Explaining Polarization Reversals in STEREO Wave Data

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Abstract.   Recently *Breneman et al.* [2011] reported observations of large amplitude lightning and transmitter whistler mode waves from two STEREO passes through the inner radiation belt (L<2). Hodograms of the electric field in the plane transverse to the magnetic field showed that the transmitter waves underwent periodic polarization reversals. Specifically, their polarization would cycle through a pattern of right-hand to linear to left-hand polarization at a rate of roughly 200 Hz. The lightning whistlers were observed to be left-hand polarized at frequencies greater than the lower hybrid frequency and less than the transmitter frequency (21.4 kHz) and right-hand polarized otherwise. Only right-hand polarized waves in the inner radiation belt should exist in the frequency range of the whistler mode and these reversals were not explained in the previous paper. We show, with a combination of observations and simulated wave superposition, that these polarization reversals are due to the beating of an incident electromagnetic whistler mode wave at 21.4 kHz and linearly polarized, symmetric lower hybrid sidebands Doppler-shifted from the incident wave by ± 200 Hz. The existence of the lower hybrid waves is consistent with the parametric decay mechanism of *Lee and Kuo* [1984] whereby an incident whistler mode wave decays into symmetric, short wavelength lower hybrid waves and a purely growing (zero-frequency) mode. Like the lower hybrid waves, the purely growing mode is Doppler-shifted by ~ 200 Hz as observed on STEREO. This decay mechanism in the upper ionosphere has been previously reported at equatorial latitudes and is thought to have a direct connection with explosive spread F enhancements. As such it may represent another dissipation mechanism of VLF

wave energy in the ionosphere and may help to explain a deficit of observed lightning and transmitter energy in the inner radiation belts as reported by *Starks et al.* [2008].

1. Introduction

The two STEREO spacecraft, launched in 2006, were designed to study the propagation of CMEs from separated vantage points in the ecliptic plane. Part of the S/WAVES (*Bougeret et al.* [2008]) instrument suite on each is a burst waveform detector that telemeters select waveforms (usually the largest in amplitude) from the three orthogonal 6 meter electric field stacer antennas [*Bale et al.*, 2008]. The burst memory detector was primarily designed for a detailed study of Langmuir waves and therefore necessarily samples at high time resolution over a large dynamic range. These capabilities led to the unexpected discovery early in the mission (during the Earth-orbit phase) of a population of very large amplitude ($>$240 mV/m) whistler mode waves in the outer radiation belt [*Cattell et al.*, 2008], subsequently reported throughout the low density magnetosphere [*Cully et al.*, 2008; *Kellogg et al.*, 2011; *Wilson et al.*, 2011] as well as in the solar wind in association with stream interaction regions and shocks [*Breneman et al.*, 2010]. Recently, *Breneman et al.* [2011] presented a record of the once-per-minute peak voltage detector (TDSMax) data from eight STEREO perigee passes indicating that large amplitude electric field waveforms also exist throughout the high density plasmasphere. All of the burst waveforms reported were much larger in amplitude ($\sim$40-60 mV/m) than previously observed in the plasmasphere ($\sim$few mV/m). These waves may provide new energization and loss mechanisms to inner radiation belt electrons in regions thought to be dominated by coulomb collisions (L$<$1.2) and diffusive scattering via cyclotron resonance with anthropogenic VLF waves (1.2$<$L$<$2.4) [*Abel and Thorne*, 1998].

A subset of these waveforms were analyzed in detail and were identified as NPM Naval transmitter- and lightning-associated whistler mode waves, observed near the nightside mag-

netic equator from 1.1<L<1.9. The fact that the observed amplitudes of the two types of waves were similar and unusually large suggests that the observed waves grew to large amplitude from seed waves incident upon the base of the ionosphere.

In addition to their large amplitude, *Breneman et al.* [2011] showed that the NPM-associated whistler mode waves observed on STEREO A had a very unusual property: they were observed to reverse their polarization with respect to the magnetic field in a periodic fashion. Polarization reversals were also observed in the STEREO A lightning whistlers but occurred at both the lower hybrid frequency (f_{lh}) and the NPM transmitter frequency (f_{NPM}=21.4 kHz). In essence, these waves were occasionally observed to be left-hand polarized in the whistler mode frequency range ($f_{lh} \leq f \leq f_{NPM} << f_{ce}$, where f_{ce} is the electron cyclotron frequency). This is unusual because this frequency range should not support left-hand polarized waves in a plasma with $f_{pe} > f_{ce}$ (e.g. *Stix* [1992]), where f_{pe} is the electron plasma frequency.

