Kinetic Alfvén wave による選択的オーロラ電子加速過程

*齋藤幸碩[1]、加藤雄人[1]、川面洋平[2,1]、熊本篤志[1]
1: 東北大学大学院理学研究科地球物理学専攻、2: 宇都宮大学データサイエンス経営学部

Kinetic Alfvén wave (KAW)は、磁力線平行方向の波長が長く、磁力線垂直方向の波長がイオン Larmor 半径程度の電磁波動である。KAW は磁力線平行方向の電場成分$\delta E_{\parallel}$を持ち、電子を磁力線に沿って加速することが知られている[e.g., Hasegawa, 1976]。KAW は地球磁気圏のサブストームやオーロラビーズ現象と関連があり、KAW が電子を磁力線平行方向に数百 eV から数 keV 程度のエネルギーに加速し、オーロラ増光を引き起こすと考えられている[e.g., Kalmoni et al., 2015; Wygant et al., 2002]。KAW は Landau 共鳴を通して電子を加速する。Landau 共鳴には、散乱過程[e.g., Hasegawa and Mima, 1978]、捕捉過程[e.g., Hasegawa, 1976]、反射過程[Kletzing, 1994]の 3 種類が考えられる。従来の研究では特に捕捉過程に焦点が当てられてきた一方で、これらの過程が重要になる条件や KAW の持つ大きなポテンシャルの寄与、電子が大きく且つ広帯域に加速される条件などといった電子加速過程の詳細の調査は、未だ十分に行われていない。

本研究では、KAW による電子加速過程に対して、コヒーレントな電磁波動に捕捉された荷電粒子の加速過程の研究で用いられてきた 2 次共鳴理論[e.g., Matsumoto and Omura, 1981]を導入し、過程の詳細を調査した。KAW に捕捉された電子の運動は、KAW の平行位相速度$V_{\mathrm{ph}\parallel}$近傍に形成される捕捉領域による特徴づけられ、電子から見た KAW の位相ψについての単振動と、KAW の波長の空間変化と背景磁場勾配に起因する不均一性因子Sによる影響との重畳として記述される。Sが 1 に向けて増加することで捕捉領域は縮小し、電子は波の捕捉から外れやすくなる。

我々は地球磁気圏の$L = 9$磁力線を伝播する KAW による電子の運動を、テスト粒子計算により求めた。これにより、KAW による電子加速において 3 種類の主要な過程があることが明らかになった。一つ目の捕捉輸送過程では、電子は KAW に捕捉されながら高緯度に向けて輸送される。高緯度に向けて$V_{\mathrm{ph}\parallel}$とSが徐々に増加するため、電子は次第に KAW に追い付けなくなり、KAW の捕捉から外れる。この過程によって電離圏に降下した電子の運動エネルギーは、KAW の捕捉から外れた地点での値をほとんど維持するため、エネルギーは単一的になる。二つ目の反射過程では、$V_{\mathrm{ph}\parallel}$未満の速度を持つ電子が KAW のポテンシャルに反射される。この過程では、電子は$V_{\mathrm{ph}\parallel}$より大きい速度で KAW の捕捉から外れて電離圏に向かい、そのエネルギーは幅広い値を取りうることが分かった。また、この過程では電子の速度が急激に変化するため、Sの値も同様に急激に変化する。三つ目の負の加速過程では、高緯度から低緯度に向かう電子が、磁気赤道方向に加速する KAW の位相領域を通過することで、負に大きく加速される。この過程は非共鳴過程であるが、KAW のポテンシャルが大きいことで影響が大きくなり、反射過程を経るように電子の軌道を調整するという重要な役割を担う。これら 3 つの加速過程は、他の数値計算研究[Watt and Rankin, 2010]でも確認でき、結果の比較から、ポテンシャルが大きくなるほど反射過程が促進され、単色の KAW でも広帯域の電子ビームを生成することが示唆された。また、ポテンシャルが小さいときは捕捉過程が重要になることから、電子降下の結果生じるオーロラの周期的構造が期待され、一方でポテンシャルが大きい場合はオーロラの周期的構造が破壊されることが考えられる。

KAW はプラズマβが電子–イオン質量比よりも大きい領域で重要となることから、木星磁気圏のイオトーラスや水星磁気圏のプラズマシートなどでも電子加速を引き起こす可能性がある。今後の JUICE や BepiColombo によって、KAW や KAW によって加速された電子が観測されることを期待する。

