Hiss or Equatorial Noise? Ambiguities in Analyzing Suprathermal Ion Plasma Wave Resonance

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Abstract.

Previous studies have shown that low energy ion heating occurs in the magnetosphere due to strong equatorial noise emission. Observations from the Van Allen Probes Helium Oxygen Proton Electron (HOPE) instrument recently determined there was a depletion in the 1-10 eV ion population in the post-midnight sector of Earth during quiet times at L < 3. The diurnal variation of equatorially mirroring 1-10 eV H^+ ions between 2 < L < 3 is connected with similar diurnal variation in the electric field component of plasma

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waves ranging between 150 and 600 Hz. Measurements from the Van Allen Probes Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) data set are used to analyze waves of this frequency in near-Earth space. However, when we examine the polarization of the waves in the 150 to 600 Hz range in the equatorial plane, the majority are right-hand polarized plasmaspheric hiss waves. The 1-10 eV H^+ equatorially mirroring population does not interact with right hand waves, despite a strong statistical relationship suggesting the two is linked. We present evidence supporting the relationship, both in our own work and the literature, but we ultimately conclude that the 1-10 eV H^+ heating is not related to the strong enhancement of 150 to 600 Hz waves.

1. Introduction

Thermal ions in the plasmasphere have been shown to be transversely heated through ion cyclotron resonance with waves above the ion gyrofrequency and below the lower hybrid resonant frequency. Ion cyclotron resonant heating of thermal ions was demonstrated through observations and modeling of GEOS-1 and GEOS-2 data [*Young et al.*, 1981; *Roux et al.*, 1982; *Perraut et al.*, 1982; *Perraut*, 1982]. In particular, He^+ was shown to most strongly resonate with the measured frequencies in the GEOS data. Other studies concluded that cyclotron resonance heats H^+ thermal populations at geosynchronous orbit similar to the He^+ heated population [*Quinn and Johnson*, 1982]. These thermal ions require left hand or linearly polarized waves for wave-particle interactions that lead to subsequent heating. However, there is still debate as to which waves are present during times of inner magnetosphere low energy ion heating: equatorial noise or plasmaspheric hiss.

Equatorial noise has been shown to heat thermal ions through cyclotron resonance [*Olsen et al.*, 1987; *Singh and Hwang*, 1987; *Laakso et al.*, 1990]. Equatorial noise is a fast magnetosonic, low frequency wave with nearly linearly polarized magnetic field fluctuations generated by unstable energetic proton ring velocity distributions [*Perraut et al.*, 1982; *Gary et al.*, 2010]. Equatorial noise ranges in frequency from approximately 20 Hz to a few hundred Hz and lies below the lower hybrid frequency [*Němec et al.*, 2015; *Boardsen et al.*, 2016]. Typically, equatorial noise is found between 2 and 7 Earth radii and within 10 degrees of the magnetic equator [*Russell et al.*, 1970; *Němec et al.*, 2006].

Strong diurnal variation has been previously seen in Cluster observations of equatorial noise outside of the plasmasphere, with a peak at MLT = 12 and a minimum in the post-midnight sector between MLT = 0 and 6 [*Hrbáčková et al.*, 2015; *Ma et al.*, 2016]. Studies of the global wave distribution revealed that equatorial magnetosonic waves inside the plasmapause depended on substorm activity and had larger amplitudes and higher occurrence frequencies on the dayside [*Green et al.*, 2005; *Meredith et al.*, 2008; *Ma et al.*, 2013].

Based on Dynamics Explorer 1 and SCATHA observations, it was proposed that equatorial noise, generated by highly energetic ions in the ring current and/or radiation belt, heats the thermal ion population through cyclotron resonance. Wave-particle interactions elevate the thermal population to a suprathermal population via energy deposition by equatorial noise (10 eV < E < 300 eV) [*Curtis*, 1985]. The energy transference could also occur with 1-10 eV He^+ and O^+, albeit on slower time scales. Modeling work also suggests that inward propagating magnetosonic waves produced by proton ring instabilities could cause thermal plasma heating near-Earth [*Horne et al.*, 2000].

However, plasmaspheric hiss occupies a similar region of space as the equatorial noise and typically ranges from 20 Hz to approximately 1000 Hz [*Thorne et al.*, 1973; *Meredith et al.*, 2007; *Li et al.*, 2015]. Plasmaspheric hiss is a broadband incoherent electromagnetic emission that is largely confined to Earth's plasmasphere [*Meredith et al.*, 2009]. Plasmaspheric hiss can be generated from magnetospherically reflecting whistler waves or from inward propagating chorus emissions that lose coherency when they cross the plasmapause [*Draganov et al.*, 1992; *Bortnik et al.*, 2008]. Hiss amplification at the equator due to wave turbulence from the electron gyroresonance instability leads to enhanced plasmaspheric hiss in the magnetic equatorial plane [*Thorne and Barfield*, 1976; *Church and Thorne*, 1983; *Solomon et al.*, 1988; *Santolik et al.*, 2001]. Unlike equatorial noise, plasmaspheric hiss is right hand polarized and primarily interacts with electrons [*Tsurutani et al.*, 1975; *Li et al.*, 2007; *Summers et al.*, 2007]. Without looking at polarization or spectral lines, it is difficult to distinguish between plasmaspheric hiss and equatorial noise [*Gurnett*, 1976; *Santolík et al.*, 2002].

Plasma waves are a likely cause for the observed minimum in the high energy tail (1-10 eV) of the inner plasmasphere (L-Shell $<$ 3) in the post-midnight sector [*Lennartsson and Reasoner*, 1978; *Sarno-Smith et al.*, 2015]. A previous study revealed that in the post-midnight sector specifically, the H^+ pitch angle (PA) = 90^o population between $2 < L < 3$ was depleted but plasma was still flowing upward from the ionosphere [*Sarno-Smith et al.*, 2015a]. Upward flowing plasma in the post-midnight sector suggests that the apparent loss of plasma in the post-midnight sector is not driven by the cooling of plasma in the topside ionosphere. Instead, plasma wave influence may be heating/scattering the particles in such a way to lead to strong diurnal variation in the 1-10 eV population.

Three instruments onboard the NASA Van Allen Probes mission enable further exploration of the connection between 1-10 eV ions of the inner plasmasphere and plasma wave activity. The Van Allen Probes, launched in late 2012, are a pair of satellites that are in highly elliptical, low inclination orbits [*Mauk et al.*, 2014]. The Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instrument measures plasma waves between approximately 2 Hz and 12 kHz using three search coil magnetometers and the three Electric Field and Waves (EFW) instrument's electric field antennas [*Wygant et al.*, 2013; *Kletzing et al.*, 2014]. EMFISIS also measures the DC magnetic field with onboard magnetometers. The plasma wave range we examine is between 150 Hz and 600 Hz, well within the resolution capabilities of EFW and EMFISIS. The Helium Oxygen Proton Electron (HOPE) instrument measures the ion and electron populations of the equatorial inner magnetosphere between 1 eV and 50 keV [*Funsten et al.*, 2014]. HOPE also uses the EMFISIS magnetometer measurements to map the observed fluxes into pitch angle space and assign nominal pitch angle bins.

We examine the connection between 150 Hz - 600 Hz waves with the 1-10 eV ion population of the L < 3 inner plasmasphere. As previous studies have found, we find the diurnal variation in the 150 Hz - 600 Hz waves is linked with the 1-10 eV ion equatorially mirroring population growth and loss [*Olsen et al.*, 1987; *Singh and Hwang*, 1987]. Polarization analysis reveals that the near-Earth emissions near the equator are primarily plasmaspheric hiss and do not cyclotron resonate with the low energy ions and are not responsible for the ion heating. We corroborate our results with observations from EMFISIS and HOPE, opening up several questions in magnetospheric physics of our understanding of thermal plasma and wave interaction.

2. Particle and Wave Statistics

Following the 1-10 eV ion depletion in the post-midnight sector discovery in *Sarno-Smith et al.* [2015], we examine the fluxes measured at different pitch angles from February 2013 to April 2015. The polar angle resolution on the HOPE instrument is 18 degrees full width. Pitch angle bins are 18 degrees wide, except for 9 degree bins centered at 4.5 and 175.5 degrees. In every spin period of approximately 11 seconds, HOPE differential number flux values were calculated and assigned a pitch angle designation based on the magnetic field direction as measured by EMFISIS. Initial analysis of the pitch angle distributions were conducted by *Sarno-Smith et al.* [2016b], and here the analysis is taken further to examine the evolution of the full velocity-space distribution in both energy and pitch angle.