This study presents a close analysis of these observations which reveals that the polarization reversals are the result of the beating of two types of waves: right-hand polarized electromagnetic whistler mode waves propagating at an angle to the magnetic field and linearly polarized lower hybrid waves propagating perpendicular to the magnetic field. A simulation is presented showing that this interaction can indeed result in reversals of polarization. The existence of the lower hybrid waves is attributed to the parametric (four-wave) decay of the incident whistler mode wave into symmetric lower hybrid waves and a field-aligned purely-growing mode as described by *Lee and Kuo* [1984]. The analysis of the lightning-associated waves is more complicated because these waves are dispersive, but it is suggested that the polarization reversals occur for a similar reason.

2. Observations and Analysis

On November 6th, 2006 both STEREO spacecraft passed through the Earth's nightside inner radiation belt. STEREO A telemetered eight large amplitude (40-60 mV/m) electric field waveform captures at 128 kHz with timestamps between 09:06:53-09:07:04. These had frequencies peaked at $\sim$21.4 kHz and were identified by *Breneman et al.* [2011] as associated with the NPM Naval transmitter in Hawaii (L=1.17). During this time STEREO A was at an altitude of 550 km, a magnetic latitude of 14°, SM longitude of 161°, and the spacecraft magnetic footprint was almost directly above the transmitter[1]. A short time later the magnetic footprint was over a lightning storm on the western coast of Mexico and the spacecraft telemetered 19 waveform captures with similar amplitudes from 09:11:53-09:30:16 (L=1.1-1.9, altitude from 670 to 2660 km, magnetic latitude from 6° to -9°, and SM longitude from 187° to 226°). These were identified from their signature dispersive tones as lightning-associated whistler mode waves. Lightning-associated whistler mode waves were also observed in the same region 1.5 hours earlier on STEREO B which had a nearly identical orbit. The similar amplitudes of both the NPM- and lightning-associated whistler mode waves suggest that they attained their amplitude after propagation through the ionosphere because they are expected to have vastly different amplitudes at the base of the ionosphere ($\sim$100 km).

Our analysis begins with an NPM-associated burst waveform observed on STEREO A, discussed in detail by *Breneman et al.* [2011]. Figure 1a plots the waveform in field-aligned coordinates where the magnetic field lies along the $\hat{z}$ axis and the wave vector is defined to lie in the $\hat{x}$-$\hat{z}$ plane. The background magnetic field direction and magnitude were obtained with 3-axis fluxgate magnetometer measurements from the IMPACT magnetometer [*Luhmann et al.*, 2008].

Note that this was incorrectly stated in *Breneman et al.* [2011] as 750 km

The wave polarization is predominantly perpendicular to the magnetic field, as is expected for the whistler mode. Figure 1b plots three frequency/time quantities for the waveform, the wave normal angle as determined from the cold plasma dispersion relation, the polarization ratio in the plane transverse to the magnetic field (E_x/E_y) and the wave handedness, where red(blue) indicates right(left) hand polarization with respect to the background magnetic field and black shows where the wave becomes linearly polarized, defined arbitrarily as $E_x/E_y > 8$. The handedness changes four times during the 32 msec burst capture with a repetition rate of ~200 Hz. Figure 1c plots the wave magnitude which oscillates between large and small amplitudes near the times where the polarization reversals occur. This is the result of the waveform becoming linearly polarized at this time. A more transparent measure of the polarization is shown in the field-aligned hodograms in Figure 4 of *Breneman et al.* [2011] where it can be clearly seen that the handedness cycles from right-hand to linear to left-hand polarization exactly as Figure 1b indicates. Figure 2a shows a lightning-associated burst capture from STEREO A in field-aligned coordinates. The changes in handedness are evident in panel c. The aggregate of the lightning-associated waveform captures suggests that the polarization reversals occur near the NPM and lower hybrid frequencies and that the waves are left-hand polarized in this frequency range and right-hand polarized otherwise.

