Generation of proton aurora by magnetosonic waves

Fuliang Xiao¹, Qiugang Zong², Yongfu Wang², Zhaoguo He³, Zhenpeng Su⁴, Chang Yang¹ & Qinghua Zhou¹

¹School of Physics and Electronic Sciences, Changsha University of Science and Technology, Changsha 410004, China, ²School of Earth and Space Sciences, Peking University, Beijing 100871, China, ³Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing, 100190, China, ⁴Chinese Academy of Sciences Key Laboratory for Basic Plasma Physics, University of Science and Technology of China, Hefei 230026, China.

Earth’s proton aurora occurs over a broad MLT region and is produced by the precipitation of low-energy (2–10 keV) plasmasheet protons. Proton precipitation can alter chemical compositions of the atmosphere, linking solar activity with global climate variability. Previous studies proposed that electromagnetic ion cyclotron waves can resonate with protons, producing proton scattering precipitation. A long-outstanding question still remains whether there is another mechanism responsible for the proton aurora. Here, by performing satellite data analysis and diffusion equation calculations, we show that fast magnetosonic waves can produce trapped proton scattering that yields proton aurora. This provides a new insight into the mechanism of proton aurora. Furthermore, a ray-tracing study demonstrates that magnetosonic wave propagates over a broad MLT region, consistent with the global distribution of proton aurora.

Results

On September 16, 2003 an interplanetary coronal mass ejection (CME) interacted with the Earth’s magnetosphere, leading to a small geomagnetic storm ($D_{st} \approx -50$ nT). The Cluster spacecrafts, which stayed around the noon near the Earth’s equator for about ten minutes then, recorded strong MS wave activities for a duration of ~10 minutes in the frequency range ~10–150 Hz and around the noon local time sector from 11.47 to 11.41 MLT (Fig. 1a). MS wave is confined within a few degrees of the geomagnetic equator and exhibits a notable harmonic structure, viz., spaced at $4f_{cp}$ and $12f_{cp}$ (Fig. 1a). Moreover, MS wave has a normal angle $\theta < 90^\circ$ (Fig. 1b) and an ellipticity $\approx 0$ (Fig. 1c), implying that MS wave propagates very obliquely with respect to the ambient magnetic field direction.
Figure 1 | Satellite data on 16 September 2003 storm. Data collected by the Cluster STAFF instrument during ~ 10 minutes duration for MS wave power (a), wave normal angle (b), the angle between the Earth’s magnetic field and the normal to the plane of the wave; and wave ellipticity (c), the degree of elliptical polarization. MS waves are right hand polarized electromagnetic waves which occur as a series of narrow tones, spaced at multiples of the proton gyrofrequency $f_{cp}$ up to the lower hybrid resonance frequency $f_{LH}$. a, MS waves maximizes basically at frequencies from ~ 10–150 Hz, spaced at $4f_{cp}$ ($f_{cp} < 5$ Hz) and $12f_{cp}$. The white dotted line denotes the lower hybrid resonance frequency $f_{LH}$. b–c, The observed waves have a high normal angle $h < 90^\circ$ and a high degree of elliptical polarization (ellipticity < 0), indicating that the k vector is approximately perpendicular to the ambient magnetic field direction. d, Pitch angle distribution of protons for different indicated energies (2–10 keV) measured by CIS instrument. Proton fluxes peak at a pitch angle of 90° and drop dramatically at small pitch angles. e–j, Auroral snapshots for northern hemisphere and southern hemisphere as a function of magnetic local time (MLT) and magnetic latitude (MLat) obtained by FUV-SI12 onboard IMAGE spacecraft when IMAGE spacecraft travels at the location ~ 15 MLat and altitude=8 Re. Proton aurora bands are present from the morning sector to dusk sector 09:00–18:00 MLT, with the strongest emission basically in 14:00–18:00 MLT. The auroral emission is asymmetric with a more intensity and a broader latitude in the northern hemisphere than those in the southern hemisphere.
Figure 1d shows a pancake distribution of proton flux for different indicated energies (2–10 keV) measured by CIS instrument. Proton flux maximizes at a pitch angle of 90° and drops remarkably at small pitch angles at each energy, particularly for energy above 3.53 keV. Since a pancake distribution is produced when protons with smaller pitch angles have been scattered into the loss cone, any endeavor to identify whether MS waves are really responsible for proton auroral precipitation must also explain the formation of pancake distributions.

