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Excitation of nightside magnetosonic waves observed by Van Allen Probes

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Abstract During the recovery phase of the geomagnetic storm on 30–31 March 2013, Van Allen Probe A detected enhanced magnetosonic (MS) waves in a broad range of $L = 1.8$–4.7 and magnetic local time (MLT) = 17–22 h, with a frequency range ~10–100 Hz. In the meanwhile, distinct proton ring distributions with peaks at energies of ~10 keV, were also observed in $L = 3.2$–4.6 and $L = 5.0$–5.6. Using a subtracted bi-Maxwellian distribution to model the observed proton ring distribution, we perform three-dimensional ray tracing to investigate the instability, propagation, and spatial distribution of MS waves. Numerical results show that nightside MS waves are produced by proton ring distribution and grow rapidly from the source location $L = 5.6$ to the location $L = 5.0$ but remain nearly stable at locations $L < 5.0$. Moreover, waves launched toward lower L shells with different initial azimuthal angles propagate across different MLT regions with divergent paths at first, then gradually turn back toward higher L shells and propagate across different MLT regions with convergent paths. The current results further reveal that MS waves are generated by a ring distribution of ~10 keV proton and proton ring in one region can contribute to the MS wave power in another region.

1. Introduction

Fast magnetosonic (MS) wave (also called equatorial noise) is an electromagnetic wave emission observed close to the geomagnetic equator [*Russell et al.*, 1970; *Němec et al.*, 2005]. Early observational studies have shown that the waves can be observed at a wide range of L shells from $L = 2$ to 8 [*Perraut et al.*, 1982; *Boardsen et al.*, 1992]. Recently, *Zhou et al.* [2014] have presented the first report of MS waves at dipolarization fronts beyond $L = 9$. MS waves are present as a series of narrow tones, spaced at multiples of the proton gyrofrequency f_{ci} up to the lower hybrid resonance frequency f_{LH} [*Perraut et al.*, 1982]. They are nearly linearly polarized and propagate with wave vector **k** almost perpendicular to the ambient magnetic field **B**$_0$ [*Russell et al.*, 1970]. On the basis of observations and numeric simulations, it has been proposed that MS waves are excited by a ring distribution of protons at energies of ~10 keV with the ring velocity exceeding the local Alfvén speed [*Curtis and Wu*, 1979; *Boardsen et al.*, 1992; *Horne et al.*, 2000; *Meredith et al.*, 2008; *Gary et al.*, 2010; *Liu et al.*, 2011]. *Chen et al.* [2010a] have presented a global simulation of the MS wave instability in the storm time magnetosphere. Their simulation result shows that the MS wave instability occurs at the local Alfvén speed comparable to the proton ring velocity, and the unstable frequency band can be modulated by the ratio of the ring velocity and the local Alfvén speed. *Boardsen et al.* [1992] and *Horne et al.* [2000] have performed ray tracing to calculate the raypath and path-integrated gain of MS waves.

MS waves have attracted considerable research interest because they play an important role in the dynamics of relativistic electrons. MS waves can lead to either local electron acceleration from 10 keV up to a few MeV in the outer radiation belts because of Landau resonance [*Horne et al.*, 2007], or nonresonant transit time scattering of outer radiation belt energetic electrons because of the equatorial spatial confinement [*Bortnik and Thorne*, 2010; *Li et al.*, 2014]. A recent study shows that MS wave can generate proton aurora by efficiently scattering energetic (a few keV) protons into the loss cone [*Xiao et al.*, 2014a]. The analysis for

