Observation of proton gyroharmonic echoes and resonances by IMAGE

Introduction

The IMAGE satellite contains a sweep-frequency radio sounder, the Radio Plasma Imager (RPI), used to probe the surrounding plasma environment. We studied signals detected by RPI during the inbound part of the orbit, at altitudes ranging from 1500 km to 20,000 km. On several hundred orbits, echoes and resonances appear in frequency ranges unanticipated by cold plasma theory, as does a related class of echoes in the Whistler mode domain. These phenomena are now believed to be proton gyroharmonic (PGH) effects occurring close to the satellite, in the localized environment of a plasma sheath.

Figure 1. Dispersion diagrams for electron plasma frequency and gyrofrequency values.

Our main region of study constrains the electron plasma frequency $f_{pe}$ and electron gyrofrequency $f_{ce}$ values to be $f_{pe} > \sqrt{2} \cdot f_{ce}$. This is the case of the first dispersion diagram in Figure 1a. The stop band region exists between $f_{ce}$ and $f_z$, where

$$f_z = \frac{f_{ce}}{2} \left( -1 + \sqrt{1 + 4 \left( \frac{f_{pe}}{f_{ce}} \right)^2} \right).$$

We examine echoes and resonances observed in this stop band, and also extend our observations to the low-altitude “Whistler” echoes. Non-Whistler echoes and resonances span magnetic latitudes from 0 degrees to 30 degrees (see Figure 2), while Whistler echoes extend from 0 degrees to 45 degrees.
Previous authors who have examined ionograms taken from the Alouette and ISIS satellites have noticed proton-cyclotron echoes. Unlike IMAGE, these topside sounders stayed at low altitudes (less than 3000 km). From Alouette I data, King and Preece [1967] saw repeated echoes near the electron gyrofrequency $f_{ce}$. They termed the echoes “spurs.” They found a close match between each spur’s delay time and the proton gyroperiod $\tau_p$. The spurs have since been described as signatures of proton cyclotron motion around the spacecraft.

The first class of echoes we observe we call $f_{ce}^+$ echoes (see the illustration in Figure 3) because they appear on the high frequency side of $f_{ce}$. Because of certain differences from spurs, we prefer this new terminology. At lower frequencies, the related Whistler-mode proton cyclotron phenomena are called “Whistler” echoes.

Matuura and Nishizaki [1969] found spurs on ISIS II ionograms and further suggested the existence of a local plasma structure around the antenna, in which electrostatic mid-frequency (MF) waves can propagate. Low-to-mid frequency voltages
on the antenna, they claimed, can generate this plasma structure. The MF waves may be what Morin and Balmain [1993] call sheath waves that exist between \( f_{ce} \) and \( f_{pc} \).

Gould [1965] proposed a model for an ensemble of gyrating ions in a plasma disturbed by pulses. Oya [1978] believed an electron stream intercepts the proton concentration around the antenna. Muldrew [1998] refined the explanation to cover a process in which a pulse excites some protons initially and at \( n\tau_p \) (multiples of the proton gyroperiod), the energized protons replicate the original wave. Given the existing literature and our newly gathered RPI data, we describe the conditions under which \( f_{ce}^+ \) and Whistler echoes are prevalent and explain their physical origin.

Despite all the research on spurs, few previous authors have reported seeing resonances that appear alongside spurs slightly offset from \( f_{ce} \). Horita [1987] identified spikes close to harmonics of \( f_{ce} \), but most of the spikes had a maximum range of 1000 km. The resonances we describe extend to virtual ranges of several Earth radii. They occur predominantly next to the first harmonic \( f_{ce} \) on the high frequency side. For that reason, we term them \( f_{ce}^+ \) resonances. Over the different months, they show a range of amplitudes, minimum delay times, and interrelationships with the PGH echoes.

**Physical Model for Echo and Resonance Generation**

The model presented is a synthesis of the theory put forth by Oya [1978] and Muldrew [1998]. An RF pulse is applied across either the X or Y 500-m sounding antenna on IMAGE, disturbing the ambient plasma. During the positive half cycle of the pulse, a group of electrons are attracted to the antenna. During the negative half cycle, though, the group of protons that migrate to the antenna cannot be as large as the preceding group of electrons because protons have much lower mobility. This asymmetrical movement of charge enables the antenna to attain a negative potential. By equilibrium, the antenna has potential

\[
\phi_a = -\phi_0 - \frac{kT_p}{e} \ln \left( \frac{m_p}{m_e} \right),
\]

where \( \phi_0 \) is the amplitude of the RF signal, \( m_e \) and \( m_p \) are the electron and proton masses, \( T_p \) is the proton temperature, \( k \) is Boltzmann’s constant, and \( e \) is the electric charge. The negative potential causes a proton concentration to develop around the antenna, forming a plasma sheath with a tapered profile described by Grard [1965].