Figure 1e–j show auroral snapshots observed by FUV-SI12 instrument onboard IMAGE spacecraft18 for the northern hemisphere and southern hemisphere produced by the precipitation of 2–10 keV protons originating from the plasma sheet. The SI12 instrument detects the Doppler-shifted Lyman-α photons corresponding to precipitating charge-exchanged protons with energies of a few keV19,20. Proton aurora covers a broad MLT region 09:00–18:00 MLT, with stronger emissions roughly in 14:00–18:00 MLT. Such a broad MLT distribution of proton aurora requires MS waves which can produce proton scattering to occur over a similar broad MLT region.

Unfortunately, there is no direct wave data over such a broad MLT region during this event. Here, we adopt the previously developed programs21,22 to trace MS waves with different frequencies based on the wave data (Fig. 1a–b). MS waves are launched at 12:00 and 15:00 MLT for different locations at the geomagnetic equator. The modeled results (Fig. 2) confirm that MS waves can indeed propagate over the similar MLT region from the morning sector to the dusk sector 09:00–18:00 MLT.

Resonant interactions between MS waves and protons take place when the wave frequency equals a multiple of the proton gyrofrequency in the proton reference frame. These cyclotron MS-proton interactions produce efficient exchange of energy and momentum between waves and protons, leading to stochastic proton scattering. Such stochastic scattering can be evaluated in terms of pitch angle and momentum diffusion coefficients23. Here, we use this method to model evolutions of the proton distribution following their injection into the magnetosphere.

Calculation of the diffusion coefficients requires a detailed knowledge of the amplitudes and spectral properties of the waves. A standard way is to assume that the wave spectral density obey a Gaussian distribution in wave frequency and wave normal angle24 (see the details in Methods). To allow the data fitting more reasonable, we...
average the observed wave magnetic field intensity over the indicated
time period in this event and then present a least squares Gaussian fit
to the observed two-band spectral intensity (Fig. 1a), together with
the corresponding fitting parameters as shown in Figure 3. We then
calculate bounce-averaged diffusion coefficients for MS waves as
shown in Figure 4a–c. All the diffusion coefficients cover a broad
region of pitch angle and energy, with high values at lower pitch
angles. In particular, the pitch angle diffusion rate above
7 keV

\( \frac{1}{s} \)
can approach around the loss-cone, allowing efficient pitch
scattering of protons into the loss-cone in a time scale of tens of
seconds. Moreover, pitch angle and cross diffusion coefficients are
higher than momentum diffusion coefficients particularly at lower
pitch angles, implying that pitch angle diffusion dominates over the
energy diffusion while cross diffusion coefficients should also con-
tribute to proton-MS interaction.

Using those diffusion rates in Figure 4a–c, we solve a two-dimen-
sional Fokker-Planck diffusion equation by a recently introduced
hybrid difference method and calculate phase space density \( f \) evolu-
tion of protons due to scattering by MS waves from a numerical solution to the two-dimensional Fokker-Planck diffusion equation. MS wave causes
a rapid loss of low-energy (2–10 keV) protons within tens of seconds (e–f), leading to the strongest proton auroral precipitation from the morning sector
to the dusk sector 0900–1800 MLT.

Discussion
The simultaneous observation and corresponding modeling pre-
sented in this study firstly link MS waves to the origin of proton
aurora. Our results definitively demonstrate that, as presented in
Fig. 5, MS waves can produce rapid proton precipitation responsible
for proton aurora, naturally accounting for the remnant pancake
proton distribution left behind in space and the broad MLT distri-
bution of proton aurora. Although our simulations were performed
around the noon 11:30 MLT, this conclusion should be valid over the
entire region of excited MS waves since the basic properties of MS-
proton interaction should not change no matter whether the amplitude
and morphology of MS waves are different under different
locations.
As shown in Figure 1, the proton auroral emission maximizes in the afternoon sector, which appears to be inconsistent with the recent statistical survey of MS waves observed on THEMIS spacecraft\textsuperscript{26} that such waves are strongest in the dawn to pre-noon sector. However, the proton aurora emission intensity primarily depends on two factors: the number of the precipitating protons and the MS wave intensity. Since the precipitating protons originating from the plasma sheet drift westwards around the Earth (see Fig. 5), the protons encounter resonance with the afternoon sector MS waves at first, allowing part of protons precipitating into the atmosphere. Then the rest of protons continue resonating with MS waves on other sectors in their drifting. Moreover, the potentially existing plume EMIC waves along the duskside (though not observed directly here) may also contribute to the proton scattering. This probably explains why the proton aurora peak in the afternoon sector, instead of in the dawn to pre-noon sector.