Figure 1 displays the median 1-10 eV H^+ differential number fluxes at L = 2.5 for times when Kp ≤ 3 between February 2013 and April 2015 measured by HOPE sorted by pitch angle, MLT, and energy. The fluxes are corrected for spacecraft charging, and the process is detailed in *Sarno-Smith et al.* [2016b]. We note that the Van Allen Probes tend to charge slightly positive. The L = 2.5 bin spans from 2.375 to 2.625 (0.25 L-Shell). The fluxes are not always centered near-PA = 90^o due to seasonal effects, such as increased upwelling ion fluxes from the summer hemisphere compared to the winter hemisphere. At MLT = 2, the near PA = 90^o population is at a minimum for all energies shown. The flux measurements at near PA = 0^o and near PA =180^o are lower compared with other MLTs for these pitch angle bins but are larger than the near PA = 90^o measurements. The equatorially mirroring population begins to refill for the 1 eV energy channels at MLT = 4, but the near PA = 90^o population minimum is prevalent at the higher energies (energy > 2 eV). MLT = 6 demarcates the transition from a dominant refilling population at 0^o and 180^o to a more equatorially mirroring focused population. Above 6 eV, however, the near PA = 90^o population is still at a relative minimum compared to the 0^o and 180^o

degree pitch angle flux measurements or the distribution is isotropic.

A balance is struck between MLT = 8 to MLT =18 where the near PA = 90^o population is still at a relative minimum above 8 eV, but the near PA = 90^o population remains in a steady state throughout the day. MLT = 22 fluxes reveal that the equatorially mirroring population has begun to recede. While the near PA = 90^o population still dominates below 3 eV, the pitch angle distributions are either refilling ($0^o/180^o$ dominated) or isotropic beyond 3 eV. MLT = 0 exhibits similar behavior, with the last of the near PA = 90^o population at 1.5 eV narrowing.

In Figure 1, there are two indications that the loss of the equatorially mirroring population may not simply be a balance of ionospheric outflow and scattering. The first indicator is if the change in 1.5-10 eV plasma in the inner magnetosphere was from ionospheric diurnal variation and consequent transport to the plasmasphere, it would be expected that the higher energy ions should appear first at L = 2.5 and scatter first since they move the fastest. Instead, we see that the lowest energies for PA = 90^o rise the fastest and the higher energies above 8 eV either never have a near PA = 90^o population maximum or take longer than the lower energies. For example, the 2 eV equatorially mirroring population is at a maximum by MLT = 6, but the 8 eV population is not at a maximum until MLT = 8.

The other indication is the depletion in the near PA = 90^o population compared to the near PA = $0^o/180^o$ measurements. While the equatorially mirroring populations have > 2.5 orders of magnitude of variation, the field aligned fluxes show about 2 orders of magnitude diurnal variation. We use the 18^o and 162^o bins to describe the field aligned PA bins because the 175.5^o and 4.5^o bins are smaller and less accurate. Figure 2 shows the L = 2.5 spacecraft potential corrected fluxes of 1.55, 1.83, 2.18, 2.53, 2.95, 3.38, 3.94, 4.64, and 5.35 eV normalized by the highest values at each energy at pitch angles of 18^o, 54^o, 90^o, 144^o, and 162^o. For the more field aligned pitch angles, the normalized fluxes show that the high energy H^+ ions rise first at dawn compared to the slower particles. At PA = 90^o, the opposite occurs, with the lowest energy fluxes increasing first.

The PA = 90^o fluxes also show an energy dependent decrease. Starting at MLT = 18, the PA = 90^o fluxes start decreasing. The highest energy ions are depleted first, with over an order of magnitude drop occurring before midnight. The low energy ions (1-3 eV) have a delayed depletion until the post-midnight sector. The steady growth of the PA = 90^o population across the morning to a saturation point at MLT = 10 suggests perpendicular heating the H^+ ions throughout the dayside. The flatness of the curves across the dayside at all pitch angles in Figure 2 indicates that the fluxes are in equilibrium, with the wave heating balanced by the scattering and loss.

From Figures 1 and 2, we can conclude that wave activity, not ionospheric breathing, is responsible for the 1-10 eV ion depletion because of the behavior of the PA = 90^o population. Following the theory of equatorial noise heating thermal plasma from *Olsen et al.* [1987], we explore the possibility of a wave-particle interaction by examining the EMFISIS survey mode data over the course of 26 months. The survey mode on EMFISIS includes a set of spectral matrices every 6 seconds [*Kletzing et al.*, 2014]. The EMFISIS instrument uses a fast Fourier transform on board to analyze the electric field samples from EFW and the results are telemetered to the ground. The EMFISIS survey mode data are averaged onboard into 65 logarithmically spaced bins between 2 Hz and 10 kHz and binned by 0.5 MLT and 0.25 L-Shell for times when Kp < 3.

To identify peak wave activity, Figure 3 shows the relative intensity of EMFISIS Wave-Form Receiver (WFR) frequencies as a function of MLT at L = 2.5. Figure 3A shows the median power spectral densities from February 2013 to April 2015. Figure 3B uses the same binning strategy and displays the normalized power spectral densities. The power spectral densities in each frequency bin are normalized by the highest power spectral density in that frequency bin. The silver line is the 6th harmonic of the H^+ cyclotron frequency. We use the 6th harmonic of the H^+ cyclotron frequency because it is approximately where we see enhanced power spectral densities. We show the geometric mean lower hybrid frequency instead of the lower hybrid frequency because it is difficult to get a true estimate on plasma density at L < 3, where EMFISIS electron number density estimates from the upper hybrid frequency saturate [*Kurth et al.*, 2015]. This technique has been used in previous studies to estimate the lower hybrid frequency using only the electron and ion gyrofrequencies [*Olsen et al.*, 1987]. It only works under the approximation of dense plasma, otherwise it provides only an upper estimate of the lower hybrid frequency.

Figure 3 shows strong diurnal variation in the frequency band above the 6th harmonic of H^+ cyclotron frequency (silver line). The frequencies which show dayside enhancement extend from 150 Hz to 600 Hz. Figure 3B highlights the change in power spectral density with MLT in this range of frequencies with a peak in the morning sector and the lowest values occurring across the night side. This frequency band includes equatorial noise/plasmaspheric hiss. The diurnal variation in plasmaspheric hiss is attributed to keV electron injection into the outer plasmasphere on the dayside in conjunction with substorms and to whistler-mode chorus, which is known to be a source of plasmaspheric hiss, which can not propagate into the plasmasphere on the nightside due to stronger Landau damping caused by higher suprathermal electron flux [*Bortnik et al.*, 2007; *Li et al.*, 2013; *Chen et al.*, 2014; *Li et al.*, 2015]. Diurnal variation is also common in equatorial noise and proton ring distributions can provide a source of free energy ring velocity (+/- a factor of 2 above or below the Alfvenic speed) and generate equatorial noise [*Chen et al.*, 2010, 2011; *Hrbáčková et al.*, 2015].

Figure 4 highlights the power spectral densities for frequencies below 1000 Hz. Using data from February 2013 to April 2015, EMFISIS WFR frequency channels were binned by 0.25 L-Shell and 0.5 MLT for quiet times when Kp < 3. We did not set a limit on the satellite's magnetic latitude in Figure 4. The wave amplitudes peak beyond 150 Hz, with a dayside maximum at all L-Shells beginning at f = 200 Hz and continuing through f = 300 Hz. At 1000 Hz, the strong diurnal variation is absent, with a minimum at L < 3 dayside MLTs.

3. Quantitative Relationship Between Wave Amplitude and Low Energy Ions

In this section, we show how the Van Allen Probes observations dovetail with a resonant interaction occurring between low energy ions and 150 Hz - 600 Hz waves. Figure 5 compares the median wave power spectral densities at harmonics of the H^+ cyclotron frequency with median H^+ 1-10 eV partial densities at all MLTs for different L-Shells from February 2013 to April 2015. Figure 5A shows L = 2.0, Figure 5B shows L = 2.5, and Figure 5C shows L = 3.0. For each 4 second measurement of the magnetic field, the gyrofrequency and harmonics of the gyrofrequency were calculated and then the electric field power spectral density at the nearest frequency to the gyrofrequency was extracted and binned.

The partial density and wave power spectral density behave differently at each of the L-Shells. At L = 2.0, The 6th and 10th harmonic wave power spectral density begin to decline at MLT = 14, dropping to approximately 10^{-12} $V^2/m^2/Hz$ between MLT = 19 to MLT = [illegible]. The wave power spectral densities increase in three stages at MLT = 4, 6, and 10 before reaching approximately 10^{-11} $V^2/m^2/Hz$ across the dayside. The 16th harmonic wave power spectral density is largely flat with little diurnal variation. The 1-10 eV H^+ density has a maximum at MLT = 6, beginning to increase at approximately MLT = 4. The density gains and losses do not precisely follow the power spectral densities, but both exhibit general diurnal variation.