proton phase space density (PSD) observed by the Los Alamos National Laboratory magnetospheric plasma analyzer during the 2001 April storm show that distinct proton rings are formed over a broad magnetic local time (MLT) range from 10 h to 22 h, and MS wave instability is present over a broad range of wave frequency from ~5 to 35 f_{ci} in this region [*Chen et al.*, 2011]. Recently, *Xiao et al.* [2012] have studied the propagation characteristics of MS waves by a three-dimensional ray tracing. They show that dayside MS waves originating from different L shells can propagate either into or out of the plasmasphere, eastward or westward over a broad region of MLT. Their results can explain the different MLT distribution of observed proton source and MS waves. *Xiao et al.* [2013] have reported correlated observations of MS waves and distinct proton ring distributions collected by Cluster satellite and performed the corresponding calculation of the MS wave instability. However, they have assumed the same proton distribution everywhere from the source locations to the observed location due to lack of the simultaneous data. Furthermore, based on our knowledge, how propagation characteristics affect the spatial distribution of MS waves has seldom been reported so far.

The launching of Van Allen probes have led to the latest findings of the radiation belt electron dynamics, which include the reconfirmation of electron phase space density peak associated with local accelerations [*Reeves et al.*, 2013], the discovery of a new relativistic electron ring [*Baker et al.*, 2013] and together with the corresponding explanations [*Thorne et al.*, 2013a; *Shprits et al.*, 2013], and the identification of efficient chorus-driven acceleration of the radiation belt electrons [*Thorne et al.*, 2013b; *Xiao et al.*, 2014b]. In this study, we shall present simultaneous observations of nightside MS waves and proton rings collected by detectors onboard the Van Allen Probe A and perform a MS wave instability analysis based on the proton ring distribution at different L shells. Moreover, we shall in detail study how propagation characteristics affect the spatial distribution of MS waves.

2. Observation

The Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instrumentation suite onboard the Van Allen Probes uses a triaxial fluxgate magnetometer, a triaxial magnetic search coil magnetometer, and the signals from the Electric Fields and Waves experiment to measure the background magnetic fields and a comprehensive set of wave electric and magnetic fields. The High Frequency Receiver (HFR) of EMFISIS is designed to provide spectral information from 10 kHz to 400 kHz. The Waveform Receiver (WFR) measures all six components of the electromagnetic waves in the frequency range from ~10 Hz up to 12 kHz and provides spectral matrices by applying the fast Fourier transform method to the autocorrelations and cross correlations of the components. The spectral matrices can be used to investigate the power spectral densities and the propagation characteristics of waves [*Kletzing et al.*, 2013].

