably encountered during the formation of the sixth spectral sequence from the top, where the magnetic field is most disturbed. Here, the low-frequency (0.56-3.0 kHz) components are enhanced two orders of magnitude above their upstream amplitudes. The 0.56- to 3.0-kHz peak relaxes downstream to amplitudes which are above the solar-wind upstream level. Thus, high frequencies are quenched near the shock, while lower-frequency waves are greatly enhanced at the shock and relax downstream. During this entire sequence, no magnetic signals with amplitudes greater than 4×10^{-8} G were detected in our 15% bandwidth magnetic channels centered at 0.56 kHz.

Next, we discuss another shock crossing, this time inbound, on 12 March 1968. During 4-19 March 1968, data in 0- to 5-V telemetry units from many particle and field experiments aboard OGO-5 were made simultaneously available in real time in analog strip-chart form, thus permitting visual correlations between related experimental results. A portion of such a raw-data display is shown in Fig. 2 for a shock crossing near 0052:30 h universal time. Our tentative best estimates for the relevant satellite and plasma parameters are as follows: geocentric distance 14.5 earth radii; ecliptic longitude 27°N, latitude 25°W; satellite speed 1.8 km/sec^{-1}; interplanetary field 5.5×10^{-5} G; solar wind speed[2] 400 km/sec^{-1}, and density[2,3] 7 ± 3 cm^{-3}. Included in Fig. 2 are the filter envelopes on a log

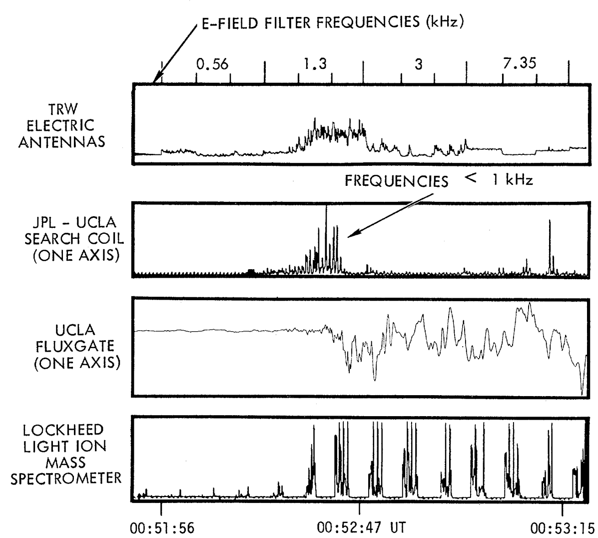

FIG. 2. Simultaneous particle and field measurements during an inbound bow shock crossing of 12 March 1968. The figure shows raw (uncalibrated) data outputs of the TRW electric dipoles (filter channels), a uniaxial spectrum from the JPL-UCLA search coil, one axis (Z) of the UCLA flux gate, and the 0- to 600-eV proton flux measurement by the Lockheed light-ion mass spectrometer.

scale of the three principle TRW electric dipoles at the frequencies indicated; one axis of the JPL-UCLA search-coil magnetometer[4] spectrum channel shows a sudden onset of electric-field noise, and the Lockheed 0- to 600-eV proton channels, empty in the solar wind, show significant counts in the disturbed region. Ordinarily, the ion spectrometer, which does not look in the nominal flow direction, shows low count rates in the supersonic solar wind, since the mean flow energy (850 eV, on this date) is above 600 eV, and the thermal velocity spread is small (T_+ probably 15 eV). The 0- to 600-eV counts indicate that the low-energy portion of the ion distribution is being filled in by shock thermalization. More detailed discussions will be presented separately by the individual experiment groups However, all four experiments show a simultaneous sudden change in plasma conditions consistent with traversal of, or encounter with, a collisionless shock wave.

More detail for this shock crossing is shown on an expanded time scale in Fig. 3. All three components of the UCLA flux-gate output have been summed, and the total magnitude $|\vec{B}|$ is plotted versus time in the lower trace. At the 8-kbit/sec data rate for this crossing, there is a datum point each 144 msec. The simultaneous 1.3-kHz electric-field filter envelope outputs are plotted linearly versus time in the center plot. At the top, the 1.0- to 3.4-kHz portion of the 1- to 22-kHz uniaxial waveform is displayed Fourier analyzed in a frequency-time display. The intensity of the shading is a crude measure of amplitude. The 1.3-kHz electric-field filter outputs are not smooth, but show impulsive enhancements, several of which are more than an order of magnitude over the mean level. Some of the more intense impulses appear to correlate with regions of large gradients in $|\vec{B}|$. The dynamic spectrum (top of diagram) reveals that these impulses observed on the 1.3-kHz narrow-band channel correspond to almost undispersed broad-band impulses, which decay somewhat in intensity from 1.0 to 3.4 kHz. The two electric dipoles at 200 Hz (not shown here) also exhibit this impulsive behavior. The 560-Hz TRW magnetic loops showed no signal above their threshold ($\approx 4\times 10^{-8}$ G rms in a 15% bandwidth). If the 560-Hz electric channel had the same amplitude as the 1.3-kHz channel, and if the waves observed were the electric components of whistler-mode waves, the magnetic amplitudes would have saturated the TRW 560-Hz magnetic channel.