For L = 2.5, the 6th, 10th, and 16th harmonic power spectral densities show the most diurnal variation, varying between approximately 10^{-11} $V^2/ m^2/Hz$ from MLT = 6 to

MLT = 16 and approximately 10^{-12} V^2/ m^2/Hz from MLT = 17 to MLT = 3. The different harmonic power spectral densities also follow each other closely with very similar power spectral densities at different MLTs. The partial density also shows the most diurnal variation of the three L-Shells shown, peaking from MLT = 6 to MLT = 22. The rise of the 10th and 16th harmonics of the H^+ gyrofrequency occur before the rise in the partial density, although the peak power spectral density occurs after the partial density has risen above 10^1 cm^{-3}.

The L = 3.0 panel shows the least diurnal variation of the 6th, 10th, and 16th harmonic power spectral densities. The heightened dayside power spectral densities occur from MLT = 6 to MLT = 14 and the nightside low extends from MLT = 20 to MLT = 3. The 16th harmonic is strongest at this L-Shell, whereas the 6th and 10th harmonic are much lower. The 1-10 eV density takes much longer to reach the high dayside values at this L-Shell, not reaching peak value until MLT = 9 after a gradual increase starting at MLT = 1.

There are many factors contributing to the partial density increases in Figure 5. It is important to note that harmonic cyclotron resonance occurs at multiple frequencies and heats the ions differently based on the degree of the harmonic and the background magnetic field conditions [*Schmitt*, 1976; *Mauk et al.*, 1981]. So, in considering how power spectral densities at different harmonics affect the 1-10 eV H^+ partial densities across MLTs, a holistic approach should be taken. For example, at L = 2.5 where all the power spectral densities are high, the cumulative heating impact on the 1-10 eV ions from equatorial noise will be greater than at L = 3.0 where the 16th harmonic has a higher power spectral density dayside value than the other harmonics. Also, at L-Shells closer to Earth, the ionospheric contribution is greater and topside ionospheric plasma is transported into the equatorial plasmasphere faster.

We developed a binary contingency table test to quantify if there was a connection between waves with power spectral density above a certain level and high H^+ fluxes. Figure 6 shows the outcome of our threshold test. Each panel of Figure 6 shows the percentage of each contingency table element based on MLT and L-Shell location. The grid is divided into 0.25 L-Shell bins between 1.5 and 4 and 0.5 MLT bins between 0 and 24. The threshold bars were 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1} for H^+ 2.5 eV fluxes and 10^{-12} V^2/ m^2/Hz for EMFISIS power spectral densities at 250 Hz. The power spectral density boundary is based on the electric field power spectral densities necessary for observable transverse heating of a few eV per hour in the $2 < L < 3$ region [*Singh and Hwang*, 1987]. The flux threshold is based on measured HOPE fluxes at all MLTs for this energy channel.

The High Wave and Particle category denotes HOPE H^+ fluxes of 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1} or greater and a power spectral density of 10^{-12} V^2/ m^2/Hz or greater. The Low Wave and Particle section denotes ion fluxes less than 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1} and power spectral densities less than 10^{-12} V^2/ m^2/Hz. Only High Wave occurs where the power spectral densities are greater than 10^{-12} V^2/ m^2/Hz but the ion fluxes are less than 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1}. Only High Particle occurs when power spectral densities are less than 10^{-12} V^2/ m^2/Hz and the ion fluxes are greater than 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1}.

There are several key ideas that emerge from Figure 6. When ion fluxes on the dayside are high, in most cases between L-Shells of 1.5 to 3.25 and MLTs between 5 and 20, the EMFISIS power spectral densities will be high and vice versa. This relationship is demonstrated by the High Wave and Particle contingency outcome, where high percentages ($>$ 70 %) are seen in these L-Shell/MLT bins. On the other hand, the Low Wave and Particle category shows us that in the post-midnight region between 0-5 MLT and 1.5 to 3.5 L-Shell, the opposite is seen with approximately equal occurrence frequency; low ion fluxes are accompanied by low power spectral densities.

The Only High Particle and Only High Wave outcomes of the threshold test reveal the areas subject to extenuating factors. The Only High Wave, where ion fluxes are low despite high power spectral densities, occurs at higher L-Shells across many MLTs. We attribute this largely to the declining ion densities from the conservation of the second adiabatic invariant at higher L-Shells, so the threshold of 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1} is no longer a fair threshold mark at L $>$ 3. The Only High Particle outcome, where power spectral densities are low but the particle fluxes are high, occurs at high percentages for low L-Shells at MLTs of 5 to 20 and at higher L-Shells around MLT = 18. We attribute this effect to ionospheric influence. From this binary contingency table, we can see that there is a clear connection between wave amplitudes and high H^+ fluxes.

We supplement this statistical result with a case study to show the relationship between dayside 1-10 eV H^+ flux enhancement and high wave amplitudes. Figure 7 highlights from 9:00-11:30 UT on July 2, 2013, when the Van Allen Probes A crossed the post-midnight sector between $2 < L < 3$ on the outbound leg of the orbit. Figure 7A shows the EMFISIS frequency spectrogram for the electric field component of the waves over the same time period between 100 and 800 Hz. Figure 7B is the singular value decomposition (SVD) ellipticity based on the magnetic component of the 250 Hz waves during this time period [*Santolik et al.*, 2003]. The ellipticity indicates the polarization of the wave, with -1 as a left hand polarized wave, 1 as a right hand polarized wave, and 0 as a linearly polarized wave. Figure 7C is the pitch angle spectrogram from HOPE for the 3.38 eV energy channel. The black line is the 250 Hz power spectral density. In all of the panels, the orange dotted lines highlight the post-midnight sector between $2 < L < 3$ and the pink dotted lines highlight the $2 < L < 3$ afternoon ($15 < MLT < 18$) sector.

From the panels in Figure 7, there is an enhanced population around PA = 90^o between 10:25 - 11:30 UT. At this same time, there are enhanced power spectral densities at or near the sixth harmonic of the H^+ cyclotron frequency. The waves in the equatorial noise frequency range, however, are primarily right hand polarized, indicating plasmaspheric hiss. In the post-midnight sector, there is also an absence of high power spectral densities and the pitch angle spectrograms reveal a relative minima in the PA = 90^o population in this region. The overall fluxes in the 3.38 eV energy range are severely depleted between 9:00 - 9:45 UT compared to the 10:25 - 11:30 UT 3.38 eV fluxes.

Figure 7C also shows relatively low 250 Hz power spectral densities in the post-midnight sector compared to the inbound orbit power spectral densities and a near constant refilling population from the 0^o and 180^o pitch angle fluxes. This case study shows an example of nightside observations of low power spectral densities paired with little to no PA = 90^o H^+ population, as well as dayside observations when both of these values are high. This provides additional evidence supporting the idea that plasma waves could be heating the low energy ions. This theory is supported by previous results in the literature [*Curtis*, 1985; *Olsen et al.*, 1987; *Singh and Hwang*, 1987; *Horne et al.*, 2000].

4. Polarization Reveals It's Mostly Plasmaspheric Hiss

However, there is conclusive evidence that these waves between 150 and 600 Hz at 2 < L < 3 with large power spectral densities are plasmaspheric hiss. Figure 8 shows the median magnetic field ellipticity of 614 days of available data from both Van Allen Probes A and B (double counting, so approximately 307 unique days from each satellite) between February 2013 and April 2015 without distinguishing times of low/high Kp. Left Hand waves are defined as having ellipticity < -0.2, Right Hand waves as having ellipticity > 0.2, and Linear Polarization as waves with ellipticity falling between -0.2 and 0.2 [*Santolík et al.*, 2004; *Li et al.*, 2015]. We only take times where planarity > 0.5. The dotted lines highlight between 150 Hz and 600 Hz, where we see the peak wave amplitudes. Each event is a 1 second measurement between 2 < L < 3. Figure 8 shows that approximately 1% of the wave measurements between 2 < L < 3 at frequencies of 150 to 600 Hz are linearly polarized or left hand polarized.

Figure 9 shows the median polarization and power spectral density of right hand waves versus linearly polarized waves at L = 2.5 at MLT = 3, 9, 15, and 21 from February 2013 to April 2015 at times where Kp < 3. The top panel shows the median polarization, or the ellipticity without sense of direction, of all the waves between 0 and 90 degrees. The middle panel shows the power spectral density of waves with polarization greater than 0.7, which we know from case studies and Figure 8 are right hand polarized waves. They could be left hand polarized waves since our SVD polarization algorithm can only differentiate between circular and linearly polarized without offering information direction like the limited EMFISIS L4 files can. However, Figure 8 confirms that 99% of measurements are right-hand polarized between 150 - 600 Hz, and Figure 9 contains analyzed data from every day between February 2013 and April 2015 and was screened based on the Kp index. The lowest panel shows the linearly polarized waves with polarization < 0.2. The dotted lines highlight between 150 Hz and 600 Hz.