Kinetic Alfvén waveによる選択的オーロラ電子加速過程

第26回惑星圏シンポジウム O-D2-22

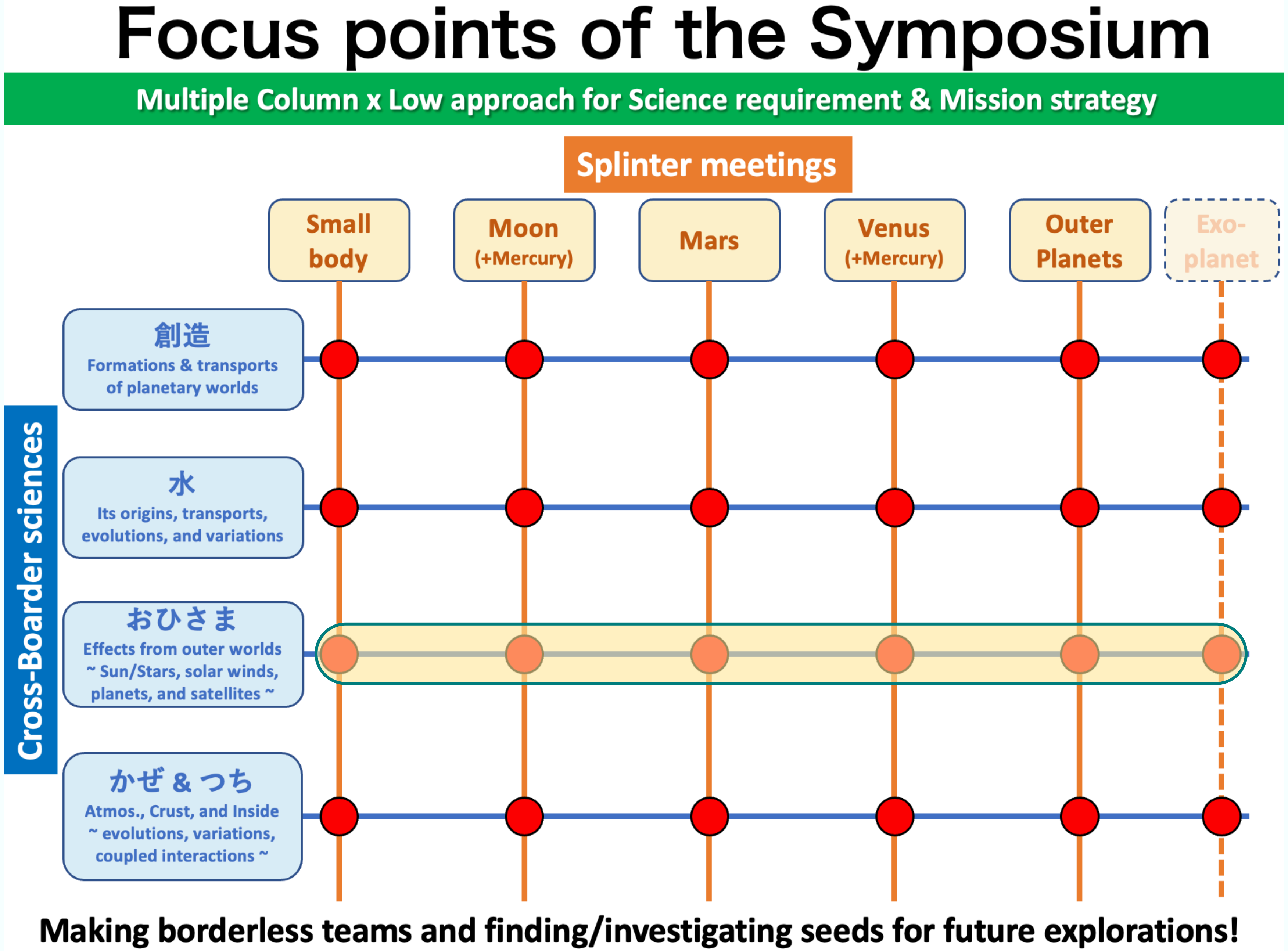
2025年 3月 4日 16:15-16:35

齋藤幸碩[1]、加藤雄人[1]、川面洋平[2, 1]、熊本篤志[1]