2.1. Physical mechanism

To understand the physical mechanism behind the polarization reversals we start with a detailed analysis of the frequency spectrum as a function of time for the NPM waveform in Figure 1. The other seven NPM burst waveforms are qualitatively similar. Figure 1d plots four frequency spectrum snapshots for different representative times of the NPM burst capture. These times are indicated by the color-coded bars at the top of the figure. The $\hat{y}$ direction was selected

because the waveform modulations in Figure 1 are most noticeable in this direction, and also because the polarization reversals occur near the nulls of this component. Hodograms in the plane perpendicular to the magnetic field are inset for a subset of the time (chosen for illustrative effect) for each snapshot. The first panel (green) shows the snapshot for the times 3-10 msec after the start of the waveform and is centered on the transition from left- to right-hand polarization that occurs at 7 msec. The spectrum shows two clear peaks at 21.4 kHz ±200 Hz with a deficit of wave energy at 21.4 kHz, the transmission frequency of the NPM transmitter. The inset hodogram indicates that the waveform is linearly polarized perpendicular to the magnetic field. The second panel (purple) shows the snapshot for the times 7-14 msec. During most of this time the waveform is singly-peaked at 21.4 kHz and the inset hodogram is right-hand elliptically polarized, indicative of an electromagnetic whistler mode wave propagating oblique to the magnetic field. For times intermediate between the first and second snapshots a sliding spectrogram shows that the two peaks at 21.4 kHz ±200 Hz smoothly transition into the single peak at 21.4 kHz. From 14-21 msec (red panel) the waveform returns to a linear polarization in the perpendicular plane with peaks at 21.4 kHz ±200 Hz. Finally, the third snapshot shows that the waveform is once again singly-peaked at 21.4 kHz, elliptically polarized, and rotates in the right-handed sense. These snapshots suggest that two types of waves exist at various times throughout the waveform: an electromagnetic elliptically polarized whistler mode wave at 21.4 kHz and electrostatic linearly polarized perpendicular waves at 21.4 kHz ±200 Hz. The polarization reversals themselves occur with a frequency of ~200 Hz. Thus it appears that the beating of these two types of waves is the cause of the polarization reversals.

To show that this is the case we simulate a simplified version of the observed waveform by superimposing an elliptically-polarized electromagnetic whistler mode wave ($E_{1x} = Acos(f_1t)$,

$E_{1y} = Bsin(f_1t))$ and a linearly polarized electrostatic wave ($E'_{2x} = Ccos(f_2t + \phi)$), where $f_1 = 21.4$ kHz and $f_2 = 21.2$ kHz. Furthermore, we can rotate the electrostatic wave by an arbitrary azimuthal angle α in the transverse x-y plane, so that $E_{2x} = E'_{2x}cos(\alpha)$ and $E_{2y} = E'_{2x}sin(\alpha)$. For simplicity we ignore the electrostatic wave at 21.6 kHz and assume that both simulated waves exist for all time. Figure 3 shows the simulated superposition of these waves with the following parameters: A=40, B=20, C=50, ϕ =180° and α =45°. The two waves create periodic polarization reversals similar to those observed in Figure 1b. Test runs indicate that a wide range of the above parameters give rise to reversals in polarization. Thus the beating of these two waveforms is able to produce polarization reversals similar to those observed.

2.2. Parametric instability

As is shown in Figure 1d the spectra oscillate back and forth between a form that is peaked at symmetric sidebands with a depletion at the carrier frequency and a form that is peaked at the carrier frequency. This is typical of a four-wave parametric type instability whereby a large amplitude incident wave (ω_o, $\vec{k}_o$) decays into symmetric Stokes and anti-Stokes sidebands ($\omega_{\pm}$, $\vec{k}_{\pm}$) and a low frequency mode (ω_s, $\vec{k}_s$), satisfying the real frequency and wave vector matching conditions

$$\omega_o = \omega_+ - \omega_s = \omega_- + \omega_s \tag{1}$$

$$\vec{k}_o = \vec{k}_+ - \vec{k}_s = \vec{k}_- + \vec{k}_s \tag{2}$$

The interaction of the sidebands and the low frequency mode can produce a current that leads to the re-excitation of the incident electromagnetic wave. This cycle can then repeat until sufficient energy in the system is dissipated.