From Figure 8 and Figure 9, we know waves that show high occurrence probability with elevated 1-10 eV populations levels are right hand polarized waves which would not be cyclotron resonant with ions of these energies. Anomalous resonance between the ions and plasmaspheric hiss was considered, as described by *Tsurutani and Lakhina* [1997]; *Tsurutani et al.* [1998]; *Kozyra et al.* [1994, 1995]. However, anomalous resonance requires that the phase velocity of the wave is smaller than the particle parallel velocity, which is in contradiction with our extremely low energy ions with near PA = 90^o and reasonable k vector magnitudes in the inner magnetosphere of 10^{-3} m^{-1} [*Walker et al.*, 2015]. Therefore, right hand plasmaspheric hiss, despite evidence in Figure 6 and suggestion in previous work [*Curtis*, 1985; *Olsen et al.*, 1987; *Singh and Hwang*, 1987; *Horne et al.*, 2000], is not responsible for the variation in the suprathermal 1-10 eV ion population. Underlying left hand or linearly polarized components of plasmaspheric hiss, however, could be responsible for the ion heating, which will be explored in a follow-up study.

5. Conclusions

We have demonstrated that the 1-10 eV H^+ ions measured by the Van Allen Probes exhibit strong diurnal variation in flux measurements with pitch angles near 90^o. In particular, this effect is prominent in lower energy particles as seen in Figure 2. Also, when examining pitch angle fluxes against energy, the low energy fluxes at near PA = 90^o rise first and then the higher energy equatorially mirroring H^+ fluxes increase in Figure 1. With these factors combined, the depletion of ions described in [*Sarno-Smith et al.*, 2015] is not actually a loss or a transport effect - it is the result of low energy ion heating across the dayside, likely due to wave-particle interactions.

We then demonstrated a possible cause for the 1-10 eV ion heating across the dayside - higher order cyclotron resonance. Enhanced levels of polarized plasma waves between the ion cyclotron frequency and lower hybrid frequency at $2 < L < 3$ showed similar statistical rises and falls as the 1-10 eV ions in this same region. The binary contingency tables demonstrated that times where waves had amplitudes above 10^{-11} V^2/ m^2/Hz aligned well with times of high low energy ions fluxes. In more than 70% of cases on the dayside at $2 < L < 3$, high power spectral density waves occurred with high particle fluxes. In the post-midnight sector, over 70% of the instances had low power spectral densities and low particle fluxes below $L < 3$.

To further solidify this relationship, a case study was presented where high power spectral densities at 250 Hz occurred when HOPE measured high PA near 90^o populations. In the post-midnight sector, this case study showed that the equatorially mirroring population was at a relative minimum while the 0^o and 180^o pitch angle bins were at a relative maximum. However, this case study also highlights that these high power spectral density waves on the dayside at 2 < L < 3 are right hand polarized plasmaspheric hiss not linearly polarized equatorial noise. Figures 8 and 9 confirm that the 150 - 600 Hz waves that exhibit similar diurnal variation to the 1-10 eV ion fluxes are right hand polarized approximately 99% of the time and would not cyclotron resonate with the 1-10 eV ions.

Open questions still remain. Previous studies connected suprathermal ions with the presence of high power spectral density equatorial noise in the equatorial plane; however, the polarization analysis performed in our study reveals that these waves between 2 < L < 3 are primarily plasmaspheric hiss. Nevertheless, the binary contingency table in Figure 6 demonstrated a connection between the 1-10 eV H^+ fluxes and plasmaspheric hiss, so there may be a third variable affecting both plasmaspheric hiss presence and 1-10 eV H^+ energization on the inner plasmasphere dayside. The potential heating of He^+ and O^+ has not been examined in regards to a connection with plasmaspheric hiss. Also the low energy electrons (< 500 eV) have not been examined in the Van Allen Probes dataset yet in regards to wave activity or in relation to fluctuations in the low energy 1-10 eV population, similar to the findings of *Knudsen et al.* [1998]. Our study concludes that contrary to prior evidence [*Curtis*, 1985; *Olsen et al.*, 1987; *Singh and Hwang*, 1987; *Horne et al.*, 2000], large power spectral density right hand waves with frequencies between 150

Hz and 600 Hz in the near-Earth equatorial plane do not interact with the 1-10 eV ion population although they exhibit similar diurnal variation.

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Figure 1. Median differential number fluxes corrected for spacecraft potential for 1.5-10 eV H^+ measured by HOPE at L = 2.5 at several MLTs from February 2013 to April 2015. The fluxes were binned by energy channel and pitch angle.

Figure 2. Normalized median differential number fluxes corrected for spacecraft potential for 1.5 eV, 1.83 eV, 2.18 eV, 2.53 eV, 2.95 eV, 3.38 eV, 3.94 eV, 4.64 eV and 5.35 eV H^+ measured by HOPE at L = 2.5 from February 2013 to April 2015 for PA=18^o, 54^o, 90^o, 144^o, and 162^o. The median fluxes were normalized based on the maximum value for each energy at all MLTs.

Figure 3. A shows the median power spectral density of the electric field component of waves measured from EMFISIS in 0.5 MLT bins and logarithmically spaced frequency bins between 10 Hz and [illegible] kHz over from February 2013 to April 2015 at L=2.5. B is the power spectral density of the electric field wave component normalized across all MLTs by the max value at each frequency/0.5 MLT bin over the same time period at L=2.5. In both A and B, the silver line is the 6th harmonic of the H^+ cyclotron frequency.

Figure 4. Median equatorial noise electric field power spectral densities at different frequency bands from EMFISIS. Each frequency band was sorted by 0.25 L-Shell and 0.5 MLT from February 2013 to April of 2015 at times when Kp < 3.

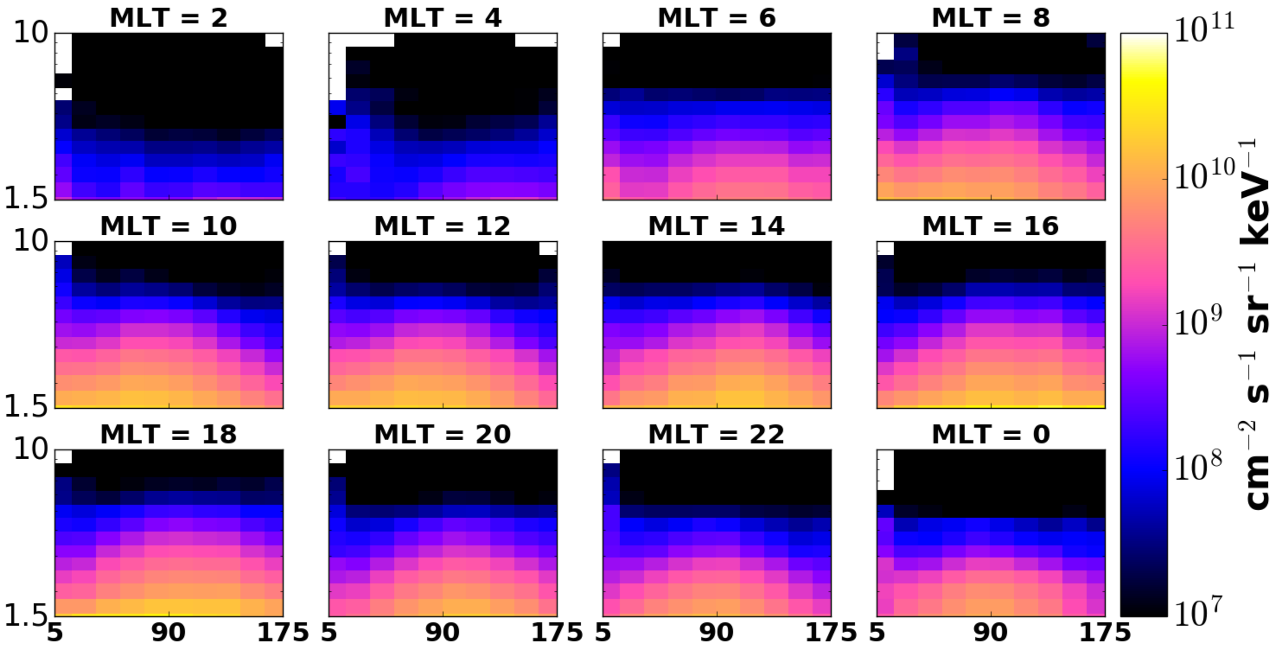
Figure 5. The blue, green, and gold lines are the median electric field power spectral density measured by EMFISIS from February 2013 to April 2015 for the 6th harmonic, 10th harmonic, and 16th harmonic of the H^+ gyrofrequency, approximately 100 - 250 Hz. The different panels show different L-Shells, with A at L = 2.0, B at L = 2.5, and C at L = 3.0. The dashed black line is the median H^+ partial 1-10 eV density over the same time period at the same L-Shell. Both the power spectral densities and H^+ partial densities were binned by 0.25 L-Shell and 0.5 MLT.

