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Excitation of Magnetospheric Hydromagnetic Waves by Solar-Flare-Induced Change in Ionospheric Conductivity

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(Received 20 July 1981)

Observations are reported of magnetospheric hydromagnetic (Alfvén) waves excited by rapid changes in ionospheric conductivity induced by solar flare x-ray and extreme-ultraviolet fluxes. The observed wave frequencies (~0.01–0.02 Hz) are those expected for fundamental eigenoscillations of the geomagnetic field at middle latitudes. The measurements confirm a natural hydromagnetic wave generation mechanism not associated with the solar wind or geomagnetic storms. These results have implications for Alfvén wave generation in other cosmic plasmas.

PACS numbers: 94.30.Va, 94.20.Yx

Alfvén waves have been measured and studied in Earth's magnetosphere and in the solar wind and are believed to be important in stellar and interstellar plasmas as well.[1-3] We report in this Letter observations of the excitation of Alfvén waves in Earth's magnetosphere following sudden changes in the conductivity of the sunlit ionosphere. We believe this is the first confirmation of natural hydromagnetic wave generation in the magnetosphere not associated with the solar wind or geomagnetic storms. Although an earlier report[4] presented evidence for ground-based geomagnetic field oscillations following some solar flares, the limited (one-station) magnetic data could not be used to determine either the global nature of the phenomenon or its relationship to the state of the ionosphere.

The data reported here were acquired using four sensitive magnetometers[5] spaced in geographic latitude between 43° and 49° in New Hampshire and southern Quebec.[6] These instruments record changes in the magnetic field at Earth's surface from variations occurring in ionospheric currents produced by magnetospheric processes. The changes in ionospheric conductivity were measured at each magnetometer site by a sensitive radio receiver (riometer) with broadbeam (60°) zenith-directed antenna that records variations in the 30-MHz cosmic noise transmitted through the ionosphere. Of special importance for establishing the global, magnetospheric character of the observations are the measurements of magnetic field and cosmic noise made in the southern hemisphere at Siple Station, Antarctica, in the region magnetically conjugate to the North American observations.[5] The data were obtained during conditions when the southern ionosphere was in near darkness and the northern ionosphere was in daylight (solar zenith angles of 89°–93° and 39°–55°, respectively, at 100-km altitude). Two of several events in 1980 that have been observed during the increasing phase of the 21st solar cycle are described.

Figure 1 illustrates solar x-ray and ionization-related data for a solar flare event that began near 2030 UT. The top two panels show the count-

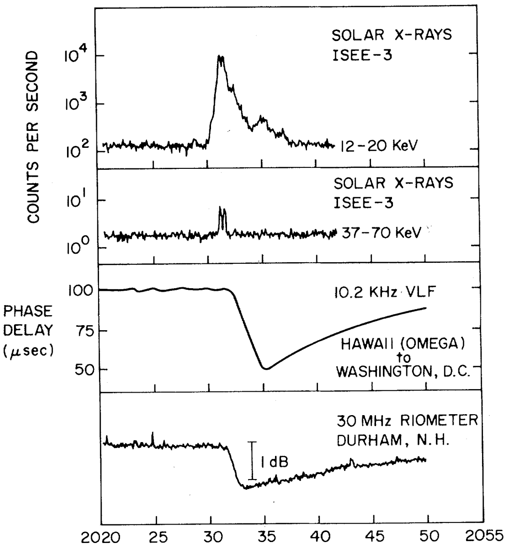

FIG. 1. Solar x rays in two energy channels (upper two panels) for a flare event. The response of the dayside ionosphere is indicated by a sudden phase anomaly on long-path VLF propagation (third panel) and enhanced absorption of 30-MHz galactic radio noise (bottom panel).

ing rate response of two channels (12–20 and 37–70 keV) of the ISEE-3 spacecraft x-ray detector.[7]

Two responses of the dayside ionosphere to the enhanced x-ray flux are shown (i) in the third panel by the sudden phase anomaly in the 10.2-kHz Omega navigation signal propagating from Hawaii to Washington, D. C. and (ii) in the bottom panel by the ionospheric absorption of 30-MHz galactic radio noise recorded by a riometer located at Durham, New Hampshire. The onset of these effects at 2031–2032 UT was essentially coincident with the time of peak solar x-ray flux. These ionosphere responses, exhibiting rapid excursions (~ 1–3 min) to maximum disturbance, followed by slow (~ 15–30 min) exponential-like recoveries, are characteristic of solar-flare x-ray–induced ionosphere events. The rise and decay times depend on the time profile and spectral intensity of the x-ray (and ultraviolet) flux, the solar zenith angle, and the response time of the ionosphere.