Subsequent RF pulses traverse the sheath and energize the protons, sending them into cyclotron motion. A sufficient number of protons have to be excited for echoes to be observed later. Remarkably, the protons exhibit a plasma memory phenomenon, in which they can replicate the original wave at \( n\tau_p \). If the resultant electron Bernstein waves travel in a direction that is conducive to signal reception on the antennae, then the proton cyclotron echoes are detected by IMAGE. For higher \( n \) (longer time delays), the effect may be less noticeable due to time-dependent loss of energy.
Observations and Discussions

$f_{ce}^{+}$ Echoes

Figure 4. $f_{ce}^{+}$ echoes on high frequency side of gyrofrequency.

Figure 5. Delay time of the lowest-range echo is inverse of proton gyroperiod.

Pulses at frequencies slightly higher than the electron gyrofrequency are most effective at triggering the appearance of $f_{ce}^{+}$ echoes. The mid frequency is defined to be the center of the bandwidth of the echo as observed on a plasmagram. Most echoes are seen with mid frequency at 10-20 percent above $f_{ce}$, as shown in Figure 4. This implies that they are dependent on the local magnetic field, since $f_{ce} \propto B$. As protons gather around the antenna, one or more pulses energize them. At $n \tau_p$, the protons echo back the original triggering signal to be picked up by the antenna. Figure 5 shows the strong inverse relationship between the delay time of the lowest-range $f_{ce}^{+}$ echo and the proton gyrofrequency.

Benson [1974] found the most number of echoes when the ratio between the electron plasma frequency $f_{pe}$ and $f_{ce}$ was an integer. The $f_{ce}^{+}$ echoes we observe are not
dependent on the ratio being integral but are found when $2 < \frac{f_{pe}}{f_{ce}} < 18$. When $f_{pe}/f_{ce} \sim 1$, Whistler waves become pervasive and prevent $f_{ce}^+$ echoes from being isolated, although this condition gives rise to the closely related Whistler echoes described in the next section. When $f_{pe}/f_{ce}$ is too high, we did not see any echoes, either because a low $f_{ce}$ value created a proton gyroperiod above the maximum detectable range or a high ambient electron (proton) density disrupted echo formation.

![Figure 6.](image)

Figure 6. (a) Echo observed on August 15, 2004 at 21:59:55. The value of $f_{pe}$ is 185 kHz. (b) Echoes observed on August 15, 2004 at 22:16:38. The value of $f_{pe}$ is 208 kHz. (c) Echoes observed on August 15, 2004 at 22:23:55. The value of $f_{pe}$ is 227 kHz.

Of all measurement programs used by RPI, program 38 offers the best spectral resolution at low frequencies for observing the $f_{ce}^+$ echoes. The program sends a 3.2 ms pulse at each frequency and advances the frequency by 300 Hz every 250-ms, from 6 kHz to 62 kHz. Figure 6a-c show successive plasmagrams produced by program 38 taken on the same orbit on August 15, 2004. As $f_{ce}$ increases, meaning that the proton gyrofrequency $f_{ci}$ also increases, the median echo delay time drops. The virtual range limit of $4.2R_e$ in the first plasmagram prevents us from seeing the second echo at $2\tau_p$. 
although it probably exists as can be seen from the second plasmagram. Three $f_{ce}^+$ echoes appear in the last plasmagram, although the diminished amplitude of the echo at $3\tau_p$ makes it almost indistinguishable.

Several features of this set are typical of most other observed echoes. As IMAGE approaches lower altitudes and $f_{ce}$ increases, multiple echoes can be seen on the same plasmagram because the delay time decreases. Echoes at farther delays, however, tend to have lower amplitudes and eventually become too weak to be recognizable (see Table 1). When more time elapses, the energized protons lose the plasma memory effect and make echoes at higher $n\tau_p$ unlikely. The echoes also cover a range of bandwidths and curvatures, and an inverse relationship exists between bandwidth and curvature.