Figure 6. Binary contingency table results of median HOPE 2.5 eV fluxes and EMFISIS electric field power spectral densities at 250 Hz. The study used data from February 2013 to April 2015 which was sorted into 0.25 L-Shell and 0.5 MLT bins. The High Wave and Particle category denotes HOPE H^+ fluxes of 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1} or greater and a power spectral density of 10^{-12} $V^2/m^2/Hz$ or greater. The Low Wave and Particle section denotes ion fluxes less than 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1} and power spectral densities less than 10^{-12} $V^2/m^2/Hz$. Only High Wave occurs where the power spectral densities are greater than 10^{-12} $V^2/m^2/Hz$ but the ion fluxes are less than 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1}. Only High Particle occur when power spectral densities are less than 10^{-12} $V^2/m^2/Hz$ and the ion fluxes are greater than 10^8 cm^{-2} s^{-1} sr^{-1} keV^{-1}. The color of each bin reflects the percentage of the bins that lie in each respective category.

Figure 7. Case study on July 2, 2013 from 9 to 11:30 UT with Van Allen Probes A data. Panel A is the EMFISIS WFR spectra between 100 to 700 Hz. Panel B is the ellipticity calculated using singular value decomposition, where +1 indicates right hand polarized waves, 0 is linearly polarized waves, and -1 is left hand polarized waves. Panel C is the H^+ 3.38 eV energy channel differential number fluxes measured in each pitch angle bin over this time interval. The black line is 250 Hz power spectral density. In all panels, the orange dotted lines demarcate where $2 < L < 3$ where $1 < MLT < 4$ and the green dotted lines highlight where $2 < L < 3$ on the dayside between $15 < MLT < 18$.

Figure 8. Using 614 days of data from both RBSP-A and RBSP-B (double counting, so approximately 307 unique days), we use ellipticity to determine the sense of the waves in addition to the polarization. Left Hand waves are defined as having ellipticity < -0.2, Right Hand waves as having ellipticity > 0.2, and Linear Polarization as waves with ellipticity falling between -0.2 and 0.2. The dotted lines highlight between 150 Hz and 600 Hz, where we see the peak wave amplitudes. Each event is a 1 second measurement between 2 < L < 3.

Figure 9. These panels show the median polarization and power spectral density of right hand waves versus linearly polarized waves at L = 2.5 at MLT = 3, 9, 15, and 21 from February 2013 to April 2015. The top panel shows the median polarization of all the waves between 0 and 90 degrees. The middle panel shows the power spectral density of waves with polarization greater than 0.7, which here we know from case studies are right hand polarized waves. The lowest panel shows the linearly polarized waves with polarization < 0.2. The dotted lines highlight between 150 Hz and 600 Hz.