It should be point out that, we use the quasi-linear theory of wave-particle interaction. Analogous to the Particle-in-cell treatment, the quasi-linear theory has been frequently adopted by the space plasma physics and magnetosphere research community to treat wave-particle interaction. The quasi-linear theory is valid by assuming that each individual particle randomly walks in velocity space, resonates with a succession of uncorrelated waves, and is scattered in a small amount in pitch angle and energy each time. Those conditions are basically satisfied in the Earth’s radiation belts for naturally generated MS waves, where the bandwidth is generally above the proton cyclotron frequency up to the lower hybrid frequency. Moreover, this study is intended to propose a new mechanism of proton aurora by MS-driven scattering, but not to exclude EMIC waves as a potential wave responsible for the proton scattering. The relative contribution to the proton aurora emission from MS or EMIC waves deserves a future study.

Finally, in a departure from the previous works\textsuperscript{27}, we focus on the pitch-angle scattering by the MS waves instead of the instability of MS waves in this study. The enhanced MS waves appear to be excited by those injected anisotropic protons with a typical ring distribution at energies of ~10 keV or above prior to this event. Unfortunately, there is no direct data on MS waves or energetic proton distributions before this event because the Cluster satellite doesn’t stay in the radiation belt. We leave the instability of MS waves to a future study.

**Methods**

The ray tracing of waves is performed by using the following standard Hamiltonian equations\textsuperscript{8}:

\[
\frac{d\mathbf{R}}{dt} = -\frac{\partial D}{\partial \mathbf{k}} \frac{\partial D}{\partial \omega} \tag{1}
\]

\[
\frac{d\mathbf{k}}{dt} = \frac{\partial D}{\partial \mathbf{R}} \frac{\partial D}{\partial \omega} \tag{2}
\]

where \(\mathbf{R}, \omega, \mathbf{k}\), and \(t\) represent the position vector of a point on the ray path, the wave frequency, the wave vector, and the group time, respectively. The wave dispersion relation \(D(\mathbf{R}, \omega, \mathbf{k}) = 0\) at every point along the ray path, has well been documented in the previous work. The spatial variation in \(D\) can be written:

\[
\frac{\partial D}{\partial \mathbf{R}} = \frac{\partial D}{\partial \mathbf{B}_0} \frac{\partial \mathbf{B}_0}{\partial \mathbf{R}} + \frac{\partial D}{\partial N} \frac{\partial N}{\partial \mathbf{R}} + \frac{\partial D}{\partial \mathbf{k}} \frac{\partial \mathbf{k}}{\partial \mathbf{R}} \tag{3}
\]

where \(\mathbf{B}_0\) is a ambient magnetic field and \(N\) is the background plasma density.

Here, two Cartesian coordinate systems are adopted for the ray-tracing calculation\textsuperscript{11,21}. The first is Earth centered Cartesian coordinate system (OXYZ), in which Z axis points north along the geomagnetic axis; and the X and Y axes stay in the geomagnetic axis equatorial plane. The second is a local Cartesian system, in which...
The z axis points along the direction of the ambient magnetic field, the x axis is orthogonal to the z axis and stays in the meridional plane pointing away from the Earth at the equator, and the y axis completes the right-hand set. The wave vector $\mathbf{k}$ makes an angle $\theta$ with the z axis and the projection of $\mathbf{k}$ onto the xy plane makes an angle $\eta$ with the x axis, viz., $\mathbf{k} = k \cos \theta \mathbf{k} + k \sin \theta \cos \eta \mathbf{k} + k \sin \eta \sin \phi \mathbf{k}$, $\eta = 0^\circ$, $90^\circ$, and $270^\circ$ correspond to the perpendicular component $\mathbf{k}$, pointing away from the Earth, toward later MLT (eastward), toward the Earth, and toward earlier MLT (westward), respectively.