<table>
<thead>
<tr>
<th>Time of record</th>
<th>First $f_{ce}^+$ echo</th>
<th>Second $f_{ce}^+$ echo</th>
<th>Third $f_{ce}^+$ echo</th>
</tr>
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<tbody>
<tr>
<td>2004-08-14, 17:45:55</td>
<td>27.55</td>
<td>21.67</td>
<td>--</td>
</tr>
<tr>
<td>2004-08-14, 17:50:38</td>
<td>36.03</td>
<td>23.93</td>
<td>--</td>
</tr>
<tr>
<td>2004-08-14, 17:57:54</td>
<td>28.2</td>
<td>25.04</td>
<td>22.56</td>
</tr>
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<td>2004-08-15, 22:11:55</td>
<td>40.32</td>
<td>35.25</td>
<td>--</td>
</tr>
<tr>
<td>2004-08-15, 22:16:38</td>
<td>38.18</td>
<td>32.41</td>
<td>--</td>
</tr>
</tbody>
</table>

* Amplitudes are in units of dB nV/m. Some measurements do not contain a third $f_{ce}^+$ echo because of limits on the max virtual range.

Spurs seen on past ionograms branched off of tall resonance spikes, both on the high and low frequency sides. The $f_{ce}^+$ echoes, on the other hand, are near but not attached to the $f_{ce}$ resonances; there usually is some spectral separation between $f_{ce}$ and the starting echo frequency. Spurs also decrease in range as they approach a resonance from the high frequency side, whereas $f_{ce}^+$ echoes do the opposite by increasing in range as they approach the $f_{ce}$ resonance. This increase in range results from the lower group velocity experienced by the electron Bernstein waves nearer $f_{ce}$.

King and Preece [1967] described the effect of satellite spin, noting that proton-cyclotron echoes occur most frequently when the satellite antenna is parallel to Earth’s magnetic field B. In our present work, we have found antenna angle has no significant effect on echo detection. Instead, satellite motion relative to the magnetic field is a key factor. The $f_{ce}^+$ echoes are more likely to be seen when the satellite’s velocity vector and magnetic field approach being parallel, because both the energized protons and the satellite move in the direction of the field. This provides a better chance for the electron Bernstein waves generated by the proton concentrations to reach the antenna. When the velocity and field approach being perpendicular, far fewer echoes are observed. The nearer-parallel and nearer-perpendicular cases are provided by June of 2004 and July of 2005, respectively, during which similar measurement schedules were run. (See Figure 7.) They exhibit an almost factor of 3 difference in the number of orbits with detected echoes.
Figures 7. (a) Orbit in June of 2004. (b) Orbit in July of 2005.

*Whistler Echoes*

While studying the $f_{ce}^+$ echoes, it was noticed that at lower frequencies in the Whistler-mode domain there were discrete echoes with ranges that corresponding to the ranges of the $f_{ce}^+$ echoes. Figure 8 from August 14, 2004 shows an example with $f_{ce}^+$ echoes with a mid frequency of 46.8 kHz and a range for the first $f_{ce}^+$ echo of 1.05 $R_E$. The Whistler echo can be seen on the left between 9 and 17 kHz and at a range of 1.05 $R_E$.

Figure 8. Whistler echo on August 14, 2004 at 17:57:54. The value of $f_{pe}$ is 334 kHz.
The Whistler echoes begin to appear at altitudes where the $f_{ce}$ echoes are seen less frequently (around 2.9 RE), and they continue to be seen even at altitudes as low as 1.4 RE. Given that they are a low frequency phenomenon, Whistler echoes were mainly detected in the previously mentioned program 38, as well as program 63, which sweeps in steps of 300 Hz from 7 to 19.9 kHz. Figure 9 shows two meridian-cross sections of the locations of the satellite where Whistler echoes were recorded in the two periods of November 1 to 20, 2001 and August 14 to 22, 2004. We have observed Whistler echoes at magnetic latitudes between –45 and 45 degrees but not over the polar cusps.

Figure 9a shows the distributions of the magnetic local times of the Whistler echoes for the same two periods shown in Figure 9. As can be seen, for brief periods of time, Whistler echoes only occur in a small domain of magnetic local times. This domain, however, changes as the orbit progresses over the months, covering both daytime and nighttime zones. They are predicted to be present across all magnetic local times.