The matching conditions indicate a phase relationship between an incident wave and side-bands generated via parametric decay. Such a relationship can be elucidated with a bicoherence analysis [*Kim and Powers*, 1979] that quantifies (via the bicoherence statistic) the degree of nonlinear coupling between multiple waves. Unfortunately no statistically meaningful value of the bicoherence between the incident 21.4 kHz NPM transmitter wave and the sidebands can be obtained for the reason that the bicoherence noise level is too high for any analysis attempt that has sufficient frequency resolution to resolve the lower hybrid sidebands. We are therefore not able to explicitly show that any nonlinear wave couplings are occurring.

One four-wave decay process is described by *Lee and Kuo* [1984] whereby an incident electromagnetic whistler (NPM whistler mode wave in this case) decays into lower hybrid sidebands and a purely growing (zero frequency) mode. The (real) frequency matching equation above then reduces to $\omega_o = \omega_{\pm}$. However, since both lower hybrid waves and the purely growing mode are short wavelength, they can have a measurable Doppler-shift in the spacecraft frame. Thus the purely growing mode will be observed to have a finite frequency and the lower hybrid waves will be symmetric about the incident whistler mode wave frequency. This process has been invoked to explain various observations in the upper ionosphere [*Labno et al.*, 2007; *Dalkir et al.*, 1992; *Liao et al.*, 1989; *Groves et al.*, 1988] where anthropogenic transmitter waves are above the threshold for growth of this instability.

Another parametric decay mechanism, described by [*Sotnikov et al.*, 1991], involves the nonlinear conversion of a whistler mode wave into lower hybrid waves and a low frequency propagating component identified as electromagnetic ELF noise with a lower cutoff at the H^+ cyclotron frequency.

The purely growing mode in the theory of *Lee and Kuo* [1984] is expected to take the form of density striations elongated along the magnetic field and with wave vectors perpendicular to the magnetic field. In addition, the excited lower hybrid waves will have much shorter wavelengths than the incident whistler mode wave ($k_\pm >> k_o$). These constraints reduce the wave vector matching condition to $\vec{k}_\pm \sim \vec{k}_o \pm \hat{x}k_s \sim \pm\hat{x}k_s$. Therefore we find that the excited lower hybrid waves must be polarized primarily perpendicular to the magnetic field direction, as observed in the inset hodograms in Figure 1d.

2.2.1. NPM captures

A wavelet analysis of the NPM-associated burst waveforms indicates that there is a low frequency (100-300 Hz) component, also primarily polarized perpendicular to the magnetic field direction as required from the vector matching conditions. For the NPM transmitter-associated burst captures the waves exhibit a complex polarization in the perpendicular plane. The STEREO spacecraft only effectively provide single-point electric field measurements which are insufficient to measure wavelength directly. Because of this, we start with the assumption that the ∼200 Hz separation of the lower hybrid waves from the carrier 21.4 kHz waveform ($\Delta f = 200$ Hz) is due to Doppler-shift and estimate the wavelength (λ) by solving the Doppler-shift equation $\Delta f = \vec{k} \cdot \vec{V}_{sc} = 2\pi\vec{V}_{sc}cos(\delta)/\lambda$. This would be the case if the parametric decay is that described by *Lee and Kuo* [1984] and the low frequency mode is purely-growing. Before proceeding we must determine the angle between the wave vector of the lower hybrid wave and the spacecraft velocity ($cos(\delta) = \vec{V}_{sc} \cdot \vec{k}/|\vec{V}_{sc} \cdot \vec{k}|$). During the time of the NPM-associated burst capture STEREO A was moving at 10.7 km/s in the direction $\hat{V}_{sc}$=[-0.31,-0.91,-0.29] (solar magnetic coordinates). The co-rotation velocity of the plasma at the spacecraft location at this time (550 km altitude) is roughly 0.5 km/s and is ignored in this analysis. The NPM-associated

wave in Figure 1a is the most linearly polarized between the times of 16.5 and 17.2 msec. During this time the unit wave normal vector points in the direction of the electric field and is given in SM coordinates as $\hat{k}_\pm = \pm[0.63,0.15,-0.76]$; thus the acute angle between the wave vector and the spacecraft velocity vector is $\delta \sim 84°$. Using the determined values of $\vec{V}_{sc}$ and $\hat{k}_\pm$ in the Doppler-shift equation we find that a wavelength of $\sim$35m is needed to obtain a Doppler-shifted of 200 Hz.