For ray-tracing, we adopt a dipole magnetic field model and the global core plasma density model. Considering that MS wave propagate very obliquely, we choose the initial wave normal angle $\theta = 88^\circ$, and the initial azimuthal angle $\eta = 150^\circ$ (toward earlier MLT) and $30^\circ$ (toward later MLT). The other ray-tracing parameters for different wave frequencies and source locations are shown in Table 1.

| $L$ | $f_{\text{cp}}$ ($\text{Hz}$) | $F_\parallel$ ($\text{Hz}$) |
|-----|----------------------------|-----------------|
| 5.0 | 11, 12, 13, 14, 23, 27, 31, 35 | 41.8, 45.5, 49.3, 53.0, 87.2, 102.4, 117.5, 132.7 |
| 5.5 | 12, 14, 16, 18, 30, 35, 40, 45 | 34.2, 39.8, 45.5, 51.2, 85.4, 99.7, 113.9, 128.2 |
| 6.0 | 16, 18, 20, 22, 40, 45, 50, 55 | 35.1, 39.5, 43.9, 48.0, 87.8, 98.7, 109.7, 120.7 |

To calculate the diffusion rates, we assume that the MS wave spectral density $B_i$ follows a typical Gaussian frequency distribution with a center orthogonal to the z axis and stays in the meridian plane pointing away from the Earth, toward later MLT (eastward), toward the Earth, and toward earlier MLT (westward), respectively.

As shown in Figure 3, there is a cross region between two bands with the cross frequency $f_{\text{cr}} = 70$ Hz. We consider contribution from harmonic resonances up to $n = \pm 20$ for the lower band and $n = \pm 30$ for the upper band. To avoid repeating calculation from the cross region of two bands, the lower band stops at $f_{\text{cr}} = 70$ Hz and the upper band starts at $f_{\text{cr}} = 70$ Hz. We then compute MS-driven bounce-averaged diffusion coefficients at the location $L = 4.6$.

The evolution of the proton phase space density $f$ is calculated by solving the bounce-averaged pitch angle and momentum diffusion equation

$$
\frac{\partial f}{\partial t} + \frac{1}{G} \frac{\partial}{\partial z} \left[ G \left( D_{\parallel} + \frac{1}{\beta} D_{\perp} \right) \frac{\partial f}{\partial z} \right] = 0
$$

where $X = \tan \theta (0 \leq \theta \leq \frac{\pi}{2}, X_{\parallel} = \tan \theta_{\parallel})$, with a half-width $X_0$ and a peak $X_{\parallel 0}$.

Based on the observation, we choose $X_{\parallel 0} = \tan 89^\circ$, $X_0 = \tan 86^\circ$, $X_{\parallel} = X_{\parallel 0} - X_0$, and the maximum latitude for the presence of MS waves $L_{\text{ms}} = 5$. We assume that the wave spectral intensity remains constant along the dipolar geomagnetic field line.

The evolution of the proton phase space density $f$ is calculated by solving the bounce-averaged pitch angle and momentum diffusion equation

$$
\frac{\partial f}{\partial \theta} = \sqrt{\frac{2}{\pi}} \frac{\partial f}{\partial \theta} + \left[ \frac{\partial f}{\partial \theta} \right]^{-1} - \left[ \frac{\partial f}{\partial \theta} \right]^{-2} \frac{\partial f}{\partial \theta}
$$

where $X = \tan \theta (0 \leq \theta \leq \frac{\pi}{2}, X_{\parallel} = \tan \theta_{\parallel})$, with a half-width $X_0$ and a peak $X_{\parallel 0}$.

Based on the observation, we choose $X_{\parallel 0} = \tan 89^\circ$, $X_0 = \tan 86^\circ$, $X_{\parallel} = X_{\parallel 0} - X_0$, and the maximum latitude for the presence of MS waves $L_{\text{ms}} = 5$. We assume that the wave spectral intensity remains constant along the dipolar geomagnetic field line.

The evolution of the proton phase space density $f$ is calculated by solving the bounce-averaged pitch angle and momentum diffusion equation

$$
\frac{\partial f}{\partial \theta} = \sqrt{\frac{2}{\pi}} \frac{\partial f}{\partial \theta} + \left[ \frac{\partial f}{\partial \theta} \right]^{-1} - \left[ \frac{\partial f}{\partial \theta} \right]^{-2} \frac{\partial f}{\partial \theta}
$$

where $X = \tan \theta (0 \leq \theta \leq \frac{\pi}{2}, X_{\parallel} = \tan \theta_{\parallel})$, with a half-width $X_0$ and a peak $X_{\parallel 0}$.

Based on the observation, we choose $X_{\parallel 0} = \tan 89^\circ$, $X_0 = \tan 86^\circ$, $X_{\parallel} = X_{\parallel 0} - X_0$, and the maximum latitude for the presence of MS waves $L_{\text{ms}} = 5$. We assume that the wave spectral intensity remains constant along the dipolar geomagnetic field line.