The observations were made by Probe A during 30–31 March 2013, the recovery phase of a moderate magnetic storm with a minimum *Dst* = −60 nT (Figure 1a). Figure 1b shows the electric field spectral density in the HFR channel from 21:40 on 30 March to 00:20 UT on 31 March. During this period, Probe A moved from deep inside the plasmasphere to the outside of the plasmapause. The plasmapause crossing occurred at $L \approx 4.9$ at ~23:35 UT, as indicated in Figure 1b by the rapid drop in the upper hybrid line. Figures 1c and 1d show the magnetic and electric field spectral density in the WFR channel, respectively. Intense electromagnetic waves are observed over a broad range of L = 1.8–4.7 and MLT = 17–22 h, with wave frequencies from ~10 Hz to ~100 Hz. We use the magnetometer_uvw data from EMFISIS to define the field-aligned coordinate (FAC) system and build the UVW-FAC transformation matrix. Then we transform the spectral matrices from the UVW scientific coordinate system [*Kletzing et al.*, 2013] into the FAC system and determine the wave vector direction and wave polarization properties by the singular value decomposition (SVD) method [*Santolík et al.*, 2003]. We have checked the same data as those in the previous studies [*Li et al.*, 2013; *Paulson et al.*, 2014] and found that our results using the SVD method are consistent with theirs. Figures 1e and 1f show the wave normal angle θ and ellipticity (the ratio of the two axes of the polarization ellipse), respectively. It is indicated that the intense waves between ~10 Hz and ~100 Hz are magnetosonic waves, because they propagate at $\theta \approx 89°$ and are nearly linearly polarized (ellipticity ≈ 0). MS waves are relatively weak at the region where $L < 3$ and are considerably enhanced at the larger L shell region. By using the differential fluxes data recorded by the Helium, Oxygen, Proton, and Electron (HOPE) Mass Spectrometer onboard Probe A, we derive the PSD of protons (12 eV–52 keV) for the pitch angle $\alpha = 90°$. As shown in
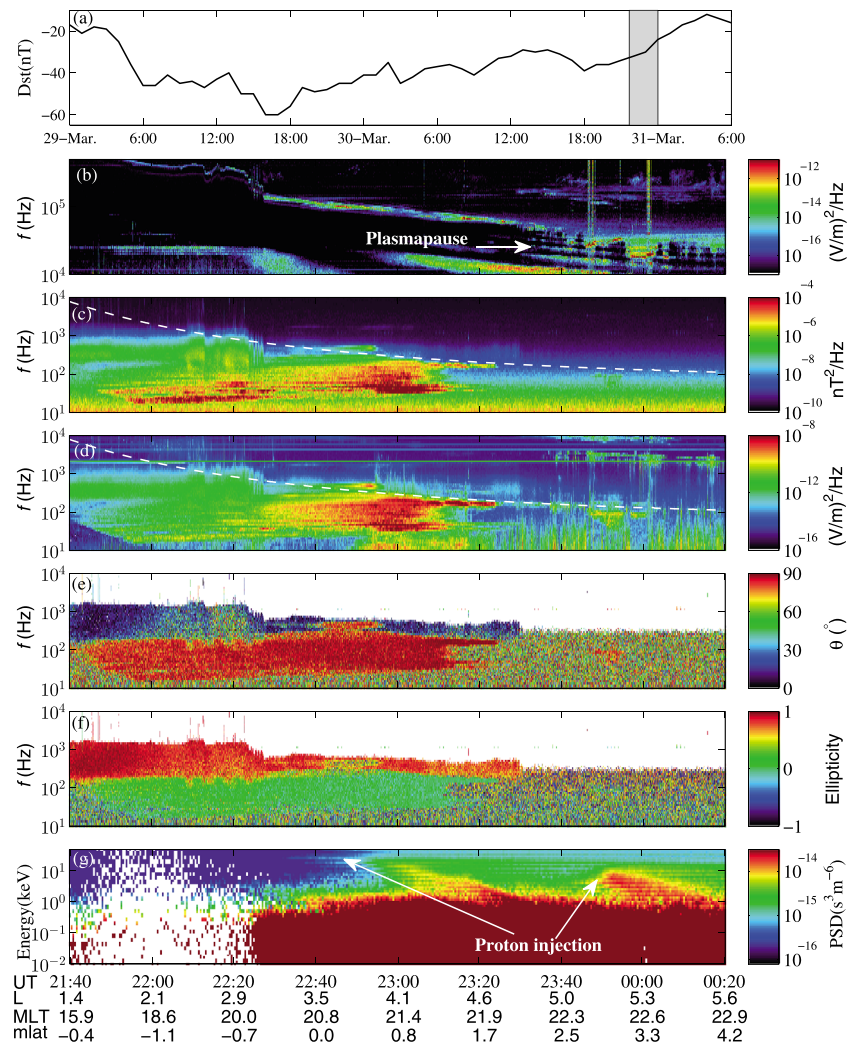
Figure 1. (a) The *Dst* index. The gray region indicates the period of the correlated data of wave and proton. (b) The electric field spectral density in the HFR channel, (c) the magnetic, and (d) electric field spectral density in the WFR channel, (e) wave normal angle, (f) ellipticity, and (g) proton PSD for the pitch angle 90° observed by Van Allen Probe A during 30–31 March 2013. The dashed lines in Figures 1c and 1d represent the local lower hybrid resonance frequency.

Figure 1g, two proton injection events were observed between 22:30 on 30 March and 00:20 UT on 31 March in an inner region ($L = 3.2$–4.6) and an outer region ($L = 5.0$–5.6).