This wavelength can be compared to the theoretical wavelength of a lower hybrid wave excited by the mechanism of *Lee and Kuo* [1984] via the lower hybrid dispersion relation $\omega_\pm = \omega_{lh}\sqrt{1 + \frac{M}{m}\frac{k_\circ^2}{k_s^2}}$, where M/m is the ion to electron mass ratio, and the lower hybrid angular frequency ($\omega_{lh} = 2\pi f_{lh}$) is defined in terms of the ion plasma (ω_{pi}) and electron plasma (ω_{pe}) and cyclotron angular frequencies (ω_{ce}) as $\omega_{lh} = \omega_{pi}/\sqrt{1 + \omega_{pe}^2/\omega_{ce}^2}$. In order to solve this equation for $k_s(\sim k_\pm)$ we need to determine the wave number of the incident whistler mode wave via the cold plasma whistler dispersion relation, requiring knowledge of the background magnetic field, plasma density and composition, and polarization of the incident whistler mode wave. During the time of the NPM-associated wave the magnetic field value is known from IMPACT measurements to be 26,121 nT. The plasma density is unknown, but is estimated from the International Reference Ionosphere 2007 model [*Bilitza and Reinisch*, 2008] to be 44,200 cm^{-3} in a plasma composed of 49% H$^+$, 47% O$^+$, and 4% He$^+$. The wavelength varies as the square root of the density is therefore relatively unchanged by reasonable variations.

The incident whistler mode wave in Figure 1 is the least elliptically polarized at 14 msec with a value $E_x/E_y \sim 2$ (ratio of semi-major to semi-minor axes in perpendicular direction). At this time the contamination from the linearly polarized lower hybrid waves is at its minimum and the polarization ratio of the incident whistler mode wave is closest to its true value. This corre-

sponds to a very obliquely propagating whistler mode wave with a wave normal angle of 60° and a wavelength of 650 m (or $|k_o|$=0.01 1/m). The large wave normal angle is not unusual for low altitude whistler mode waves which are often polarized primarily in the direction of increasing altitude because of refraction due to a horizontally stratified ionosphere. At the location of the NPM-associated wave observation, the angle between the vertical and the background magnetic field is ∼63°, similar to the calculated wave normal angle. Note that this is also consistent with the calculated wave normal angle of a lightning-associated whistler without any polarization reversals observed at 07:46:01.490 on STEREO B, where the spacecraft is at nearly the same altitude and latitude as for the NPM captures. This is consistent with our assumption that little contamination due to the lower hybrid waves occurs in the NPM wave normal angle estimate.

Using a value of $|k_o|$ =0.01 1/m in the lower hybrid dispersion relation, we find that excited lower hybrid waves will have a wavelength of ∼35 m, the same value that we obtained by assuming that the 200 Hz separation between the whistler mode wave and lower hybrid waves was due to Doppler-shift. Because there is some uncertainty in this calculation due to possible lower hybrid wave contamination, we calculated the predicted wavelength of the lower hybrid wave for an extensive range of whistler mode wave normal angles from 0° to 80°. For this range of angles, the predicted wavelength ranges from 23 to 50 meters, corresponding to a Doppler-shifts from 130-330 Hz. This is very close to the observed frequency span of the low frequency component. Thus the low frequency component is best explained as a purely growing mode with zero frequency in the plasma frame that is Doppler-shifted to the observed frequency. However, it is possible that the observed frequency of this wave could result from a combination of an innate frequency in the plasma frame along with at least 130 Hz of Doppler-shift.