The evolution of the proton phase space density $f$ is calculated by solving the bounce-averaged pitch angle and momentum diffusion equation

$$
\frac{\partial f}{\partial \theta} = \sqrt{\frac{2}{\pi}} \frac{\partial f}{\partial \theta} + \left[ \frac{\partial f}{\partial \theta} \right]^{-1} - \left[ \frac{\partial f}{\partial \theta} \right]^{-2} \frac{\partial f}{\partial \theta}
$$

where $X = \tan \theta (0 \leq \theta \leq \frac{\pi}{2}, X_{\parallel} = \tan \theta_{\parallel})$, with a half-width $X_0$ and a peak $X_{\parallel 0}$.

Based on the observation, we choose $X_{\parallel 0} = \tan 89^\circ$, $X_0 = \tan 86^\circ$, $X_{\parallel} = X_{\parallel 0} - X_0$, and the maximum latitude for the presence of MS waves $L_{\text{ms}} = 5$. We assume that the wave spectral intensity remains constant along the dipolar geomagnetic field line.

The evolution of the proton phase space density $f$ is calculated by solving the bounce-averaged pitch angle and momentum diffusion equation

$$
\frac{\partial f}{\partial \theta} = \sqrt{\frac{2}{\pi}} \frac{\partial f}{\partial \theta} + \left[ \frac{\partial f}{\partial \theta} \right]^{-1} - \left[ \frac{\partial f}{\partial \theta} \right]^{-2} \frac{\partial f}{\partial \theta}
$$

where $X = \tan \theta (0 \leq \theta \leq \frac{\pi}{2}, X_{\parallel} = \tan \theta_{\parallel})$, with a half-width $X_0$ and a peak $X_{\parallel 0}$.

Based on the observation, we choose $X_{\parallel 0} = \tan 89^\circ$, $X_0 = \tan 86^\circ$, $X_{\parallel} = X_{\parallel 0} - X_0$, and the maximum latitude for the presence of MS waves $L_{\text{ms}} = 5$. We assume that the wave spectral intensity remains constant along the dipolar geomagnetic field line.

The evolution of the proton phase space density $f$ is calculated by solving the bounce-averaged pitch angle and momentum diffusion equation

$$
\frac{\partial f}{\partial \theta} = \sqrt{\frac{2}{\pi}} \frac{\partial f}{\partial \theta} + \left[ \frac{\partial f}{\partial \theta} \right]^{-1} - \left[ \frac{\partial f}{\partial \theta} \right]^{-2} \frac{\partial f}{\partial \theta}
$$

where $X = \tan \theta (0 \leq \theta \leq \frac{\pi}{2}, X_{\parallel} = \tan \theta_{\parallel})$, with a half-width $X_0$ and a peak $X_{\parallel 0}$.
27. Xiao, F. et al. Magnetosonic wave instability by proton ring distributions: Simultaneous data and modeling. *J. Geophys. Res.* **118**, 4053 (2013).
28. Suchy, K. Real Hamilton equations of geomagnetic optics for media with moderate absorption. *Radio Sci.*, **16**, 1179 (1981).
29. Gallagher, D. L., Craven, P. D. & Comfort, R. H. Global core plasma model. *J. Geophys. Res.* **105**, 18819–18833 (2000).
30. Lyons, L. R., Thorne, R. M. & Kennel, C. F. Pitch angle diffusion of radiation belt electrons within the plasmasphere. *J. Geophys. Res.*, **77**, 3455–3474 (1972).
31. Vasyliunas, V. M. A survey of low-energy electrons in the evening sector of the magnetosphere with ogo 1 and ogo 3. *J. Geophys. Res.*, **73**, 2839–2884 (1968).

Acknowledgments
This work is supported by 973 Program 2012CB825603, the National Natural Science Foundation of China grants 41274165, 41204114, the Aid Program for Science and Technology Innovative Research Team in Higher Educational Institutions of Hunan Province, and the Construct Program of the Key Discipline in Hunan Province.

Author contributions
F.L.X. and Q.G.Z. led the idea and modelling, Y.F.W. and Z.G.H. contributed data analysis and interpretation, Z.P.S., C.Y. and Q.H.Z. contributed modelling.

Additional information
Competing financial interests: The authors declare no competing financial interests.
How to cite this article: Xiao, F.L. et al. Generation of proton aurora by magnetosonic waves. *Sci. Rep.* 4, 5190; DOI:10.1038/srep05190 (2014).

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 4.0 International License. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder in order to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc-nd/4.0/