The ground-level magnetic field variations in the plane parallel to Earth that accompanied the ionospheric event are shown in Fig. 2 for the five magnetometer stations. The riometer data for Durham (DU) and Pittsburg (PB), the lowest-latitude sites, are shown in the bottom left and right panels, respectively. Similar cosmic-

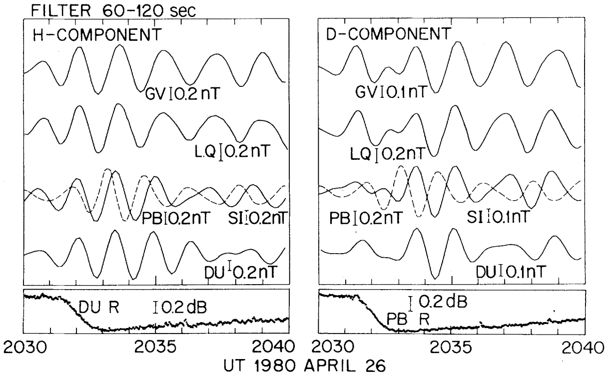

FIG. 2. Surface magnetic field variations (after application of a digital bandpass filter with cutoffs at 60 and 120 sec) in the horizontal (*H–D*) plane at four locations along a meridional chain in the northern hemisphere (GV, LQ, PB, and DU in order of decreasing latitude) and at a station (SI) in the Antaractic conjugate region during the solar x-ray event of Fig. 1. The SI data (dashed curves) are superimposed on the curves for PB which, apart from the phase shift, they most closely resemble. The *H* component (*D* component) lies along the magnetic north-south (east-west) direction. 30-MHz riometer data are also shown for the two lowest-latitude sites. The local time of these measurements is 1530–1540.

noise-absorption events were also observed at the higher-latitude sites, La Tuque (LQ) and Girardville (GV). The riometer at Siple (SI), however, did not record an absorption event, consistent with the large solar zenith angle (93.5°) at Siple at this time.

The magnetometer data, bandpass filtered in the period range 60–120 sec, show clearly the excitation of ~90-sec-period oscillations at all sites in the interval from 2031 to 2036 UT. Thereafter, the wave amplitudes decrease, the period lengthens, and in general the features of the variations become less coherent between the stations. No comparable oscillations in this period band were evident prior to 2030 UT. Note that at Siple the oscillations (dashed curves) are out of phase with those seen in the northern hemisphere. This phase shift is related to differences in the rotation directions of the magnetic vectors in the horizontal plane in the northern and southern hemispheres.

Further analysis has shown[6] that the oscillations in the *H-D* plane in the interval 2032–2035 UT are left-hand polarized at the two lower-latitude stations. At the higher latitudes the polarizations, although somewhat mixed, could be characterized as right handed. The polarization at

Siple is left handed, the same as that seen at the lower-latitude stations in the north. The apparent change in wave polarization at magnetic latitudes between $L\sim3.5$ and $L\sim4.0$ suggests that an excited wave resonance could be located in this latitude range.[8-10] Ground magnetic field measurements alone, however, cannot identify the polarization of the wave in space.

Figure 3, similar in format to Fig. 2, shows the magnetic and cosmic noise variations which accompanied another solar-flare hard–x-ray event. The main x-ray burst (not shown) began at 1508–1509 UT and lasted about 5 min. The onset of ionospheric response at 1510–1511 UT (1010–1011 local time) was essentially coincident with the time of peak x-ray flux, as for the first event discussed. The principal magnetic field oscillation excited at the two northern-hemisphere low-latitude sites appears in both the H and D components with a period of ~90–100 sec. However, at the two highest-latitude sites the dominant period in the H components (~40–50 sec) was slightly more than half the period of the D-component variations at these latitudes and in the oscillations of all components at the lower-latitude stations. The excitation of the higher-frequency wave at the higher latitudes likely indicates a plasma density gradient within the range $L\sim3.5$ to $L\sim4.0$, as suggested by contemporary hydromagnetic wave theory.[8,9] Magnetic field oscillations were also recorded at Siple (not shown), but no enhanced absorption of cosmic noise was evident (solar zenith angle ~89°).