The threshold for instability from *Lee and Kuo* [1984] depends on whether the plasma falls into Domain 1 (Equation 21b), driven by the non-oscillatory beat current, or Domain 2 (Equation 22b), driven by the thermal pressure force. For the conditions at the location of STEREO A at the time of the NPM transmitter-associated burst capture, we find that an $H^+(O^+)$ plasma satisfies the conditions of Domain 1(2). The observed wave amplitudes of 40-60 mV/m easily exceed the minimum amplitude threshold for instability for both an H^+ plasma ($\sim$5 mV/m) and an O^+ plasma ($\sim$0.25 mV/m). The growth rate (Equation 20b) is calculated to be γ=0.22 1/s (or t=4.6 sec for instability to develop) for Domain 1 (H^+) and γ=4.5 1/s (t=0.2 sec) for Domain 2 (O^+), indicating that the instability will grow much more quickly for an O^+ plasma than an H^+ plasma. The eight NPM-associated burst captures are detected over a four second time interval, indicating that a continuous train of transmitter waves from below spanning this time interval has time to destabilize. In summary, the calculations obtained above show that the polarization reversals of the NPM transmitter-associated waves observed on STEREO A during perigee on November 6th, 2006 are consistent with the four-wave interaction of *Lee and Kuo* [1984] between an incident electromagnetic whistler mode wave, two symmetric lower hybrid sidebands and a purely-growing field-aligned mode.

2.2.2. Lightning whistlers

In addition to the NPM waves presented by *Breneman et al.* [2011], polarization reversals were also seen in lightning-associated whistlers, observed on STEREO A near perigee starting five minutes after the NPM observations when the spacecraft magnetic footprint was over a lightning storm off the western coast of southern Mexico. An example is presented in Figure 2b, which shows a dispersive lightning whistler at $f > f_{lh}$ as well as a dispersive whistler at $f < f_{lh}$ (the tail end of a previous whistler) and a low frequency wave at $\sim$100-400 Hz, linearly

polarized in the plane transverse to the magnetic field. This lightning-associated whistler mode wave is representative of the observed polarization in all the STEREO A lightning-associated burst waveform captures, right-hand polarized at $f < f_{lh}$ and at $f > \sim f_{NPM}$ and left-hand polarized otherwise. Unlike with the NPM transmitter-associated waves, symmetric sidebands are not obvious in the sliding power spectra of the lightning-associated whistlers. However, if they exist at a given frequency they would likely be blurred out in a frequency spectrum due to the dispersive character of the whistlers. For the lightning-associated whistler in Figure 2 the first hints of the polarization reversal occur at roughly 4 msec, when the frequency of the dispersive whistler is near the NPM transmitter frequency. At this time the low frequency component becomes more prominent and begins to increase in amplitude and frequency. The polarization spectrum in Figure 2c of the dispersive component shows the start of a transition from right-hand elliptical to linear polarization at this time. The dispersive component is completely left-hand polarized by $\sim$7 msec, where the low frequency component reaches its maximum amplitude and spans the frequencies from 100-400 Hz. Hodograms at this time (not shown) indicate that the lightning whistler is at its most linearly polarized state, in the plane perpendicular to the magnetic field. This indicates that the change in polarization for the lightning whistler wave from right-hand polarized to linearly polarized occurs roughly at the same time as the growth of the low frequency component.

Although it is not explicitly shown here, we suggest that a beat-wave mechanism similar to that occurring in the NPM burst captures is causing the observed polarization reversals. Because the lightning whistlers are dispersive, each frequency at $f \geq f_{lh}$ could potentially give rise to a lower hybrid wave via parametric decay. This suggests that many lower hybrid waves, along with the original dispersive whistler are interacting. The low frequency component is

completely absent from the STEREO B lightning-associated whistlers seen 1.5 hours earlier, which have no polarization reversals.