The discrete plus symbols in Figures 2a–2d and 2e–2h represent the PSD of protons at pitch angle 90° measured at the inner region and the outer region, respectively. Distinct ring distributions are developed because of the injection events. The energy of the PSD peak is called the ring energy E_R. In the inner injection region, E_R varies from ∼30 keV to ∼15 keV as L increases from 3.2 to 4.6. In the outer injection region, E_R changes from ∼20 keV to ∼7 keV as L increases from 5.0 to 5.6.

3. Numerical Simulation

A sum of four subtracted bi-Maxwellian component is used to represent the proton ring distribution:

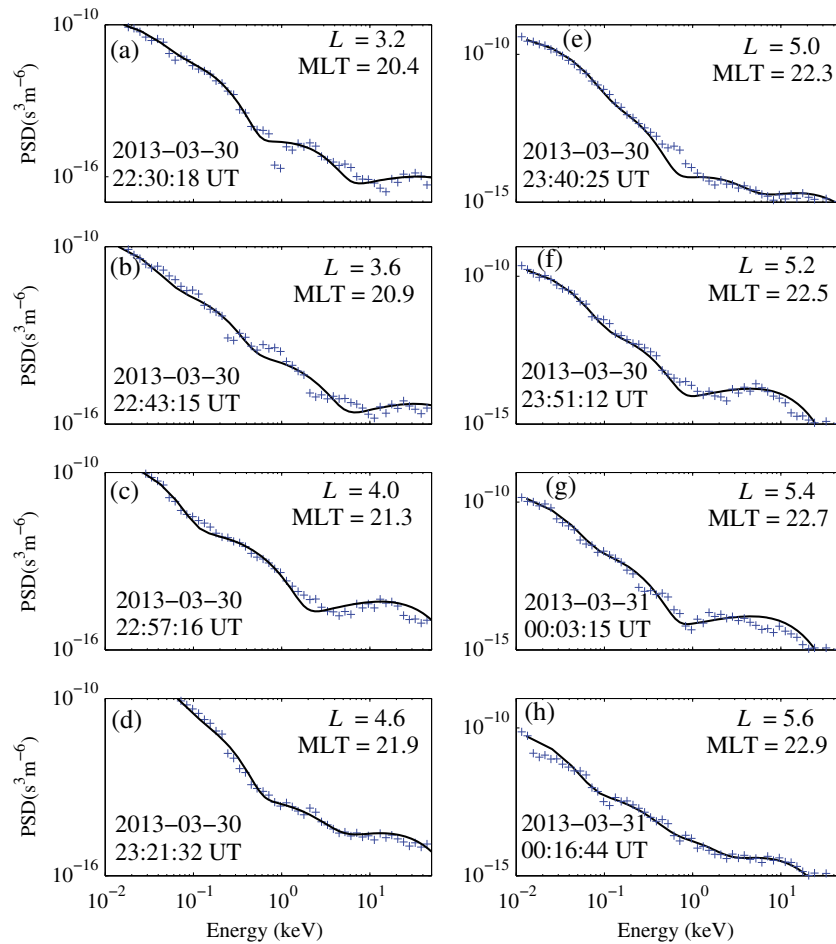$$f(v_\parallel, v_\perp) = \sum_{i=1}^{4} f_i(v_\parallel, v_\perp) \qquad (1)$$

Figure 2. (a–h) Modeled subtracted Maxwellian distribution (solid) to the observed proton PSD (plus) for the pitch angle $\alpha = 90°$ measured by HOPE onboard Van Allen Probe A at different L shells.