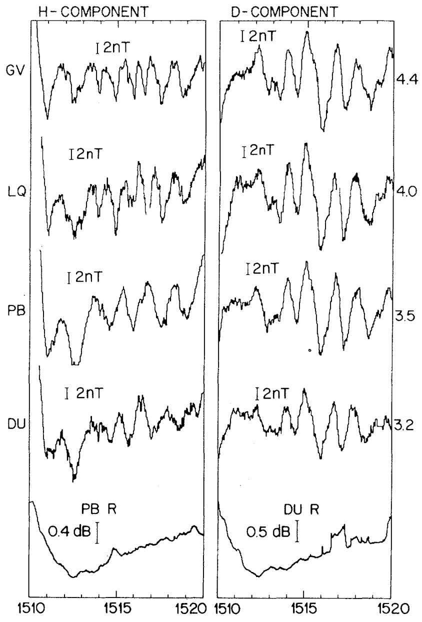

FIG. 3. Magnetic field variations in the horizontal plane (unfiltered) and riometer data during a solar hard–x-ray event. The local time of these measurements is 1010–1020.

In the examples discussed, the occurrence of magnetic oscillations at both ends of a field line, associated with solar-flare–induced conductivity change at only one end, is evidence of their global (dayside) excitation. The oscillations were not induced by, for example, similar period variations in the ionizing x rays and/or the altered conductivity, since no such variations were present. At the observed wave frequencies, which are much less than the ion gyrofrequency in the magnetospheric plasma (~1 Hz), the oscillations are hydromagnetic waves. We tentatively identify them as transverse Alfvén waves because the observed wave periods are consistent with those expected for fundamental eigenoscillations of the geomagnetic field and because of the fact that hydromagnetic waves of generally similar character, excited by solar wind and geomagnetic storm sources, can be interpreted as transverse Alfvén waves.[8,9]

The eigenoscillation periods of the geomagnetic field have been computed for magnetospheric plasma density conditions typical of the L shell (latitude) range of interest here.[11] The eigenperiods of the fundamental oscillations are in the 45–150- and 15–45-sec bands for field lines located, respectively, inside and outside the plasmapause. The average planetary geomagnetic activity index K_p for the twelve hours preceding the event of Fig. 3 (about 3+, a moderately disturbed condition) would place the dayside plasmapause at $L\sim4$ at the time of that event.[12] Thus, the observation of more than one wave at higher latitudes is consistent with the simultaneous excitation of a higher-frequency (~0.02-Hz) wave outside the plasmapause and a lower frequency (~0.01-Hz) wave inside. In constrast, the geomagnetic field was relatively quiet (average $K_p\sim1$) for the event of Fig. 2. For this condition the location of the dayside plasmapause is expected to be poleward of the highest-latitude station,[12] consistent with the excitation of only a longer-period wave within the L range observed. For both events, however, the wave amplitudes and polarizations observed at ground stations will be influenced by the proximity of the observing station to the resonant field lines[8-10] and by ground induction and atmospheric screening effects.[13]

The mechanism of excitation of these hydromagnetic waves is clearly related to the sudden increase in conductivity in the D and E regions of the ionosphere produced by the solar-flare x-ray (and ultraviolet) fluxes. Information available on the spectral content of these flares in the x-ray and extreme ultraviolet energy range is being used to determine the height- and time-dependent changes in conductivity. Detailed model calculations based on realistic configurations of ionospheric electric fields and current flows are in progress which will incorporate these large-scale changes. If we assume, for simplicity, that no change occurs in the ambient (horizontal) ionospheric electric fields on the time scale of the impulsive phase of a solar x-ray event ($\lesssim 5$ min), then a conductivity change should lead to an impulsive change in horizontal current flow and, thence, to a transverse magnetic perturbation sufficient to excite resonance oscillations.

Other processes that lead to enhanced ionospheric conductivity in the D and E regions, such as the precipitation of auroral particles[14] and artificial heating,[15] might be similarly effective in stimulating hydromagnetic waves. The excitation of hydromagnetic field line resonances might also be expected to accompany a rapid decrease of ionospheric conductivity such as could be produced by appropriate chemical releases in the ionosphere under certain active experiment conditions. Alfvén waves may also be produced in stellar atmospheres during large flares, when enhanced ionization occurs.

This work was supported in part by the National Science Foundation Division of Atmospheric Sciences (Grant No. ATM-8006496) and Division of Polar Programs (Grant No. DPP-7925014) and by the Computer Science Center of the University of Maryland. We thank Dr. S. Kane of the University of California, Berkeley, for providing the solar-flare x-ray data from the ISEE-3 satellite and L. Lutz, L. V. Medford, and C. G. Maclennan for technical assistance.

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