Plasma Waves Observed Inside Plasma Bubbles in the Equatorial $F$ Region

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Plasma waves have been detected within and around density depletions in the topside equatorial F region by the electric and magnetic field sensors of the Extremely Low Frequency Wave Analyzer (ELFWA) instrument which is part of the Low-Altitude Satellite Studies of Ionospheric Irregularities experiment on the Combined Release and Radiation Effects Satellite. The plasma waves include both electrostatic waves that have a small magnetic field component and electromagnetic waves propagating in the extraordinary mode. Thus they are not simply zero-frequency irregularities as generally assumed by previous investigators who were working without the benefit of high-sensitivity ac magnetic field measurements. The waves exhibit no resonances or cutoffs at characteristic frequencies of the plasma within the range of the ELFWA which is 2–125 Hz. They occur from late evening to early morning primarily at altitudes around 400–500 km. An example has been observed as high as 1500 km. The waves are associated with plasma depletions from a factor of 2 to a factor of 80 less than the surrounding density. The observations indicate that the waves are related to equatorial spread F.
Plasma waves observed inside plasma bubbles in the equatorial $F$ region

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Abstract. Plasma waves have been detected within and around density depletions in the topside equatorial $F$ region by the electric and magnetic field sensors of the Extremely Low Frequency Wave Analyzer (ELFWA) instrument which is part of the Low-Altitude Satellite Studies of Ionospheric Irregularities experiment on the Combined Release and Radiation Effects Satellite. The plasma waves include both electrostatic waves that have a small magnetic field component and electromagnetic waves propagating in the extraordinary mode. Thus they are not simply zero-frequency irregularities as generally assumed by previous investigators who were working without the benefit of high-sensitivity magnetic field measurements. The waves exhibit no resonances or cutoffs at characteristic frequencies of the plasma within the range of the ELFWA which is 2–125 Hz. They occur from late evening to early morning primarily at altitudes around 400–500 km. An example has been observed as high as 1500 km. The waves are associated with plasma depletions from a factor of 2 to a factor of 80 less than the surrounding density. The observations indicate that the waves are related to equatorial spread $F$.

Introduction

In this paper we describe measurements of the magnetic and electric components of naturally occurring extremely low frequency (ELF) plasma waves associated with density depletions in the nighttime, topside, equatorial $F$ region. The observations were made by the Low-Altitude Satellite Studies of Ionospheric Irregularities (LASSII) experiment [Rodríguez, 1992] on the Combined Release and Radiation Effects (CRRES) satellite. The objective of the LASSII experiment was to determine the mechanisms responsible for naturally occurring and artificially created plasma irregularities in the low-latitude ionosphere.

The LASSII experiment consists of a pulsed plasma probe ($P^3$), an extremely low frequency wave analyzer (ELFWA), and a quadrupole ion mass spectrometer (QIMS). The plasma wave measurements were report made by the ELFWA, and the electron density measurements were made by the $P^3$. The ELFWA is designed to measure both the electric and the magnetic field components of electromagnetic and electrostatic plasma waves at frequencies from 2 to 125 Hz.

Previous spacecraft [Kelley and Mozer, 1972; Hysell et al., 1977; Aggson et al., 1993; Hyseal et al., 1994] measured plasma waves and irregularities associated with spread $F$ in the topside equatorial $F$ region have used sensitive electric field detectors. However, they have either made no magnetic field measurements at all or they used aspect magnetometers that do not have sufficient sensitivity to measure the magnetic field components of ELF plasma waves. Hence previous measurements have been unable to determine if the waves they detected were electromagnetic. Under those circumstances most investigators assumed that the ac electric field fluctuations they observed were due to the antenna passing through a region of nonpropagating or zero-frequency irregularities [Holtet et al., 1993; Aggson et al., 1993]. Kelley and Mozer [1972] inferred the electrostatic nature of the waves that they observed at the equator from the fact that another satellite detected no magnetic component for "similar" emissions at high latitudes.

Kelley et al. [1979] reported a single spacecraft observation of ELF electromagnetic waves associated with equatorial spread $F$ below the $F$ peak. The electric field signals were measured in the $4–16$ Hz and $256–1024$ Hz channels, and the magnetic field was measured in a single channel at $999$ Hz.

