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Observation of electromagnetic oxygen cyclotron waves in a flickering aurora

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Abstract. Instruments on the Auroral Turbulence rocket detected several intervals of weak electromagnetic oscillations at frequencies of 6–13 Hz in a strongly flickering auroral arc. These oscillations have amplitudes of up to $\delta B \sim 3$ nT and $\delta E \sim 4$ mV/m and have downward field-aligned Poynting fluxes of up to $\sim 10^{-5}$ W/m^2. Fluctuations in the parallel electron flux at about 9 Hz were observed in association with the strongest of these oscillations. Simultaneous ground-based optical data show that the arc was flickering at frequencies of 8–15 Hz. The observed frequencies would match the oxygen cyclotron frequency at $\sim$ 4500 km altitude. In one wave/particle event the apparent lag of the waves behind the modulated electrons implies a modulation source altitude of 2500–5000 km. We interpret these waves as electromagnetic ion cyclotron waves originating in the auroral acceleration region.

Introduction

There have been several reports of particle modulations near 10 Hz in auroral arcs. *Evans* [1967] found modulations throughout the 1–120 keV range of his particle detectors, especially at higher energies. *Arnoldy* [1970] showed that the modulated electron distribution is primarily field aligned. The initial observations were made at energies above the peak of the precipitating electron flux; however, the modulations can also extend to energies of 1 keV or less [*McFadden et al.*, 1987; *Temerin et al.*, 1986]. An association between these oscillations and flickering aurora [*Beach et al.*, 1968] was long suspected but not established until the BIDARCA campaign of 1984 [*Temerin et al.*, 1986]. In the model of *Temerin et al.* [1986, 1993], oblique electromagnetic oxygen and hydrogen cyclotron waves accelerate the electrons which cause the flickering aurora.

Many satellite observations have been made of electromagnetic oxygen cyclotron waves, most recently with Freja [*Erlandson et al.*, 1994]. In contrast, there are fewer published observations of electromagnetic oxygen cyclotron waves at rocket altitudes. *Temerin et al.* [1986] reported broad-band electric field noise below 15 Hz in association with the particle modulations, but no specific association with coherent waves was found (M. H. Boehm, personal communication, 1995). Broad-band electromagnetic noise below the oxygen cyclotron frequency was also found on DE-1 [*Gurnett et al.*, 1984]. Some authors have reported observations of electrostatic O^+ [e.g., *Bering*, 1984] and O_2^+ [*Bale et al.*, 1992] cyclotron waves. In this letter we report a sounding rocket observation of simultaneous wave activity at 6–13 Hz and fluctuations in the field-aligned particle flux at these frequencies. We identify these waves as electromagnetic oxygen cyclotron waves originating in the auroral acceleration region.

Description of Data

The Auroral Turbulence sounding rocket (40.005UE) was launched March 6, 1994, at 0821 UT from Poker Flat, Alaska, into a breakup aurora. The main payload instrumentation included a three-axis magnetometer, several electric field measurements in the rocket spin plane, a Plasma Frequency Probe (PFP) for electron density measurements, and electron and ion detectors. The magnetic and electric field data were digitized to sixteen bits, giving resolutions of 1.8 nT and 16 μV/m, respectively. The spin axis was aligned within a few degrees of the background magnetic field. Two subpayloads did not obtain any useful data due to premature separation of a payload system connector. Ground-based cameras at Poker Flat and Kaktovik (Barter Island) recorded the optical aurora during the flight.

The payload traversed an arc structure at an altitude of about 400 km 272–302 seconds after launch. As the payload entered the arc it encountered a westward travelling surge which evolved into an S-fold while the payload was in the arc. Figure 1 shows 3.6 keV field-aligned electron flux, magnetic east-west δE, and a perpendicular electric field spectrogram from the arc traversal. The residual rocket spin of 0.39 Hz has been removed with

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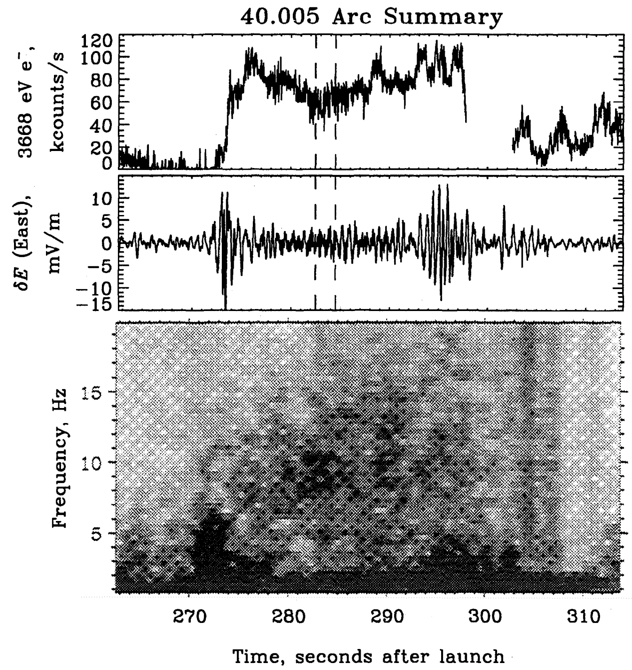