The distribution function for each species i is

$$f_i(v_\parallel, v_\perp) = \frac{N_i}{\pi^{3/2}\theta_{\perp i}^2\theta_{\parallel i}} \exp\left(-\frac{v_\parallel^2}{\theta_{\parallel i}^2}\right) \left[\Delta_i \exp\left(-\frac{v_\perp^2}{\theta_{\perp i}^2}\right)\right.$$
$$\left. + \frac{(1-\Delta_i)}{(1-\beta_i)}\left(\exp\left(-\frac{v_\perp^2}{\theta_{\perp i}^2}\right) - \exp\left(-\frac{v_\perp^2}{\beta_i\theta_{\perp i}^2}\right)\right)\right] \tag{2}$$

where N_i is the density, Δ_i and β_i are used to represent the loss cone feature of the ring distribution, and $\theta_{\parallel i}$ and $\theta_{\perp i}$ are the thermal velocities parallel and perpendicular to the background magnetic field, respectively. These parameters are obtained by performing the nonlinear least squares fitting [*Marquardt*, 1963; *Moré*, 1978] to the observed PSD. The solid lines in Figure 2 represent the distribution functions along the $v_\perp$ axis $f(v_\parallel = 0, v_\perp)$.

The fitting functions are used to calculate the local growth rate of MS waves following the method introduced by *Kennel* [1966] and *Chen et al.* [2010b]. Figure 3 plots the scaled local growth rate of waves corresponding to those proton ring distributions in Figure 2. In the simulation, the MS waves are assumed to propagate at $\theta = 89.5°$. The wave growth rates are peaked at $n\Omega_{ci}$ and rapidly fluctuate at relatively low frequencies ($3\Omega_{ci} \leq \omega < 20\Omega_{ci}$) but change smoothly at high frequencies ($\omega > 20\Omega_{ci}$). Furthermore, the growth rate at $L = 5.2–5.6$ is about 1 or 2 orders of magnitude higher than that at $L = 4.0–5.0$ or $L = 3.2–3.6$. Therefore, the MS waves observed at $1.8 < L < 4.7$ in Figure 1 should come from those waves which are generated at $L > 5.0$ and propagate toward the Earth.
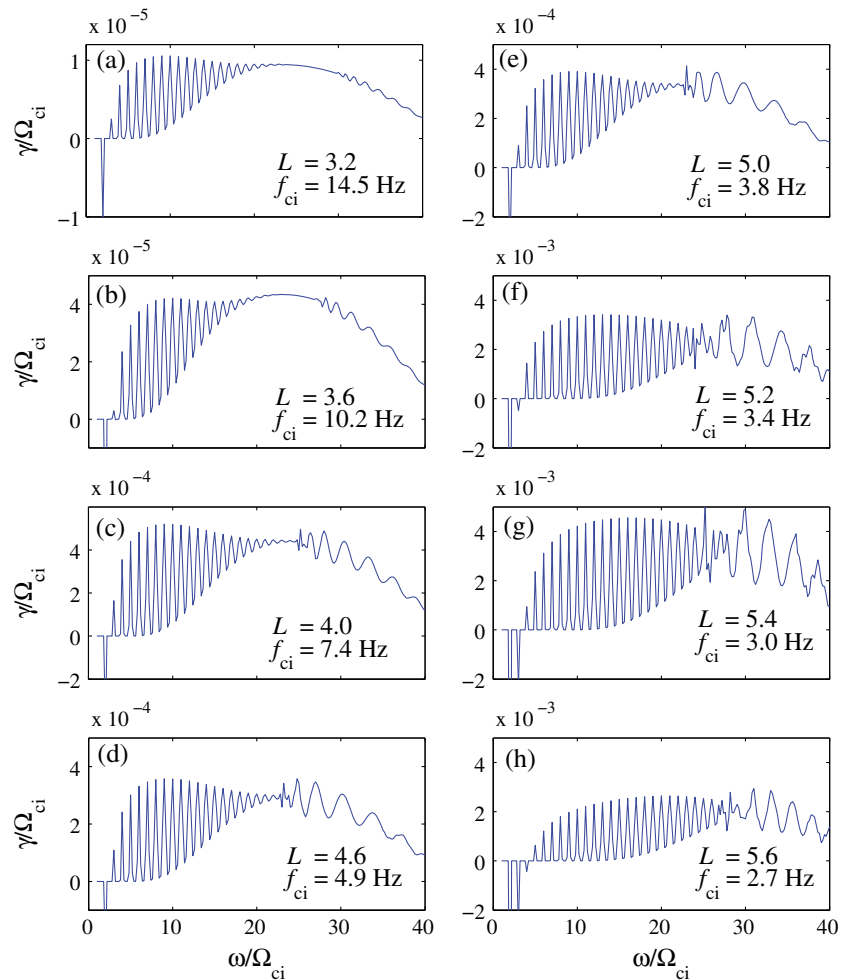
Figure 3. (a–h) Corresponding to Figure 2, simulating result of the scaled local MS wave growth rate versus the scaled wave frequency by the subtracted bi-Maxwellian distribution.