Theories for the formation of spread $F$ phenomena are extensive (for a review, see Kelley [1989, chapter 4]). It is commonly assumed that the generalized Rayleigh-Taylor instability occurs in the nighttime, bottomside $F$ region to produce large-scale density depletions. These depletions convect upward, resulting in sharp density gradients in the topside $F$ region. The large-scale features are thought to eventually generate a spectrum of small-scale irregularities via several processes. Candidate mechanisms include the turbulent cascade of long wavelength irregularities to short wavelength irregularities and the electrostatic gradient drift instability. Both of these processes produce only density variations. These density variations are detected as ac voltage variations on an antenna moving through them. There are no accompanying magnetic field variations. The observations reported here of electromagnetic waves and electrostatic waves (with small magnetic components) propagating at a nonzero angle with respect to the geomagnetic field in the topside spread $F$ region generally contradict existing theories of spread $F$ formation.

Instrument Overview

Spacecraft. The CRRES spacecraft is a spinning spacecraft with a perigee of 350 km, an apogee of 33,580 km, an
period of 30 s. This orbit provided only limited opportunities when the CRRES mission ended. The primary region of interest was the nighttime sector constrained by orbital operations which limited LASSII's duty time with an apparent period of 1.5 years. When perigee was on the nightside, LASSII performed measurements every fourth orbit below an altitude of 3000 km. When perigee was on the dayside, measurements were performed every fourth orbit below 1000 km. This schedule yielded a total of 264 perigee data acquisitions between July 28, 1990, and October 11, 1991, when the CRRES mission ended.

**Description of Data**

The primary data for this study consist of color spectrograms of the ELF electric and magnetic fields for each of the 264 perigee acquisitions between July 28, 1990, and October 11, 1991, for which data were collected by the LASSII instruments. The electric field spectrograms cover the frequency range from 2 to 125 Hz when the magnetic field data were collected and 2 to 250 Hz when only the electric field data were collected. Evidence for electromagnetic waves was found on 37 of the 264 spectrograms. In all, 53 such events were found on the 37 spectrograms.

We have determined that the largest amplitude waves are primarily electrostatic with a small magnetic component. However, electromagnetic waves propagating in the extraordinary mode were also observed. Both the electrostatic and the electromagnetic waves appear to be related to density depletions, and they may play an important role in the kilometer scale processes occurring within spread F regions. In the remainder of the paper we describe the characteristics and occurrence of these waves.

**Example event.** We will first describe the characteristics of an example event that was observed on October 7, 1991. The spectrogram in Plate 1 shows a series of field enhancements between 0522 and 0526 UT. The characteristic feature in the spectrum is the intense, wideband signal that crosses essentially the entire frequency range from 10 to 125 Hz. The feature can be seen in both the electric field and the magnetic field components. Each vertical band is about 30 s wide, and four bands can be easily discerned. At 0524 UT the spacecraft was at an altitude of 453 km and a magnetic latitude of 6.2°N moving with a velocity of 10 km s⁻¹. The local time was 0245. The total width in time of the four events is 156 s. Thus they were observed for a total distance of 1500 km along the track of the spacecraft. The length of the individual features ranges from 240 to 480 km along the track. This is essentially the horizontal size of the features because the vehicle velocity vector was pointing only 10° above the horizontal at this time. Figures 1a and 1b show the broadband intensity within the band of the receivers for the entire perigee pass shown in Plate 1. The enhancements between 0522 and 0526 UT stand out several tens of decibels above the background in the magnetic channel (Figure 1b), and there is essentially no background at the receiver gain setting used for the electric channel (Figure 1a). These enhancements dominate the electric field data during this data acquisition.

The cause of the background in the magnetic channel is not known. It may be electromagnetic interference, or it may be...
Plate 1. Spectrogram from the Extremely Low Frequency Wave Analyzer (ELFWA) on October 7, 1991. (top) Data from the magnetic field antenna and (bottom) data from the electric field antenna.
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The broadband field intensities and plasma density measured as a function of time during the perigee pass around 0520 UT, October 7, 1991. (a) The ac electric field, (b) the ac magnetic field, and (c) the electron density. The strong modulation of the electron density is caused by the rotation of the probes through the ram and wake of the spacecraft. The values on the y axis apply to the upper envelope of the modulated spectrum.

Figure 1. The broadband field intensities and plasma density measured as a function of time during the perigee pass around 0520 UT, October 7, 1991. (a) The ac electric field, (b) the ac magnetic field, and (c) the electron density. The strong modulation of the electron density is caused by the rotation of the probes through the ram and wake of the spacecraft. The values on the y axis apply to the upper envelope of the modulated spectrum.

the magnetic component of an electromagnetic wave propagating in a mode for which the electric field component is below the noise level of the broadband electric field measurement. The background in the magnetic channel shows little structure on the color spectrogram in Plate 1 and has a low-frequency cutoff above the oxygen ion gyrofrequency which was 24.8 Hz at 0520 UT.