Multiple echoes are also frequently seen. Figure 10a-c display examples of multiple Whistler echoes at different altitudes. Figure 10a, from August 17, 2004, shows an instance at a fairly high altitude of 2.68 RE. Figure 10b, from August 20, 2004, shows a mid altitude example at 2.21 RE. Lastly, Figure 10c, from Aug 17, 2004, is an example of a Whistler echo at an altitude of 1.72 RE. As demonstrated by each of these three cases, multiple echoes are equally spaced in range by the equivalent of the proton gyroperiod and monotonically decrease in amplitude for higher ranges. As the altitude decreases, the minimum range and the inter-echo spacing decreases because the proton gyroperiod decreases.
Like the $f_{\text{ce}}^+$ echoes, Whistler echoes are PGH events because the time delay of the fundamental echo is the local proton gyroperiod. In Figure 11, we plot the relationship between $f_{\text{ce}}$ and the delay time of the fundamental Whistler echo. The curve represents the virtual range associated with the proton gyroperiod $\tau_p = 1837/f_{\text{ce}}$. It is clear that the Whistler echoes are the lower-altitude version of the $f_{\text{ce}}^+$ phenomenon.

Figure 10. (a) Whistler echoes seen on August 17, 2004 at 17:12:38. (b) Whistler echoes seen on August 20, 2004 at 16:34:38. (c) Whistler echoes seen on August 17, 2004 at 3:23:38.
Figure 11. Delay time is inversely proportional to gyrofrequency.

With each successive echo, the range of frequencies over which the echoes appear narrows and often converges to a point between 8 and 12 kHz. Figure 12 shows the number of echoes for each frequency for the earlier mentioned periods in November 2001 and August 2004. (If an echo covers a particular frequency, it contributes to the overall count for that frequency. Thus, wider echoes, such as the fundamental echo, will contribute to more frequency bins than will narrower, higher-order echoes.) Echoes were determined to be present if the amplitude exceeded that of noise by 10dB. It is uncertain as to why there are two peaks fairly close in frequency instead of a single peak.

Figure 12. Number of Whistler echoes at different sounding frequencies.

Amplitude saturation at the receiver, which has a 66dB limit, prevents amplitude comparison between multiple echoes. Figure 13a, from November 5, 2001, shows a regular plasmagram with four echoes. Figure 13b is the same plasmagram with saturation highlighted in white. All four echoes are saturated, and this situation is typical of all records of Whistler echoes.
Figure 13. (a) Whistler echoes shown with normal color processing. (b) Whistler echoes shown with saturation effects.

At very low altitudes, the strength of the magnetic field strength increases to the extent that the inter-echo spacing becomes comparable to the 3.2ms (~0.08 Rₚ) sampling interval and discrete echoes can no longer be resolved. Figure 14, from April 4, 2005, shows a series of four consecutive plasmagrams taken as IMAGE moved away from the earth. These plasmagrams were generated using program 57, which starts at 20 kHz and advances in steps of 1.2 kHz. In Figure 14a-b, the multiple Whistler echoes are compressed together to form a single low-frequency, low-range PGH response. As IMAGE moves away from the earth and fₑ decreases in Figure 14c-d, the inter-echo spacing becomes large enough for discrete Whistler echoes to be observed. Discrete Whistler echoes such as those in Figure 14c-d are seldom observed by program 57 because of range resolution limitations, whereas the bunched low-range response in Figure 14a-b can be seen using program 57. From this type of transitional plasmagram set, though, we know even at low altitudes Whistler echoes are common PGH events.
Figure 14. (a) Whistler echoes seen on April 4, 2005 at 20:03:05. $f_{ce} = 512$ kHz. (b) Whistler echoes seen on April 4, 2005 at 20:06:05. $f_{ce} = 380$ kHz. (c) Whistler echoes seen on April 4, 2005 at 20:09:05. $f_{ce} = 285$ kHz. (d) Whistler echoes seen on April 4, 2005 at 20:12:05. $f_{ce} = 215$ kHz.