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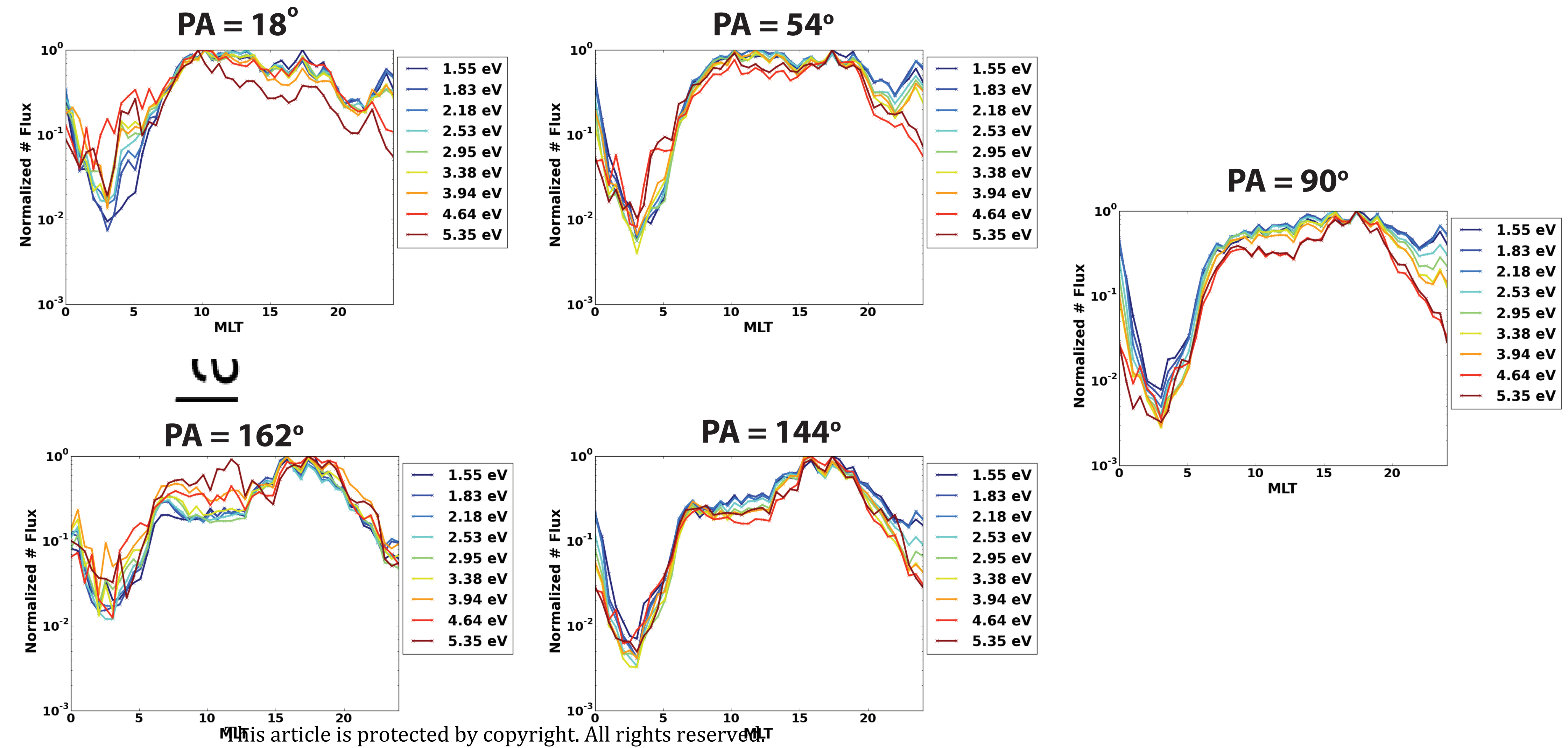
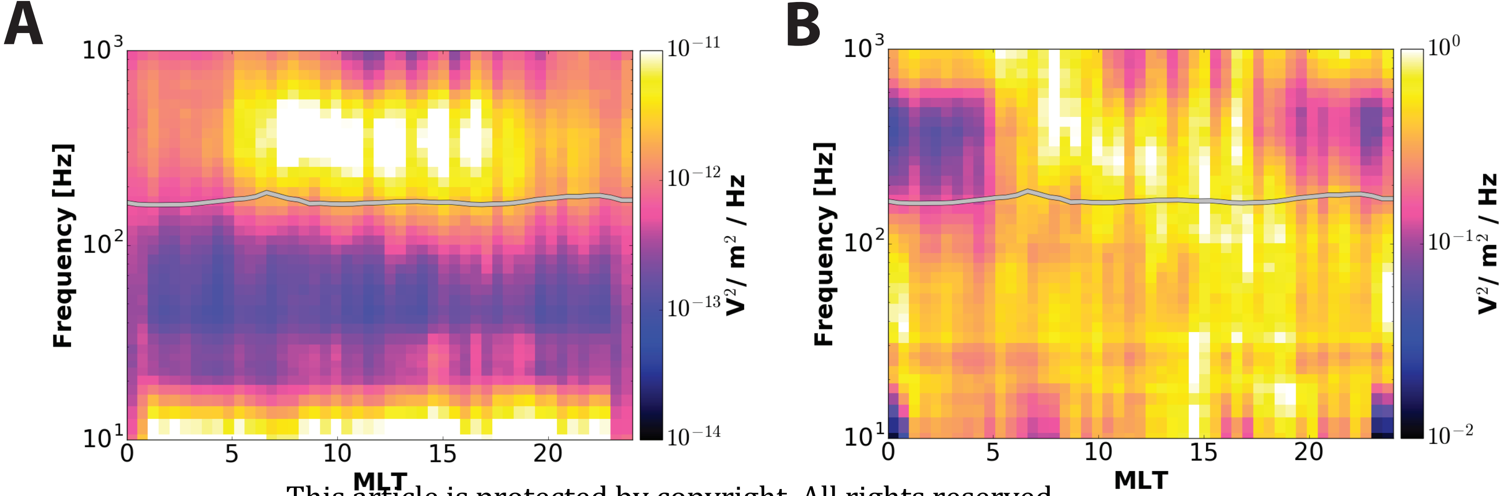
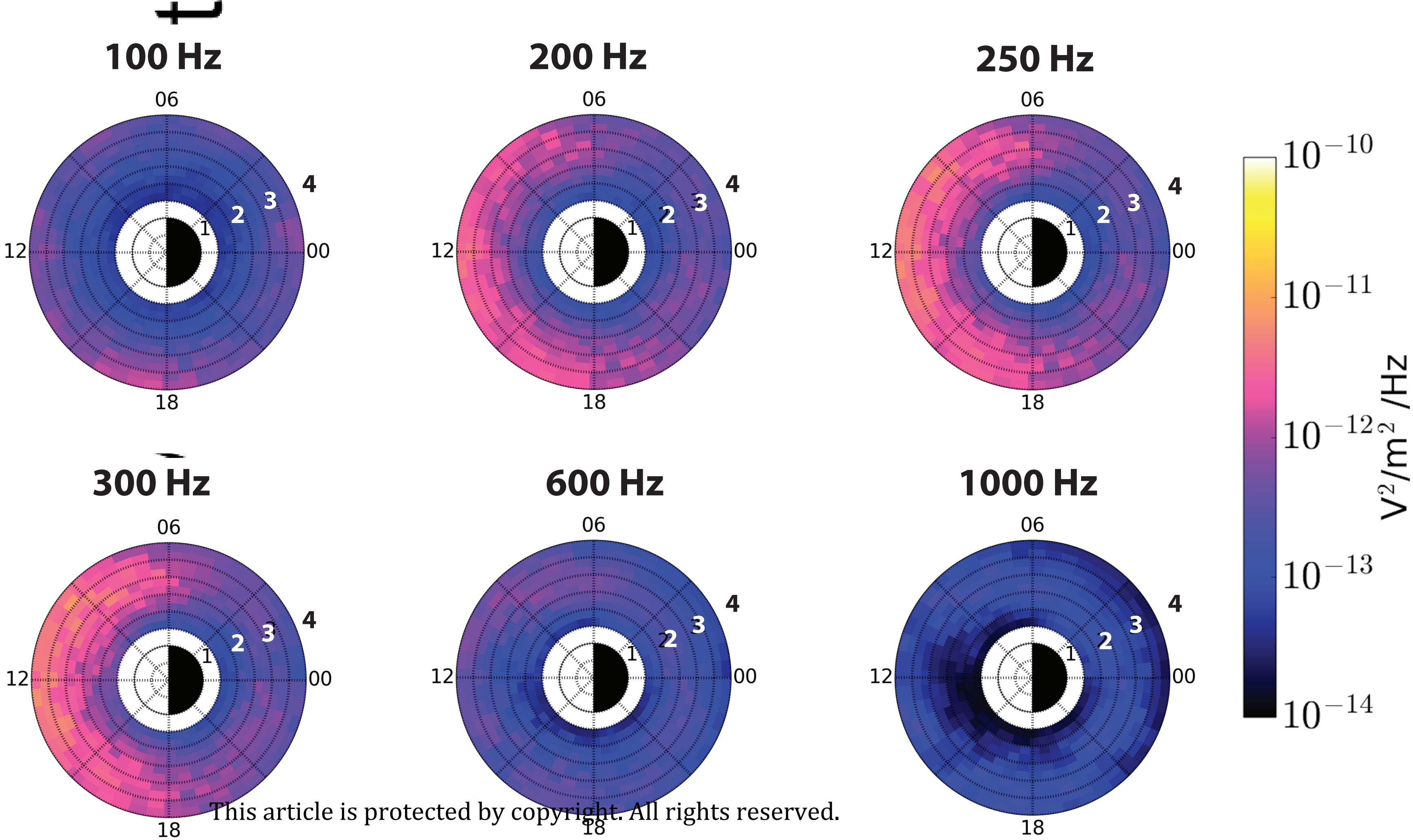
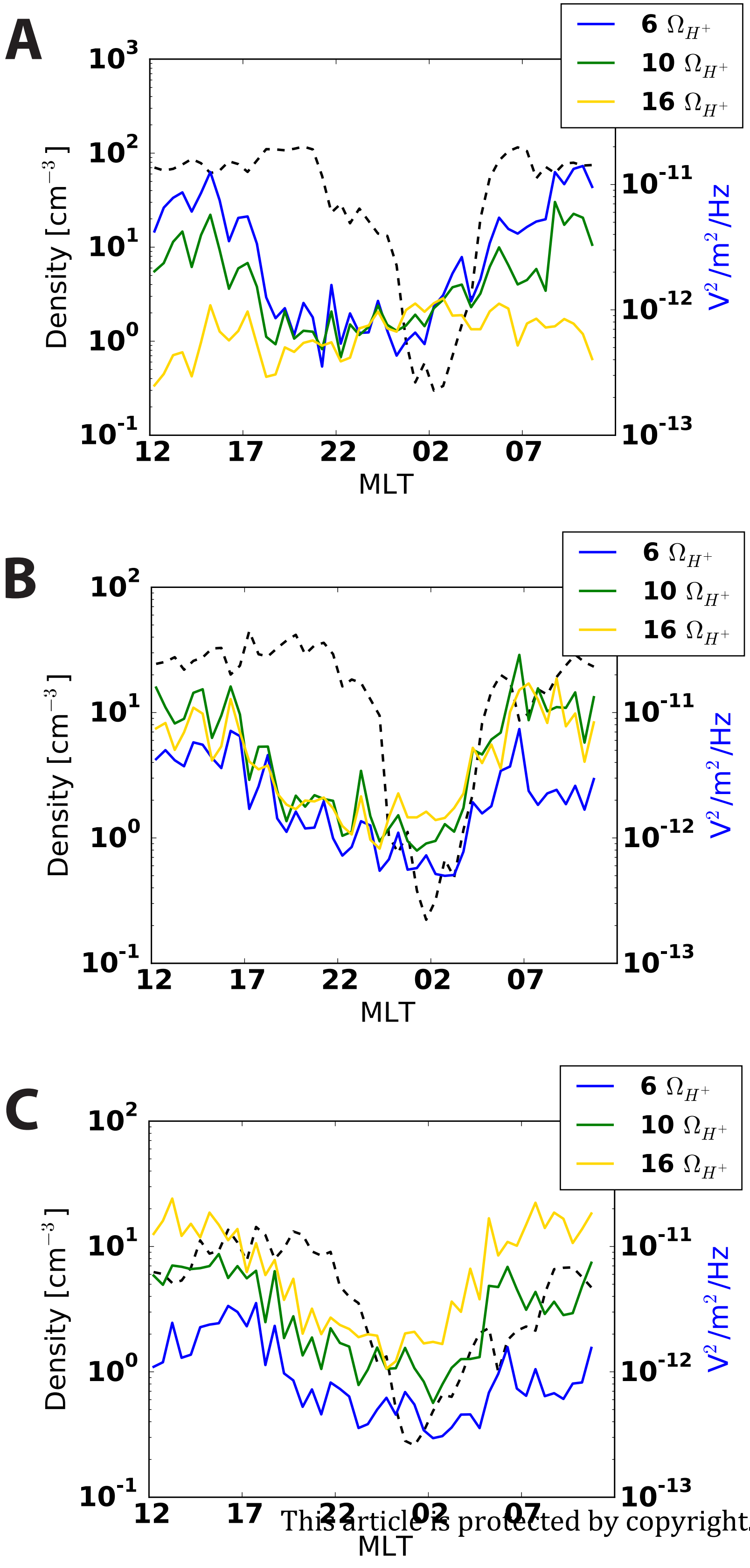
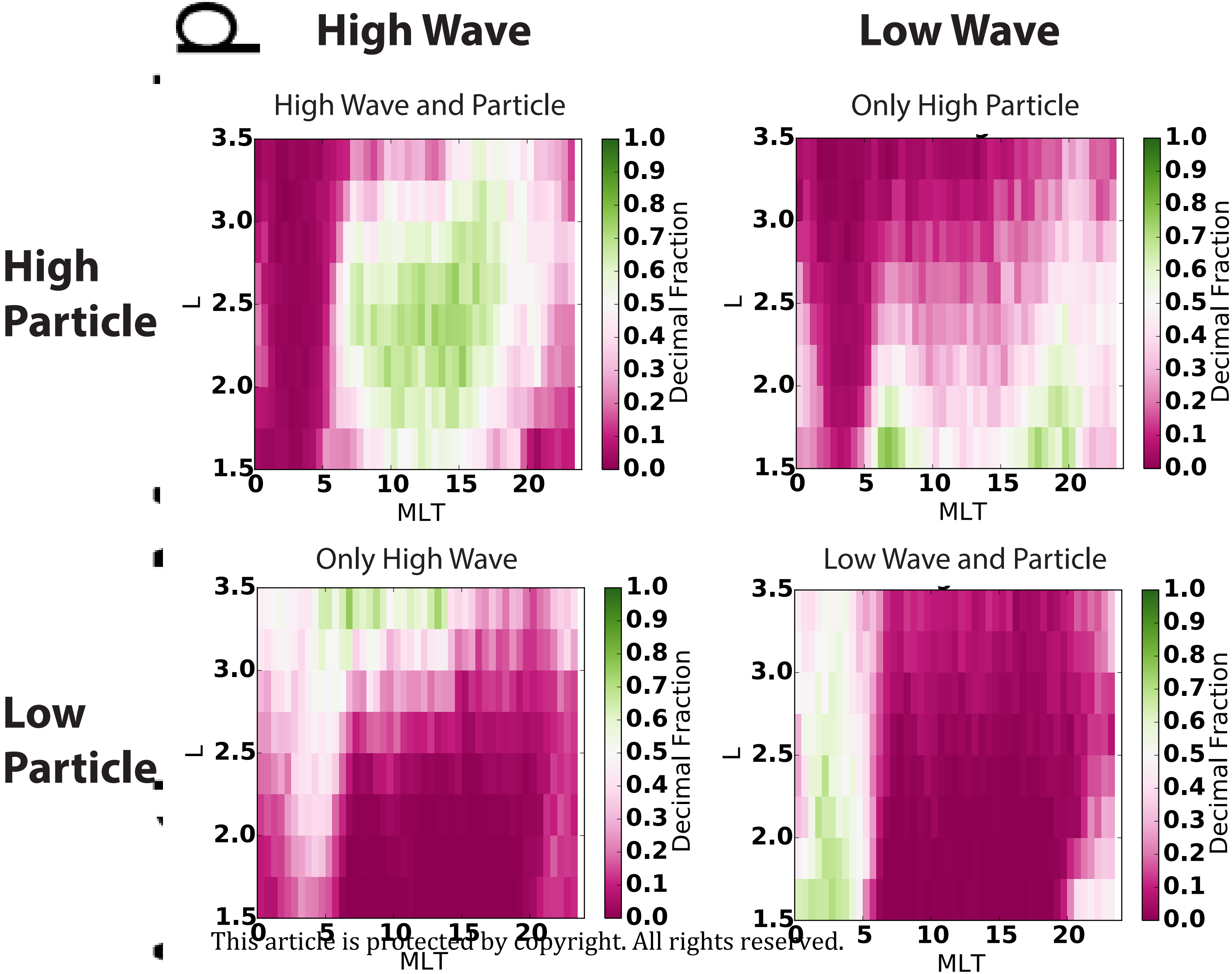