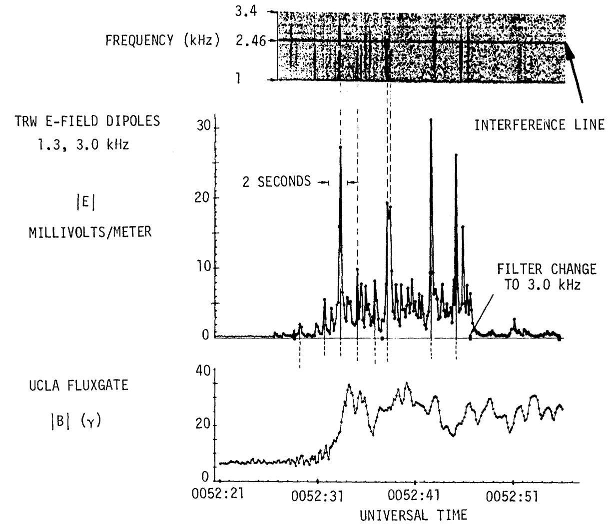

FIG. 3. A simultaneous display of the dynamic spectrum of the electric field, the filter envelope, and the flux-gate field magnitude during the 12 March inbound crossing discussed in text. Note the time correlations of electric-field noise on the dynamic and bandpass spectra with regions of large $DB/Dt \approx UdB/dx$. This suggests that electrostatic turbulence is produced by large current densities in these regions of large dB/dx, perhaps by the ion-electron two-stream instability.

The correlation of the electric-field turbulence with gradients in $|\vec{B}|$, and the apparent absence of correlated magnetic fluctuations at 560 Hz with the electric-field observations, leads us to suggest tentatively that the turbulence is produced by a current-driven instability, perhaps of the ion acoustic wave. OGO-5 Langmuir-probe measurements[5] made just prior to the first steep gradient in $|\vec{B}|$ indicate rapid production of hot ($\approx$100-eV) electrons. Such electrons were absent upstream, and persist through the structure shown in Fig. 3. Thus, the large electron-to-ion temperature ratio required to allow relatively small currents to destabilize the ion acoustic wave[6] may exist. The broad-band frequency spectrum could then possibly be explained by Doppler shifting.

We have analyzed several other shock crossings during March 1968, which exhibit a variety of detail from one to another. Thus, the specific structure shown in Fig. 3 is by no means universal. However, a majority of the crossings examined so far have significant electric-field turbulence in the shock layer.

This analysis of shock structure would have been impossible without the willing collaboration of many experimental groups. We are particularly grateful to P. J. Coleman, Jr., and L. Simmons for providing us with the magnetic-field data from the UCLA flux-gate magnetometer, and for allowing us to display the results in detail. We thank E. J. Smith and R. E. Holzer for permission to show their search coil data on Fig. 2, and G. W. Sharp at Lockheed Research Laboratories for the mass spectrometer data on Fig. 2. We thank K. Norman for information about the Langmuir-probe results, and M. Neugebauer for furnishing us with an upstream solar-wind velocity value for the 12 March shock crossing.

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[2]These speed and density estimates derive from OGO-5 plasma probe measurements (M. Neugebauer and C. Snyder, private communication). The steady aerodynamic flow model of the bow shock would predict a shock normal direction $\hat{n}$ within a few degrees of the geocentric radial direction. Upstream the solar-wind direction was measured at about 5° west of the earth-sun line, or at −150° from $\hat{n}$. The interplanetary field B_0 was directed at an angle of some +136° from $\hat{n}$.

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EVIDENCE FOR A GEOELECTRIC FIELD OVER THE POLAR CAP

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During the period of high solar and geomagnetic activity between 22 May and 25 May 1967, energetic proton fluxes were detected coming up the magnetic field lines from the earth at high magnetic latitudes ($\Lambda \geq 65$–$70°$). Because of the peaking of the flux along the magnetic field lines, the existence of a radial polar electric field is suggested. The average electric-field value required is 0.14 V/m.

Electric fields have been suggested[1] as possible explanations for aurora or other polar-cap particle precipitation. Particle fluxes which indicate the existence of a polar electric field during periods of unusually high activity were observed by Air Force satellite.

During the period of high solar and magnetic activity in late May 1967, the satellite, OV1-9, had an apogee of 4800 km approximately over the magnetic north pole. The spin of the satellite was such that a proton detector on board (240-1000 keV) was able to scan almost all pitch angles. During three orbits taken in this period, a highly collimated flux of protons was detected coming up the field lines from the earth at magnetic latitudes $\Lambda \geq 70°$. The detection of these fluxes was predominantly at local night. Each energy channel was sampled for 2 sec every 16 sec. This, together with the spin rate of satellite, restricted us to roughly six samples per energy channel over the polar regions. Although polar coverage was available for two orbits taken during the quiet time of 9 May 1967, no such fluxes were observed.

The instrument used was a solid-state silicon detector telescope with a 1000-G sweeping magnet to eliminate low-energy electrons. Five energy channels measured protons between 240 and 1000 keV with a resolution of 18 %. The full width at half-maximum opening angle of the instrument was 6.5°. This instrument has been described elsewhere.[2] The output of a triaxial 0.200-G magnetometer was fitted with a cosine curve to determine the instrument's orientation