Regardless of the specific mechanism, parametric decay involving an incident whistler mode wave decaying into lower hybrid waves and a low frequency component is not predicted to occur at frequencies $f < f_{lh}$. Therefore the polarization should be that of a usual right-hand polarized whistler mode wave, as is observed. The parametric instability of *Lee and Kuo* [1984] grows the most strongly near the lower hybrid frequency and these frequencies could presumably be dominated by excited lower hybrid waves. Thus, assuming that the beat interaction between two or more waves is causing the polarization reversals, the hodograms at frequencies just above the lower hybrid frequency would be the most likely to appear left-hand polarized. As the wave frequency increases above the lower hybrid frequency the gain of any lower hybrid sidebands falls off and, eventually, the incident right-hand polarized whistler mode wave should dominate. This may explain why the waves are again right-hand polarized at frequencies (approximately) greater than the NPM transmitter frequency. The closeness of this transition to the transmitter frequency may be coincidental or may have to do with influence of the transmitter on the local plasma. As was discussed in *Breneman et al.* [2011], the polarization reversals are not seen on similar lightning-associated whistlers observed on STEREO B, which occurred when the transmitter was emitting in a pulsed-narrowband mode rather than in the continuous-broadband mode that was operating for the times of the STEREO A lightning-associated whistlers. In addition, more than one burst waveform capture on STEREO A shows the sudden increase of the $\sim$200 Hz component as the dispersive whistler crosses the NPM transmitter frequency. These observations, along with the fact that the NPM transmitter is modulated at 200 Hz when

in the continuous broadband mode suggest that the transmitter may be indirectly responsible for the polarization reversals seen in the lightning whistlers.

One additional observation worth noting is, unlike the NPM-transmitter waves and typical whistler mode waves, some (but not all) of the lightning-associated waveforms observed on STEREO A have large field-aligned components at frequencies $f > f_{lh}$. This component possibly exists to satisfy wave matching conditions for a parametric instability. The existence of the field-aligned component remains a mystery and may offer clues to any decay mechanism that may be occurring.

3. Discussion and Conclusions

The two STEREO spacecraft each made four Earth-orbit passes in 2006 before entering their current heliospheric orbit. A survey of waves during these Earth-orbits has indicated that polarization reversals are seen in a significant percentage of the telemetered burst captures on both STEREO A and B throughout the magnetosphere as well as within the magnetosheath and foreshock. The reversals are seen in association with whistler mode, Langmuir, and lower hybrid waves. In each case analyzed, the polarization reversals seem to be caused by the beating of two or more waves with a frequency separation equal to the frequency of the polarization reversals, though the reason for the existence of the multiple waves can vary depending on the type of wave. This effect has been reported on rocket data (Thunderstorm II) by *Baker et al.* [2000] who attributed the changing polarization of lightning whistlers to the beating of a right-hand circularly polarized whistler and a quasi-electrostatic whistler. Polarization reversals are also observed in association with lower hybrid solitary structures (LHSS), generally observed in the auroral zone in association with small-scale field-aligned plasma density gradients (e.g. *Schuck et al.* [2003]). LHSS, unlike the waves presented in this paper, are right-hand polarized at

$f > f_{lh}$ and left-hand polarized at $f < f_{lh}$. The left hand polarization is due to the contribution of a Hall current formed at the density gradients.

Aside from the rocket observations of *Baker et al.* [2000], polarization reversals of the sort presented in this Paper have not, to our knowledge, been previously reported on other spacecraft. This may have to do with two characteristics of instrumentation unique to STEREO and a few other spacecraft. The sensitivity of electric field antennas to a specific wavelength depends on, among other factors, the length of the antenna. For spherical double probes, the antenna length is the distance between the spheres and for cylindrical antennas (like those on STEREO) the antenna length is the defined effective length which is shorter than the physical length. In general, antennas don't have a strong response to wavelengths much smaller than the antenna length. A majority of electric field antennas flown on spacecraft have been double probes separated by long booms ($\sim$100 m). A 100 m tip-tip separation double probe antenna would have a greatly reduced response to a 35 m wave. To measure shorter wavelength waves many spacecraft also contain a single shorter boom of a few to a few 10s of meters, usually on the spin axis. This type of boom is capable of detecting the short wavelength waves described in this Paper. However, polarization reversals would not be detected because firstly, the short wavelength wave would only be observed on a single antenna and secondly, most past spacecraft did not telemeter high resolution waveform data capable of resolving waves in the kHz range. As far as the authors are aware, only STEREO, Wind, FAST and Cassini (as well as the upcoming RBSP spacecraft) have the necessary combination of multiple short antennas and high resolution waveform capability necessary to detect polarization reversals caused by the beating of two waves when at least one of the waves is short wavelength.