The raypath and path-integrated gain of MS waves are simulated by performing ray tracing in a three-dimensional space. The ray tracing program has been developed based on the methodology of the ray tracing program HOTRAY [*Horne*, 1989] and has been applied to study the excitation and propagation of electromagnetic waves in space plasmas [*Xiao et al.*, 2012, 2013; *Zhou et al.*, 2012, 2013]. The program determines the raypath and the wave normal angle at each time step by integrating Hamiltons equations [*Suchy*, 1981; *Horne*, 1989]. Here we adopt a dipole magnetic field model and a background electron density model which is incorporated by the global core plasma density model [*Gallagher et al.*, 2000] and a field-aligned density model [*Denton et al.*, 2002]. In order to perform ray tracing, we define two coordinate systems following the previous works [*Horne*, 1989; *Chen et al.*, 2009]. The first system (XYZ) is the Cartesian coordinate system centering on the Earth. The Z axis is along the geomagnetic axis pointing north, the X axis is orthogonal to the Z axis and pointing away from the Sun, and the Y axis completes the right-handed set. The second system (xyz) is a local Cartesian system centered on a point p of the raypath. As shown in Figure 4a, the z axis is along the local magnetic field direction, the x axis is orthogonal to the z axis and lies in the meridian plane pointing away from the Earth at the equator, and the y axis completes the right-handed set. Between the wave vector **k** and the z axis θ is the wave normal angle, and η is the azimuthal angle between the projection of **k** onto the xy plane and the x axis.

We fit the observed PSD of protons by the bi-Maxwellian distribution in the region $L = 1.4$–5.6 at 0.1 spacing and assume the same distribution at the same L shell. The local growth rate γ can be evaluated by using the
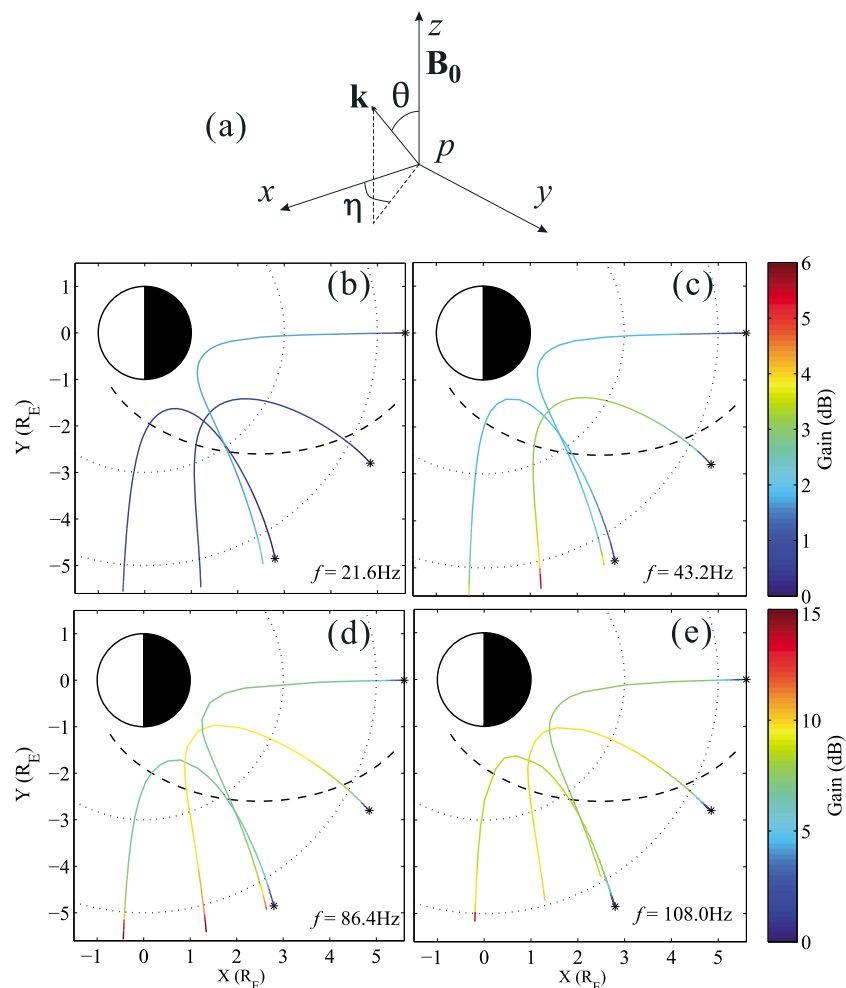
Figure 4. (a) Geometry of wave vector **k** in a local Cartesian system centered on a point p of the raypath in ray tracing. (b–e) The projections of raypaths on the X-Y plane. The waves start at the locations (stars): $L = 5.6$, MLT = 20 h, 22 h, and 24 h, with $\theta_0 = 89.5°$ and different wave frequencies. Path-integrated gain of the waves is color coded along the raypath. The dashed line indicates Van Allen Probe A orbital trajectory from 21:40 UT on 30 March to 00:20 UT on 31 March. The concentric dotted arcs indicate the locations $L = 3$ and 5, respectively.