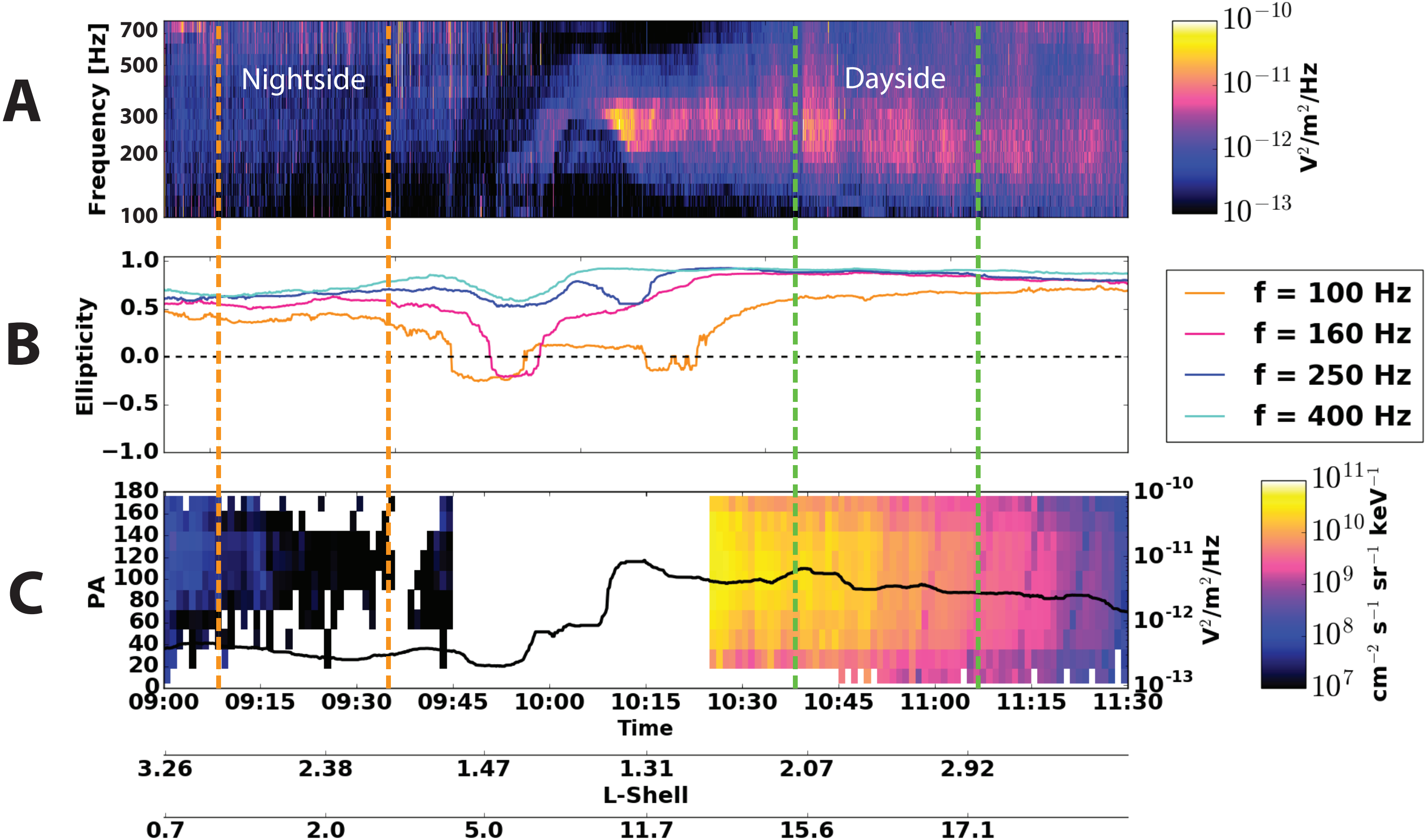
PA = 18°
PA = 54°
PA = 90°
PA = 162°
PA = 144°
Normalized # Flux
MLT
1.55 eV
1.83 eV
2.18 eV
2.53 eV
2.95 eV
3.38 eV
3.94 eV
4.64 eV
5.35 eV