Figure 2. The broadband intensity measured as a function of time within the 125-Hz bandwidth of the ELFWA. The data were taken during the perigee pass around 0520 UT, October 7, 1991. This is an enlargement of the time period from Figure 1 when the most intense emissions were observed.

Figures 2a and 2b show the broadband signal within the band of the receivers for the 10-m time period approximately centered on this event. It shows the general correlation in time on this scale of the features in the electric and the magnetic channels. Although the magnetic data appear to contain more structure, there is usually a corresponding maxima in both channels almost simultaneously.

Figure 3 shows the waveform data from each antenna for the 4-s period between 0525:08 and 0525:12 UT. The high degree of temporal relationship between the waveforms from the two channels is convincing evidence that these waves have both electric and magnetic components.

Figure 1c shows the signal from the Langmuir probe for this data acquisition. At the time the Langmuir probe was operating at a constant positive bias to collect electrons. The modulation of the signal is caused by the changing aspect angle of the collecting surface of the probe with respect to the ram direction and with respect to the geomagnetic field. The slow variation of the envelope is caused by the slow change of these aspect angles along the orbit. The rapid fluctuations are caused by the change in the aspect angles as the spacecraft rotates. At the higher altitudes near the beginning and end of the data acquisition shown in Figure 1 the Debye length in the plasma is ~2 cm, and the plasma sheath around the probe is comparable to the dimensions of the probe. Under those conditions the aspect dependent modulation is small. Near perigee the sheath is almost an order of magnitude smaller, and then the modulation is large. The electron density is determined from the upper envelope of the signal. The upper envelope represents the maximum current collected in a rotation period. This occurs when the probe axis is most nearly perpendicular to the ram and to the geomagnetic field. The actual value determined from the upper envelope is a lower limit to the density since exact perpendicularity to both the ram and the geomagnetic field is seldom realized simultaneously.

Coincident in time with the three large electric field events in Figure 1 around 0525 UT are noticeable decreases in the Langmuir probe signal. Figure 2 shows an expanded view of the data for this time period. From 0521 to 0527 UT the modulation of the signal caused by the rotation of the spacecraft is relatively small. Superimposed on this modulation are a number of irregular decreases in the signal from the probe. These decreases are actual decreases in the electron density. The density obtained from the upper envelope of the curve around 0525 UT is $8 \times 10^{12}$ m$^{-3}$. The signal at the minima in
the deeper depletions corresponds to a density of $10^{10}$ m$^{-3}$. This represents density depletions of a factor of 80 that are generally coincident with the larger ELF events. The modulation of the signal from the Langmuir probe is expected to be smaller within a density depletion because the plasma sheath surrounding the probe is large. These electron density depletions resemble the ion density depletions known as plasma bubbles observed by Ogo 6 [Hanson and Santani, 1973] and by the Atmospheric Explorer satellite AE-C [McClure et al., 1977] in both the depth of the depletion and the east-west size of the bubbles.

The correspondence between the electric field intensity and the density depletions that we have observed is essentially the same as reported by Aggson et al. [1993]. They attributed the electric field signals on the San Marco satellite to spatial irregularities along the trajectory of the spacecraft with dimensions varying from 1 m to 1 km in the east-west direction. They show that at wavelengths greater than the ion gyroradius the rms ac electric field amplitude closely tracked variations in the dc electric field. There have been no previous reports of measurements of ELF magnetic fields associated with density depletions in the topside, equatorial F region.

**Wave modes.** The density depletions complicate the determination of the wave modes for the observed ELF signals. The wave mode for an electromagnetic wave can be determined from its index of refraction in the plasma. The index of refraction for a wave can be estimated from the ratio $cB/E$, where $c$ is the speed of light, $B$ is the magnetic field intensity, and $E$ is the electric field intensity. Because the antenna system has only one axis per component, the spacecraft is rotating, and the duration of the waves is short compared with the spin period of the spacecraft, this gives only a crude estimate of the index of refraction. However, this estimate is normally adequate to distinguish electromagnetic waves from predominantly electrostatic waves.

For the index of refraction estimate we use the broadband data rather than the waveform sampled data because the calibration of the former does not depend on the response of the AGC circuit to rapidly varying signals as does the latter. Table 1 contains the values for $B$ and $E$ and the ratio $cB/E$ obtained at selected local maxima in the broadband data throughout the perigee acquisition on Orbit 1055.