3.1. Geophysical Significance

We conclude with a discussion of the potential consequences of the observed polarization reversals. The excited short wavelength waves observed may cause significant local modification of the plasma. Regions of plasma heating have, for example, been observed at low altitudes over lightning storms [*Bell et al.*, 1993] and over precipitation regions of the NPM transmitter at L=1.9 [*Bell et al.*, 2008]. Excited lower hybrid waves have also been linked to explosive spread F above thunderstorms by *Baker et al.* [2000]. Lower hybrid waves attributed to the parametric decay mechanism of *Lee and Kuo* [1984] have been shown to be the cause of explosive spread F occurrence at equatorial latitudes over Jicamarca (Peru) [*Liao et al.*, 1989] and Aricebo (Puerto Rico) [*Labno et al.*, 2007]. The observations presented in this Paper show that this parametric decay mechanism also operates over the NPM transmitter. As shown by these previous studies, the parametric decay into lower hybrid waves can cause significant attenuation of the whistler wave energy incident from below. This may partly explain why the predicted wave energy (from ray tracing simulations) deposited into the inner radiation belt over the NPM transmitter is larger than that observed [*Starks et al.*, 2008].

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Figure 1. NPM-associated burst capture in field-aligned coordinates where the magnetic field lies along the $\hat{z}$ axis and the wave vector is defined to lie in the $\hat{x}$-$\hat{z}$ plane. (a) Burst waveform where the blue, green and orange colors represent the $\hat{x}$, $\hat{y}$ and $\hat{z}$ directions respectively. (b) Frequency/time spectra of the wave normal angle (from dispersion relation), ellipticity E_x/E_y and handedness. Note that the second and third spectra are offset in the y-direction for clarity. For the handedness spectrum, red(blue) represent right(left) hand polarizations with respect to the magnetic field and black represents linear polarization, defined as $E_x/E_y \geq 8$. Vertical lines are included to indicate the locations of the polarization reversals. (c) Wave magnitude $|E| = \sqrt{E_x^2 + E_y^2 + E_z^2}$. (d) Four snapshots of the frequency spectrum ($\hat{y}$) for the times given by the colored panels above (a). The relative power scale is the same in all of the plots. The length of each snapshot is long enough to provide sufficient frequency resolution while not so long as to wash out the frequency separation effect. The inset hodograms show the polarization in the $\hat{x}$-$\hat{y}$ plane for representative times within each snapshot.

Figure 2.   (a) STEREO A lightning-associated whistler at 09:20:47.216 in the coordinate system described in Figure 1. (b) Wavelet transform that shows the simultaneous existence of three waves: a whistler bounded in frequency by the two horizontal lines (lower hybrid frequency at 7.5 kHz and NPM transmitter frequency at 21.4 kHz), the tail end of a previous whistler just below the lower hybrid frequency, and an impulsive low frequency component from $\sim$100-800 Hz. (c) The wave handedness where red(blue) represent right(left) hand polarizations with respect to the magnetic field. The vertical line indicates the time when the polarization changes. This roughly corresponds to the growth of the low frequency component.

Figure 3.   Simplified simulated version of the waveform in Figure 1. (a) The frequency spectrum of the simulated electric field showing peaks at 21.4 and 21.2 kHz, corresponding to the electromagnetic whistler carrier and a single lower hybrid sideband. The wave is rotated into field-aligned coordinates where orange is the component along the magnetic field ($\hat{z}$) and the wave vector is defined to be in the $\hat{x}$ (blue) and $\hat{z}$ plane. (b) Simulated waveforms in the defined coordinate system. (c) Simulated wave handedness spectrum, similar to that shown in Figure 1b. The reversals in polarization occur at the minimums in the waveform magnitude $|E| = \sqrt{E_x^2 + E_y^2 + E_z^2}$. For clarity, locations where the polarization becomes highly oblique/linear (at the interfaces between the red and blue) are not indicated with the color black as in Figure 1b. (d) Waveform magnitude for comparison with Figure 1c.

(a)

(b)

(c)

(d)

(a) f>8500 Hz