Figure 1. (a) 3.6 keV field-aligned electrons, (b) magnetic east-west electric field, and (c) perpendicular electric field spectrogram from an arc traversed by the Auroral Turbulence main payload at an altitude of 400 km. The data have been high pass filtered at 1.0 Hz to remove DC offsets and the fundamental and second harmonic of the rocket spin (the spin rate was 0.39 Hz). The particle data dropped out from about 298–302 s due to a change in telemetry mode. The interval between the dashed lines is expanded in Figure 2.

a 1-Hz highpass filter. The bursts of 1–7 Hz electromagnetic waves at 272–275 s and 293–297 s, which are associated with the edges of the surge, are interpreted as Alfvén waves with downward Poynting flux [*Torbert et al.*, 1994]. The amplitude of these waves does not drop to zero in the middle of the arc structure.

A narrow-field camera at Poker Flat recorded strong flickering at 8–15 Hz in both this arc and a second equatorward arc during this arc traversal. Since the camera was operated unfiltered during the flight, much of the signal was due to the 557.7 nm [O I] line, which has a radiative lifetime of 0.8 s. This line would tend to smear out 10 Hz signals, so the fluctuation in shorter-lived lines would have had to be very deep for the flickering to be so readily visible in the image.

This letter focuses on smaller amplitude oscillations at 7–13 Hz in the electric and magnetic field channels. These oscillations appear sporadically throughout the arc traversal but not during the preceding and following intervals. An example of these fluctuations is shown in Figure 2, which shows the spin-plane components of the electric and magnetic fields and the 3.6 keV and 5.9 keV channels of field-aligned electrons from the period 282.5–284.5 s.The maximum amplitude of these waves is 4 mV/m and 3 nT. The waves in this event are linearly polarized with $\delta\mathbf{E}$ mainly northeast-southwest and $\delta\mathbf{B}$ mainly southeast-northwest; they carry a downward field-aligned Poynting flux of $\sim 10^{-5}$ W/m^2. No coherent fluctuations are visible in the spin-axis component of **B**.

The electron data in Figure 2 are at pitch angles of 10° or less. Flux modulations were also detected at larger pitch angles. There is no clear dispersion in the particle data. Due to our sampling interval of 35.6 ms, however, such a dispersion would not be discernable for sources below about 6000 km. The flux modulations in Figure 2 precede the waves by about 0.4 s, although this dispersion is more ambiguous in other events.

Figure 3 shows the spectra of the electric and magnetic fluctuations for a 0.66-second interval beginning at 283.5 s. Also shown are the frequency spectra of the 3.6 keV electron channels for pitch angles less than 10° and 11–19° from an interval 0.4 s earlier than the wave spectra. All six spectra are peaked at 9 Hz. The wave spectra are similar to the magnetic field spectrum shown in Figure 2 of *Erlandson et al.* [1994] up to about 100 Hz. Our electric field spectra show wave activity at 100–250 Hz which might be consistent with electromagnetic hydrogen cyclotron waves [*Temerin et al.*, 1993; *Erlandson et al.*, 1994], but this identification must be regarded as tentative.

The PFP measured density perturbations $\delta n/n$ of a few percent in association with the EMIC waves in the arc. Due to unfavorable placement of the PFP antenna on the side of the rocket, however, this measurement was severely modified by a ram-wake effect which raised (lowered) the density to $\sim 3 \times 10^4$ cm^{-3} ($< 1.5 \times 10^4$ cm^{-3}) in the ram (wake) direction. In the