The first three events in Table 1 occurred above 1000 km. They are relatively short (less than 2 s long) and show the characteristic harmonic bands associated with satellite observations of multiple stroke lightning [Shaw and Gurnett, 1971]. This pattern of vertical dashes on the spectrogram is especially noticeable in Plate 1 for the lightning event at 0508:03 UT. They are caused by lightning-generated waves traveling in either the right-hand or the extraordinary propagation mode. At the locations where they were observed, the indices of refraction for the two electromagnetic modes were too close to distinguish them apart using the broadband data, and the duration of the signals was too short to distinguish the modes using the rotating antenna pattern to determine the direction of the components with respect to the geomagnetic field.

The peaks at 0524:07, 0524:55, and 0525:37 UT have indices of refraction below 40 and thus are predominantly electrostatic. These are the three events which stand out in intensity above the others in the electric field data shown in Figure 1a. It is interesting to note in Table 1 that it is a larger electric field that yields the lower index of refraction estimate. The magnetic field for all the events in Table 1 after 0522:21 UT has only a 16-dB intensity range from +42.5 to +58.3 dBpT. The electric field, however, has a 46.5-dB range from −90.5 to −44.0 dBV m$^{-1}$ Hz$^{1/2}$.

Figure 4 shows a graph of the index of refraction for the extraordinary and the right-hand electromagnetic modes as a function of the electron density. The values are calculated for the magnetic field intensity at the satellite at 0525 UT. The vertical dotted lines in the figure identify the upper and lower density limits obtained from the Langmuir probe data around that time. The horizontal dotted lines identify the extreme upper and lower limits for the indices of refraction based on those density limits. The index of refraction can range from 211 to 1884 for the extraordinary mode $n_e$ and from 131 to 1167 for the right-hand mode $n_r$. Since the three extreme low values for $cB/E$ in Table 1 are significantly less than the lowest expected values for $n_e$ and $n_r$, they must correspond to electrostatic waves with a small magnetic component. These waves have the same characteristics as those that were generated by the CRRES low-altitude chemical releases [Koons and Roeder, 1995]. The waves generated by the chemical releases had val-

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**Table 1.** Maximum Electric and Magnetic Field Intensities for the ELF Events Observed During Orbit 1055 on October 7, 1991

<table>
<thead>
<tr>
<th>Universal Time</th>
<th>$E_r$ dBV m$^{-1}$</th>
<th>$B_r$ dBpT</th>
<th>cB/E</th>
</tr>
</thead>
<tbody>
<tr>
<td>0508:03</td>
<td>−90.0</td>
<td>24.0</td>
<td>150</td>
</tr>
<tr>
<td>0512:02</td>
<td>−89.0</td>
<td>26.0</td>
<td>169</td>
</tr>
<tr>
<td>0512:16</td>
<td>−86.0</td>
<td>31.0</td>
<td>215</td>
</tr>
<tr>
<td>0522:12</td>
<td>−90.5</td>
<td>42.5</td>
<td>1340</td>
</tr>
<tr>
<td>0522:21</td>
<td>−78.8</td>
<td>56.0</td>
<td>1649</td>
</tr>
<tr>
<td>0522:49</td>
<td>−79.2</td>
<td>48.4</td>
<td>720</td>
</tr>
<tr>
<td>0523:41</td>
<td>−82.4</td>
<td>52.9</td>
<td>1746</td>
</tr>
<tr>
<td>0523:53</td>
<td>−77.9</td>
<td>55.1</td>
<td>1340</td>
</tr>
<tr>
<td>0524:04</td>
<td>−59.8</td>
<td>55.6</td>
<td>177</td>
</tr>
<tr>
<td>0524:07</td>
<td>−45.3</td>
<td>56.5</td>
<td>37</td>
</tr>
<tr>
<td>0524:55</td>
<td>−50.7</td>
<td>50.6</td>
<td>35</td>
</tr>
<tr>
<td>0525:08</td>
<td>−67.9</td>
<td>55.6</td>
<td>449</td>
</tr>
<tr>
<td>0525:27</td>
<td>−69.3</td>
<td>56.9</td>
<td>613</td>
</tr>
<tr>
<td>0525:37</td>
<td>−44.0</td>
<td>54.7</td>
<td>26</td>
</tr>
<tr>
<td>0525:40</td>
<td>−55.3</td>
<td>58.3</td>
<td>144</td>
</tr>
</tbody>
</table>

$E_r$, extremely low frequency; $E$, electric field; $B_r$, magnetic field; $c$, speed of light.
The locations in altitude and local time where the plasma waves associated with plasma bubbles in the equatorial $F$ region were observed. The dotted line is the lower limit of Figure 5. The locations in altitude and local time where the region accessible to the CRRES orbit during the 15 months of observations.