fitting function at each step during ray tracing. The path-integrated wave gain in decibel is calculated by integrating γ along the raypath:

$$\text{Gain} = 20 \log_{10} \left(\exp \left(\int \gamma \, dt \right) \right) \tag{3}$$

Figures 4b–4e show simulating results of raypaths and path-integrated gain (color coded). The MS waves launched at equatorial location $L = 5.6$, MLT = 20 h, 22 h, and 24 h, with initial wave normal angle $\theta_0 = 89.5°$ and different wave frequencies $f = 21.6$ Hz ($\sim 8 f_{ci}$), 43.2 Hz ($\sim 16 f_{ci}$), 86.4 Hz ($\sim 32 f_{ci}$), and 108.0 Hz ($\sim 40 f_{ci}$). These waves propagate toward lower L shell at first and then gradually turn back toward high L shells due to approaching the higher-density region [*Xiao et al.*, 2012]. All the rays pass through the observed region. Wave gain increases rapidly outside the region $L = 5.0$ but remains nearly constant in the region $L < 5.0$, consistent with the simulation results of local growth rate in Figure 3 and the previous work [*Horne et al.*, 2000].

MS waves can propagate both radially and azimuthally, so the MS waves observed at any specified location are the superposition of a series of MS waves generated in a broad source region. Figure 5 shows the raypaths of the MS waves launched at the same location as that in Figure 4, with $\theta_0 = 89.5°$, $f = 43.2$ Hz ($\sim 16 f_{ci}$), and 86.4 Hz ($\sim 32 f_{ci}$). The initial azimuthal angles cover from 161° to 199° at 2° spacing are indicated by the color lines. All the waves propagate toward lower L shells with divergent raypaths at first then
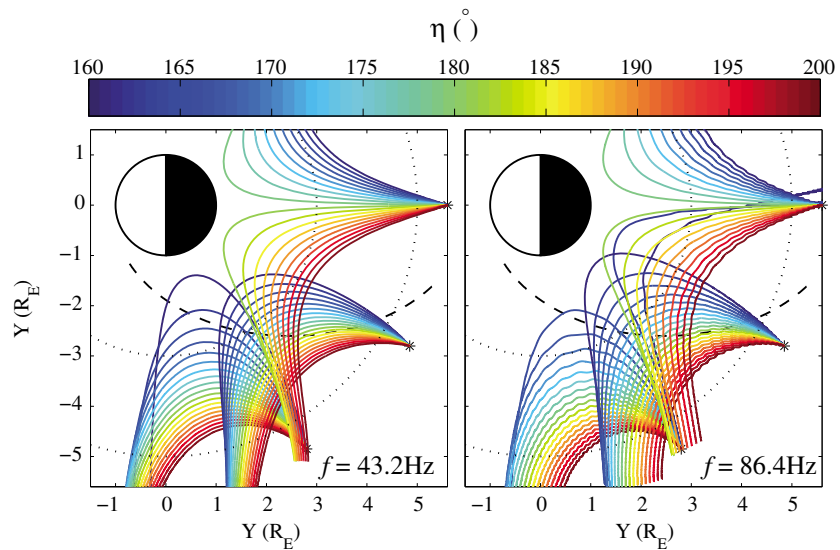
Figure 5. The projections of raypaths of the MS waves for $\theta_0 = 89.5°$ and different initial azimuthal angles η_0. The concentric dotted arcs indicate the locations $L = 3$ and 5, respectively. The asterisks denote the source locations: $L = 5.6$, MLT = 20 h, 22 h, and 24 h.

gradually turn back toward higher L shells with convergent raypaths when they approach higher-density region. The waves launched at MLT = 24 h propagate eastward (later MLT) for $\eta_0 < 180°$ and westward (earlier MLT) for $\eta_0 > 180°$. Almost all the waves launched at MLT = 20 h and 22 h propagate westward (earlier MLT), except for MLT = 20 h, $f = 86.4$ Hz, $\eta_0 = 161°$, and 163°. Only few raypaths can penetrate into the near-Earth region (e.g., $L < 3$) from a remote source region, consistent with the observation (Figure 1).