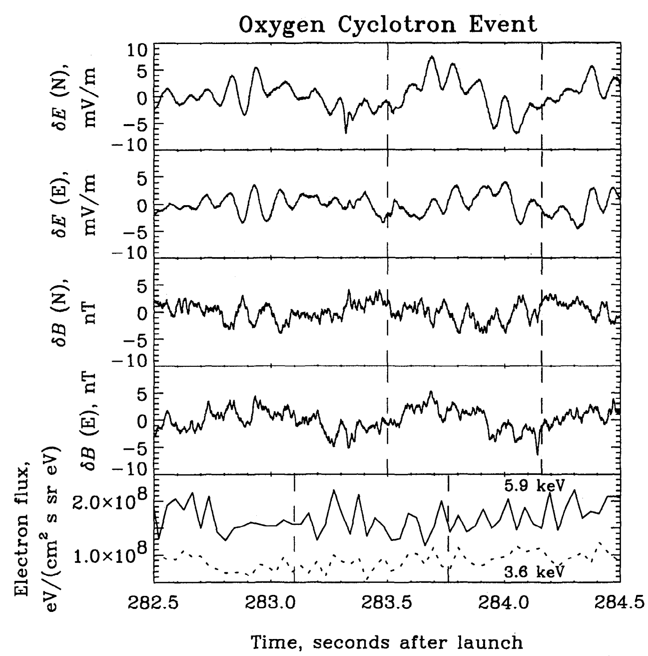

Figure 2. An expanded view of spin-plane fields 282.5–284.5 seconds after launch and electron differential energy flux at 5.9 keV and 3.6 keV at pitch angles of 10° or less during this interval. Coherent wave fluctuations begin near 283.5 s, about 0.4 s after coherent flux modulations at the same frequency. Spectra of the intervals between the dashed lines are shown in Figure 3.

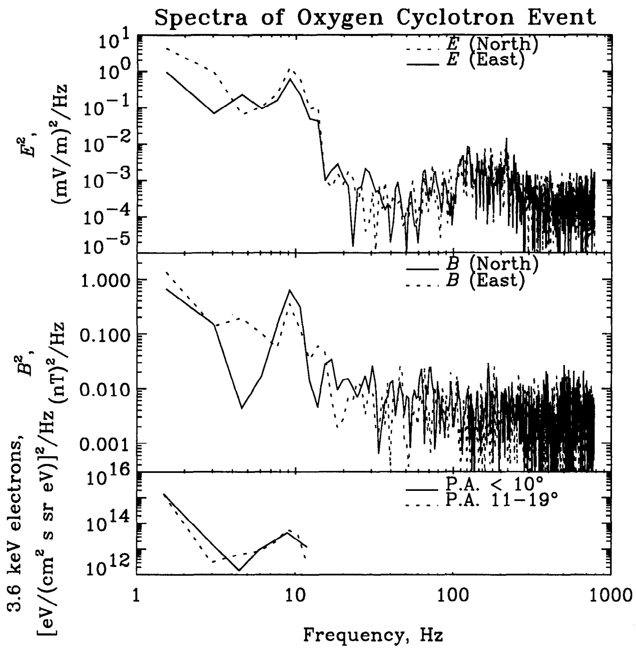

Figure 3. Spectra of the spin-plane components of **E** (top) and **B** (middle) and of the differential energy fluxes at 3.6 keV in two different pitch angle ranges for the coherent fluctuations shown in Figure 2. The wave spectra are from a 0.66-second interval beginning 283.50 s after launch; the particle spectra are from an interval beginning 283.10 s after launch.

presence of such large density gradients, an electromagnetic ELF wave can produce sizeable density fluctuations. The plasma motion relative to the rocket produces a wake with density gradient $\nabla n \sim n/d$, where n is background density and d is a rocket body dimension, and an electric field $\mathbf{E}_0 = -\mathbf{v}_{RP} \times \mathbf{B}_0$ in the rocket frame. A long-wavelength ELF wave with amplitude $\delta E \ll E_0$ will perturb this electric field, modifying $\mathbf{v}_{RP}$ and shifting the wake direction by an angle $\theta = \delta \mathbf{E} \times \mathbf{E}_0/E_0^2$. The wake will move a distance $r\theta$ where r is the effective density probe length including geometrical factors, producing $\delta n/n \sim r\delta E/dE_0$. For Auroral Turbulence $r \sim d \sim 1$ m and $E_0 \sim 50$ mV/m ($v_{RP} \sim 1$ km/s), implying $\delta n/n \sim 0.08$, comparable to the observed fluctuations.

Mode Identification and Discussion

Several observational facts indicate that these waves are electromagnetic oxygen cyclotron waves originating in the auroral acceleration zone, as in the model of *Temerin et al.* [1986]. We will defer discussion of the generation mechanism to a future paper.

The electric field fluctuations shown in Figure 2 are similar to the fluctuations reported at 200 km by *Bale et al.* [1992], which were interpreted as electrostatic O_2^+ cyclotron waves. Their hypothesis cannot explain our observations: the waves we see are electromagnetic, and the O_2^+ concentration is negligible at 400 km.

The upper frequency cutoffs of the observed EMIC bursts range from 11–13 Hz; the cutoff for the event we focus on is 11 Hz, while the frequency of maximum power $f_{\max}$ is 9 Hz. Since EMIC modes exist below the ion gyrofrequencies f_{ci}, let us assume that these cutoffs represent f_{cO+} in the source region. This assumption implies $f_{\max}/f_{cO+} = 0.7$–0.8, in agreement with the maximum growth frequencies predicted by *Forslund et al.* [1979] for current-driven EMIC waves. Using the IGRF to trace f_{cH+}, f_{cHe+}, and f_{cO+} as a function of altitude on the rocket's field line, we find that f_{cO+} is 11 Hz at an altitude of about 4500 km. Also, f_{cH+} and f_{cHe+} remain far above the observed wave frequencies throughout the auroral acceleration region, so these modes are unlikely to account for the observed waves.