The spectra of the latter three categories are essentially the same. They are broadband with no resonances or cutoffs at characteristic frequencies of the plasma within the range of the ELFWA.

The waves are not simply zero-frequency irregularities as generally assumed by previous investigators; they are associated with plasma depletions from a factor of 2 to a factor of 80 less than the surrounding density. The observations indicate that both the electrostatic and the electromagnetic waves are associated with equatorial spread $F$.

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Figure 5. The locations in altitude and local time where the plasma waves associated with plasma bubbles in the equatorial $F$ region were observed. The dotted line is the lower limit of the region accessible to the CRRES orbit during the 15 months of observations.

<table>
<thead>
<tr>
<th>Altitude, km</th>
<th>Local Time, h</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>3</td>
</tr>
<tr>
<td>400</td>
<td>6</td>
</tr>
<tr>
<td>600</td>
<td>9</td>
</tr>
<tr>
<td>800</td>
<td>12</td>
</tr>
<tr>
<td>1000</td>
<td>15</td>
</tr>
<tr>
<td>1200</td>
<td>18</td>
</tr>
<tr>
<td>1400</td>
<td>21</td>
</tr>
<tr>
<td>1600</td>
<td>24</td>
</tr>
</tbody>
</table>

These waves were not observed uniformly in space or time during the CRRES mission. They were only observed in the nightside ionosphere between 1900 and 0600 LT. Figure 5 shows a scatterplot of the wave observations in altitude and local time. The dotted line in Figure 5 is the lower limit of the CRRES observations. At launch, perigee occurred at 2000 LT. By the end of the mission, perigee had rotated to 0200 LT. This left a premidnight gap in coverage as shown in the figure. The waves occur throughout the altitude range of the LASSII observations from perigee, which varied from 327 to 350 km during the 15-month mission, up to 1000 km. Two isolated events were also detected above that at altitudes of 1308 and 1574 km. Although there is reasonably complete coverage of the dayside ionosphere between the altitudes of 350 and 1000 km, no waves with these characteristics were detected on the dayside. The peak of the occurrence distribution is between 400 and 500 km. Most of the observations in that range occurred between 0300 and 0600 LT. The waves are observed on the topside of the $F$ region between sunset and sunrise. The perigee of the CRRES spacecraft was too high to make observations below the peak of the $F$ layer. The overall morphology of these ELF plasma waves is similar to the morphology of equatorial spread $F$ [Calvert and Schmidt, 1964; Singleton, 1968].

In order to determine if the observations are related to field-aligned plasma depletions we also mapped the observations along the geomagnetic field line to the equatorial plane [Mendillo and Tyler, 1983]. A scatterplot of the equatorial altitude of the magnetic field line versus local time showed significantly more scatter in altitude than the data in Figure 5 for the postmidnight emissions and about the same scatter for premidnight emissions. For the postmidnight emissions the observation altitudes better organize the data than the equatorial altitudes of the magnetic field lines on which the observations were made. This implies that the emissions are probably not occurring throughout the entire region occupied by field-aligned plasma depletions but are primarily associated with plasma depletions in the altitude range from 350 to 800 km. We emphasize that the data points in Figure 5 represent observations of waves associated with density depletions and that the distribution shown in Figure 5 is not to be construed as the distribution of plasma bubbles in altitude and local time.

Summary

Four categories of short-duration broadband ELF emissions were observed during the data acquisition on October 7, 1991: (1) lightning-generated emissions above 1000 km, (2) predominantly electrostatic waves within density depletions, (3) extraordinary electromagnetic waves propagating in the ambient medium outside of the density depletions, and (4) extraordinary electromagnetic waves propagating within the density depletions. The wave modes are identified by the ratio $c/B_{\parallel}$.

The spectra of the latter three categories are essentially the same. They are broadband with no resonances or cutoffs at characteristic frequencies of the plasma within the range of the ELFWA. The waves are not simply zero-frequency irregularities as generally assumed by previous investigators; they are associated with plasma depletions from a factor of 2 to a factor of 80 less than the surrounding density. The observations indicate that both the electrostatic and the electromagnetic waves are associated with equatorial spread $F$. 
References


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