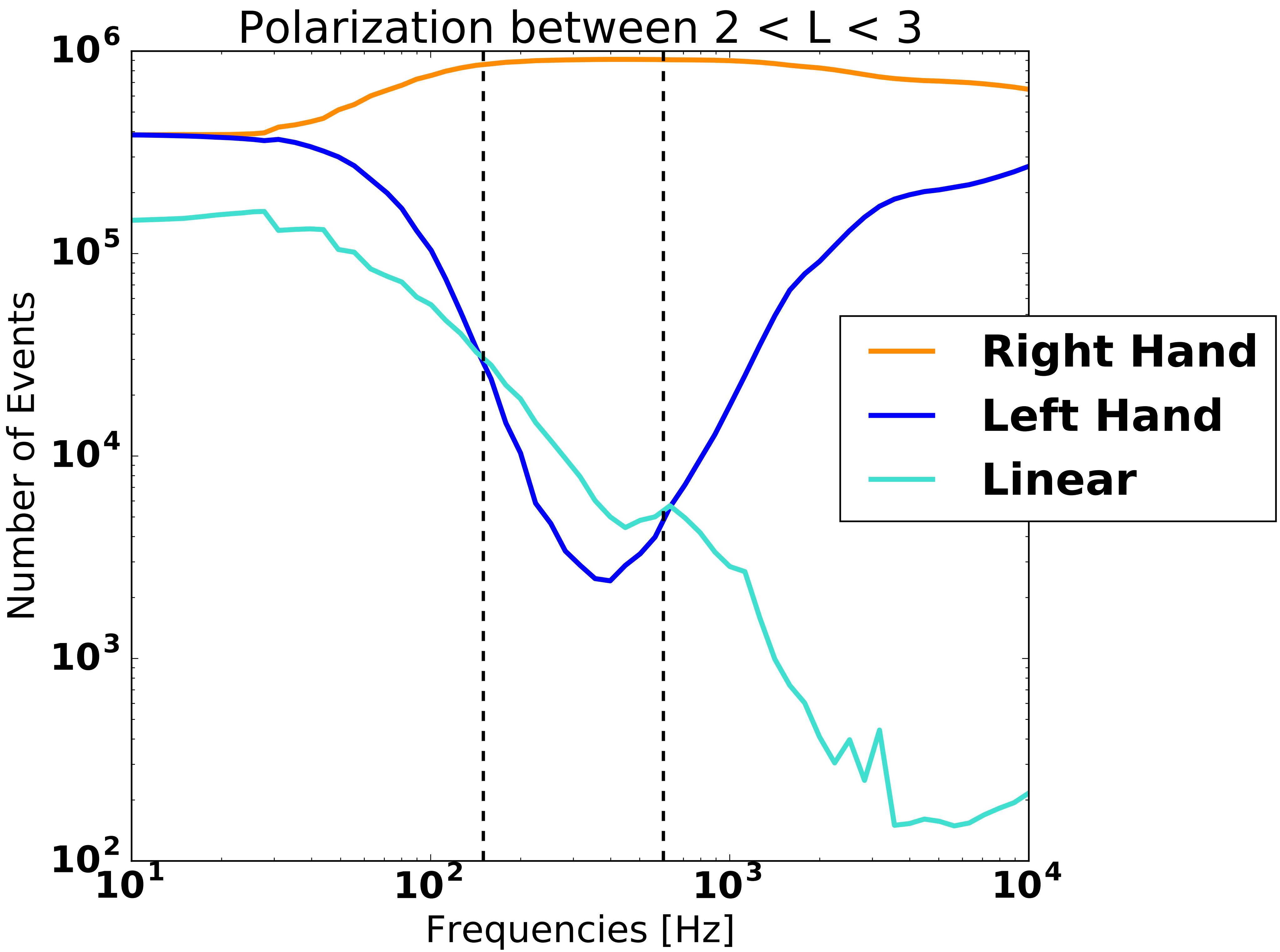

A
B
Frequency [Hz]
MLT
10^3
10^2
10^1
0
5
10
15
20
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$V^2/m^2/Hz$
10^0
10^{-1}
10^{-2}


100 Hz
200 Hz
250 Hz
300 Hz
600 Hz
1000 Hz
06
12
00
18
1
2
3
4
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
V^2/m^2 /Hz

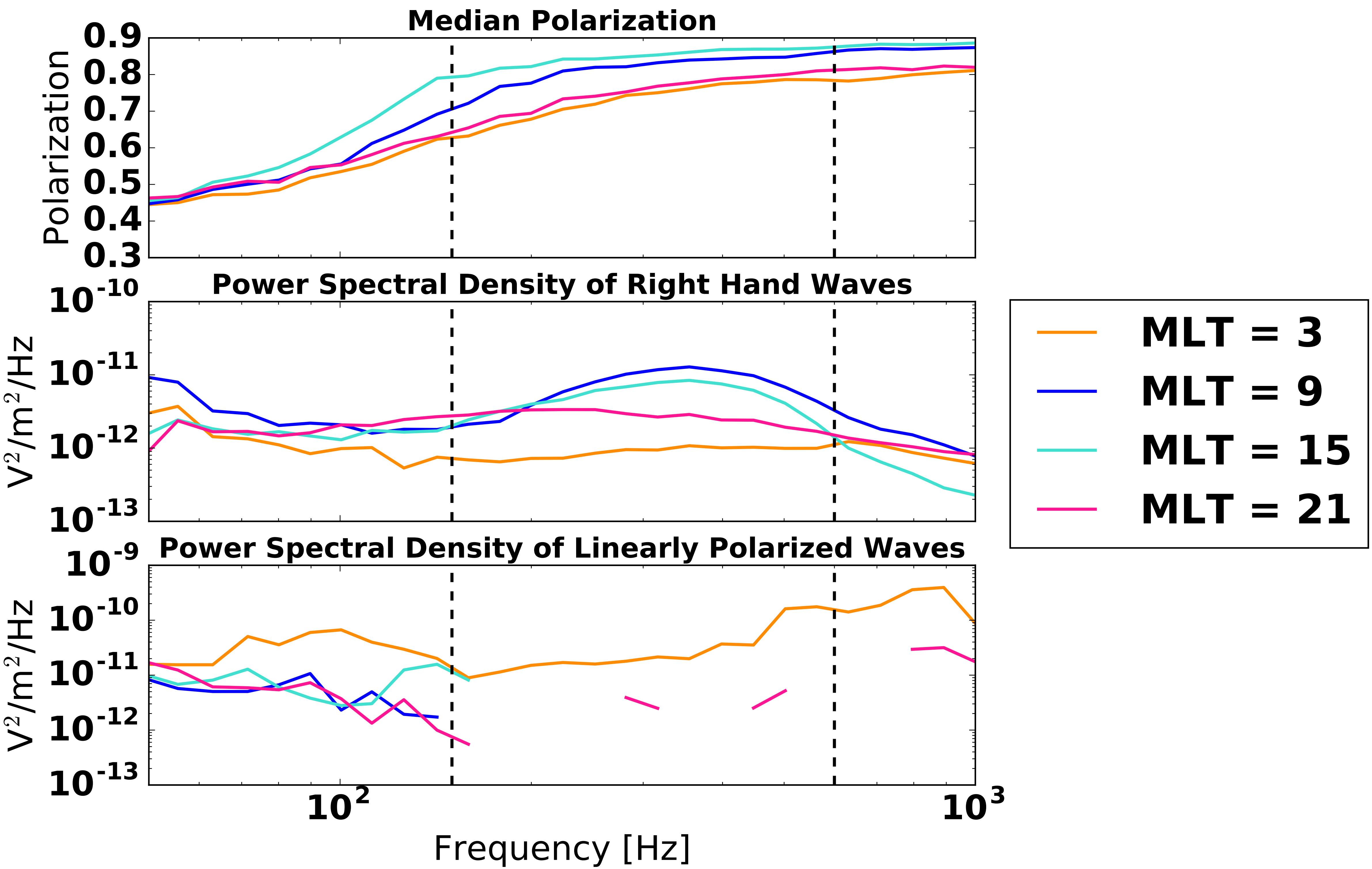

A
6 Ω_{H^+}
10 Ω_{H^+}
16 Ω_{H^+}
Density [cm^{-3}]
10^3
10^2
10^1
10^0
10^{-1}
10^{-11}
10^{-12}
10^{-13}
V^2/m^2/Hz
12
17
22
02
07
MLT
B
6 Ω_{H^+}
10 Ω_{H^+}
16 Ω_{H^+}
Density [cm^{-3}]
10^2
10^1
10^0
10^{-1}
10^{-11}
10^{-12}
10^{-13}
V^2/m^2/Hz
12
17
22
02
07
MLT
C
6 Ω_{H^+}
10 Ω_{H^+}
16 Ω_{H^+}
Density [cm^{-3}]
10^2
10^1
10^0
10^{-1}
10^{-11}
10^{-12}
10^{-13}
V^2/m^2/Hz
12
17
22
02
07
MLT


High Wave
Low Wave
High Particle
Low Particle
High Wave and Particle
Only High Particle
Only High Wave
Low Wave and Particle
L
MLT
Decimal Fraction
3.5
3.0
2.5
2.0
1.5
0
5
10
15
20
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


A
B
C
Frequency [Hz]
700
500
300
200
100
Nightside
Dayside
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$V^2/m^2/Hz$
Ellipticity
1.0
0.5
0.0
−0.5
−1.0
f = 100 Hz
f = 160 Hz
f = 250 Hz
f = 400 Hz
PA
180
160
140
120
100
80
60
40
20
0
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$V^2/m^2/Hz$
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
$cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}$
09:00 09:15 09:30 09:45 10:00 10:15 10:30 10:45 11:00 11:15 11:30
Time
3.26 2.38 1.47 1.31 2.07 2.92
L-Shell
0.7 2.0 5.0 11.7 15.6 17.1
MLT



Polarization between 2 < L < 3
10^6
10^5
10^4
10^3
10^2
Number of Events
10^1
10^2
10^3
10^4
Frequencies [Hz]
Right Hand
Left Hand
Linear



Median Polarization
Polarization
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Power Spectral Density of Right Hand Waves
V²/m²/Hz
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
Power Spectral Density of Linearly Polarized Waves
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10²
10³
Frequency [Hz]
MLT = 3
MLT = 9
MLT = 15
MLT = 21