$f_{ce}^+$ resonances

Once again, pulses slightly above $f_{ce}$ are responsible for triggering most of the events—this time, $f_{ce}^+$ resonances that extend from the minimum to the maximum virtual range. (Compare Figure 15 to Figure 4 to see the similarity.) On a plasmagram, the $f_{ce}^+$ resonance appears as a tall streak offset on the high frequency side of $f_{ce}$ (see Figure 16a-d). They sometimes appear alongside $f_{ce}^-$ echoes, where the starting frequency of an echo is the median frequency of the nearby resonance, but there is no consistent relationship. Such $f_{ce}^-$ resonances are different from the familiar $f_{Qn}$ resonances and thermal mode spikes.
During the months of interest, the aforementioned program 57 in RPI allows the identification of $f_{ce}^+$ resonances as low as 20 kHz and as high as 320 kHz. Resonances have been seen at frequencies lower than 20 kHz using other programs, but the upper 320 kHz limit is safe because when $f_{ce}$ approaches 320 kHz, the value of $f_{pe}/f_{ce} \sim 1$ (IMAGE close to Earth) and allows Whistler signals to be dominant.
Figure 16a-d show a set of successive plasmagrams containing $f_{ce}^+$ resonances, taken on the same orbit. The $f_{ce}^+$ resonance frequency tracks the growth of $f_{ce}$, staying 10-20% higher than the $f_{ce}$ spike. Several changes in this progression are interesting. The amplitude diminishes from the first to the second plasmagram before being restored in the third and fourth plasmagrams. Bandwidth increases during the sequence; the last two resonances span several kilohertz.

Unlike $nf_{ce}$ or $f_{Qn}$ resonances (see Horita and Chen [1995]), which taper off in amplitude as virtual range increases, the $f_{ce}^+$ resonance remains strong up to the maximum observable virtual range but occasionally weakens at low ranges. The second and third plasmagrams show fragmentation of the resonance at short delay times. Most of these low-range gaps are the result of interference by $f_{ce}^+$ echoes. The gap, when converted to time, is on the order of the proton gyroperiod. In the absence of the $f_{ce}^+$ resonance, a $f_{ce}^+$ echo is likely to be found over the gap (see Figure 17). In the presence of the $f_{ce}^+$ resonance, the would-be echo interferes with low-range reception of the resonance signal. Simultaneous detection of $f_{ce}^+$ echoes and resonances causes this strange exclusion conflict, though mutual existence of $f_{ce}^+$ echoes and resonances is not impossible (see Figure 8). Cases have also been seen where the $f_{ce}^+$ resonance weakens periodically, at exactly the virtual ranges for Whistler echoes (see Figure 18). In such instances, as the higher order Whistler echoes become weaker, the higher range portions of the resonance become stronger. It is not yet known why $f_{ce}^+$ echoes do not interfere with the $f_{ce}^+$ resonances on every recording.
Satellite motion relative to the local magnetic field has a similar effect on $f_{ce}^+$ resonance detection as it did on $f_{ce}^+$ echo detection. We can use the same two months for comparison as in Figure 7a-b. In June of 2004, when the average angle between satellite velocity and magnetic field was 20 degrees in the region of interest, $f_{ce}^+$ resonances were seen on 39 orbits. In July of 2004, when the average angle increased to 60 degrees, resonances were identified on only 8 orbits.

Another resonance similar to the $f_{ce}^+$ resonance can sometimes be seen slightly above $2f_{ce}$. Under our terminology, they are called $2f_{ce}^+$ resonances. They are far fewer in number, appear inconsistently over time, and are almost always accompanied by a strong $f_{ce}^+$ resonance.
Conclusion

The model of a plasma sheath resulting from a high-voltage antenna being immersed in plasma agrees well with our data. All three classes of identified PGH phenomena point to localized proton cyclotron motion being the underlying activity. Given the ability of RF pulses to form the plasma sheath during each sounding, the resultant PGH echoes are likely more prevalent than presented here but are not always detectable by the satellite.

The $f_{ce}^+$ and Whistler echoes arise directly from periodic proton cyclotron emissions. Both types of PGH echoes are affected by the local magnetic field. First, the field determines the local proton gyroperiod and therefore sets the delay times of the echoes. A greater multiplicity of echoes is seen when field strength is high and several proton gyroperiods can fit under the range limit of RPI; the extreme case is where the Whistler echoes bunch into a singular low-range PGH response. Second, the field sets the local electron gyrofrequency, which is closely tracked by the $f_{ce}^+$ echoes. Electron Bernstein waves emitted by the proton concentrations register as $f_{ce}^+$ echoes.

The $f_{ce}^+$ resonance is an even more localized event than the PGH echoes. Whereas the PGH echoes require a delay of a proton gyroperiod before registering on the plasmagram, most of the $f_{ce}^+$ resonances appear at the minimum detectable range. Such an immediate response implies that the effect is close to the antenna. Also, the interference between $f_{ce}^+$ echoes and $f_{ce}^+$ resonances suggests that they may operate under similar but distinct proton mechanisms.