If the waves were locally generated, the two candidate modes would be Alfvén waves [*Fejer and Kan*, 1969] and Doppler-shifted EMIC waves [*Forslund et al.*, 1979]. The velocity of keV electrons would match the phase velocity of neither mode, so inducing modulations of the observed magnitude would be difficult. The Alfvén mode spectrum would probably also be broader than the spectrum which we observe. The local oxygen cyclotron mode would require significant Doppler shifting. Assuming $k\rho_{O+} \sim 1$, where k is the wavenumber and ρ_{O+} is the oxygen gyroradius, we find that $T_i \lesssim 7000$ K for a rocket travelling at $v_R = 1.5$ km/s to see a 46 Hz wave Doppler shifted to 9 Hz. Such ion temperatures are often observed in the quiet nightside ionosphere. Nonetheless, we consider such a large Doppler shift unlikely; to account for the observed line width, $\mathbf{k} \cdot \mathbf{v}_R$ could not vary by more than $\sim 10\%$, which would imply an unrealistic $\mathbf{k}$ spectrum for these waves.

If, on the other hand, the waves have a distant source and are below all of the local ion gyrofrequencies everywhere along the path, then the waves will propagate as Alfvén waves. One way to test this hypothesis is by comparing the ratio of amplitudes $\delta E/\delta B$ to the local Alfvén speed .From the spectral peaks in Figure 3, $\delta E/\delta B$ is 1400 km/s for this event; other wave events yield $\delta E/\delta B$ values in the range 800–1600 km/s. The PFP measured a density of about 2.5×10^4 cm^{-3} during the event shown. For an oxygen-dominated plasma, this density gives a local Alfvén speed v_A of about 1700 km/s. Since the ionosphere should partially reflect Alfvén waves, $\delta E/\delta B$ should be somewhat less than v_A [*Knudsen et al.*, 1990].These events are therefore consistent with Alfvén mode propagation.

From the apparent 0.4-s lag of the waves behind the particles in Figure 2, we can estimate the source altitude of the modulated electrons by integrating the Alfvén speed up the field line. The altitude thus obtained should be lower than the resonance altitude since the wave must have time to grow and then modulate the electrons. Let us correct the analytic model of *Lysak* [1991] for the radial dependence of the magnetic field: $v_A(z) = v_{AI}(z_0/z)^3(\epsilon^2 + e^{-(z-z_0)/h})^{-1/2}$, where $v_{AI} = 1700$ km/s is the ionospheric Alfvén speed, $z_0 = 6770$ km is the geocentric altitude of the ionospheric measurement, $\epsilon^2 = 10^{-4}$ is the mass density ratio between the magnetosphere and ionosphere, and $h = 300$ km is the ionospheric density scale height. The result of this calculation depends strongly on h and ϵ, so it should be regarded mainly as a consistency check. For the above parameters, the wave-particle delay of 0.4 s for 3–6 keV electrons implies a source altitude of about 5000 km. This result is slightly higher than the estimate from the observed frequency spectrum and on the low end of the 4000–8000 km range obtained by *McFadden et al.* [1987] from energy dispersion of electrons modulated at about 4 Hz.

Summary and Conclusion

A sounding rocket detected electromagnetic fluctuations at frequencies of 6–13 Hz at an altitude of about 400 km in a strongly flickering auroral arc. The observed features of the waves are consistent with electromagnetic oxygen cyclotron waves originating in the auroral acceleration region and that the field-aligned electron flux is modulated at the wave frequency.

Our observations appear to confirm the model of *Temerin et al.* [1986], which predicts that oxygen cyclotron waves will produce the electron flux modulations which cause flickering aurora. The observed waves are consistent with electromagnetic oxygen cyclotron waves. In addition, we see corresponding modulations in the field-aligned electron flux. The modulated electrons appear to precede the waves; from a simple model of the Alfvén speed we find that the observed lag is consistent with the source altitude range inferred from the frequency spectrum. The time resolution of the electrons detectors was not sufficient to resolve dispersion.

These waves may also contribute to the distortion of incoherent scatter radar spectra during scattering from the auroral ionosphere. *Knudsen et al.* [1993] studied the effect of spatial fluctuations in the radar scattering volume and temporal fluctuations during the integration period; they concluded that in some cases the measured ion temperature can be significantly higher than expected. The presence of Alfvén waves at the frequencies reported here could result in such errors even for very short integration times.

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