4. Summary

An event of nightside magnetosonic waves observed by the EMFISIS instrument on the Van Allen Probe A during the recovery phase of the geomagnetic storm on 30 March 2013 are presented. Proton PSD at 90° pitch angle measured by HOPE is fitted with a sum of subtracted bi-Maxwellian components to model the ring distribution and the fitting functions are used to calculate the local growth rate of MS waves at different L shells. Then three-dimensional ray tracing is performed to studying how propagation characteristics affect the spatial distribution of MS waves in detail. The main results of this paper can be summarized as follows:

1. Intense MS waves are observed over a broad range of $L = 1.8$–4.7 and MLT = 17–22 h, with wave frequencies from ~10 Hz to ~100 Hz. Simultaneous observations of PSD show that the distinct proton ring is present in $L = 3.2$–4.6 and $L = 5.0$–5.6, which provides the source of free energy for the excitation of MS waves.
2. The wave growth rates are peaked at $n\Omega_{ci}$ and rapidly fluctuate at relatively low frequencies ($3\Omega_{ci} \leq \omega < 20\Omega_{ci}$) but change smoothly at high frequencies ($\omega > 20\Omega_{ci}$). The growth rate at $L = 5.2$–5.6 is about 1 or 2 orders of magnitude higher than that at $L = 4.0$–5.0 or $L = 3.2$–3.6, suggesting that the source waves of the observed MS waves should occur at $L > 5.0$ and propagate toward the Earth. This indicates that proton ring in one region can contribute to the MS wave power in another region.
3. The nightside MS waves launched at the equatorial location $L = 5.6$ grow rapidly at the outside of $L = 5.0$ but remain nearly stable in $L < 5.0$. The waves propagate toward lower L shells with divergent raypaths at first then gradually turn back toward higher L shells with convergent raypaths. The combination of the path-integrated gain pattern and the propagation characteristics perhaps explain the spatial distribution characteristics that the observed MS wave power is relatively weak in the near-Earth region ($L < 3$) and becomes much stronger in the region far from the Earth ($L > 3$).

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