1: 東北大学大学院理学研究科地球物理学専攻

2: 宇都宮大学データサイエンス経営学部

本研究の立ち位置



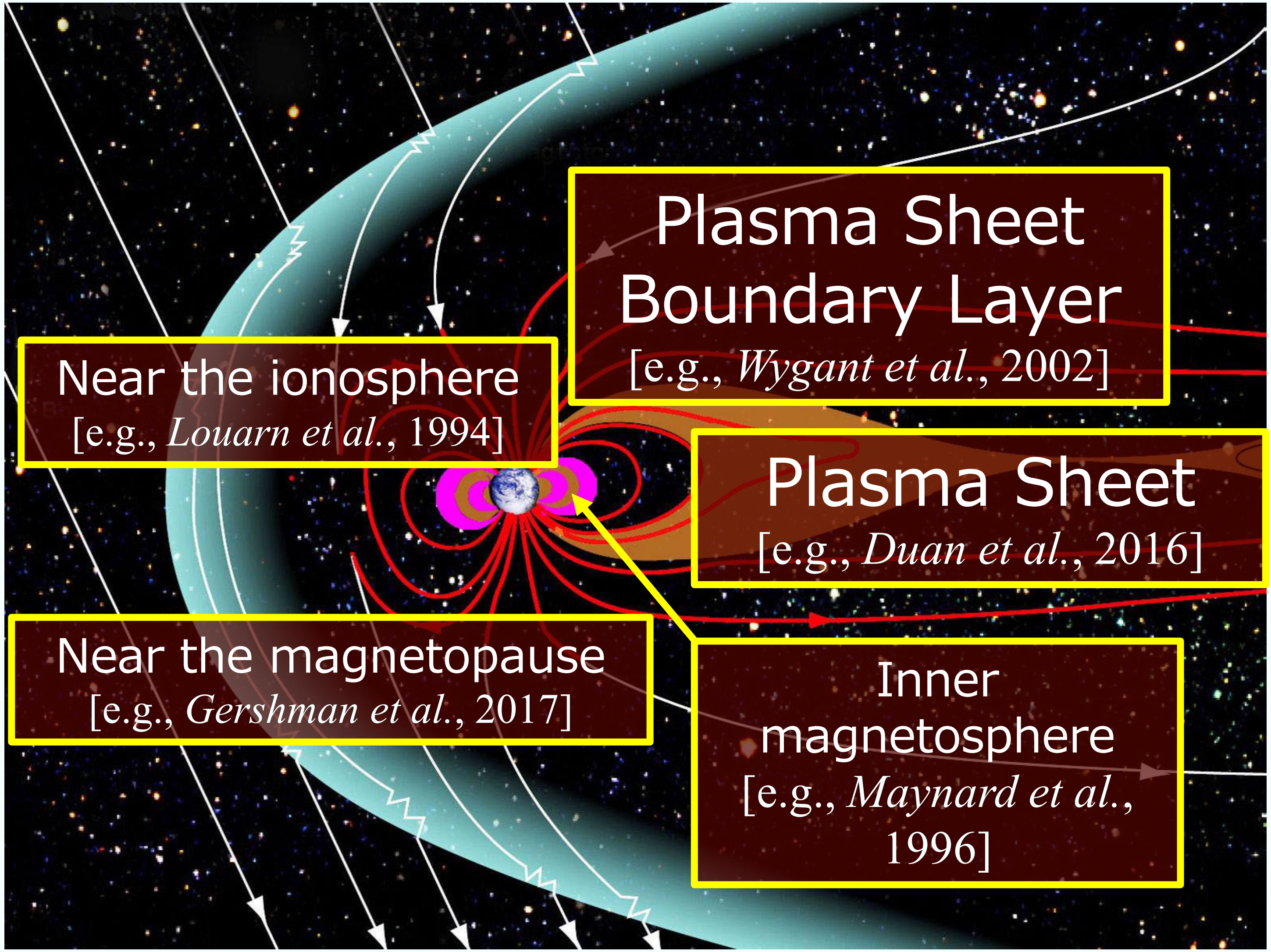
Keywords

- オーロラ
- 電子加速過程
- Kinetic Alfvén wave

研究対象: 地球磁気圏

他の惑星磁気圏や
惑星間空間などにも
通じる理論

Kinetic Alfvén waves (KAWs)
Long parallel wavelength,
Perpendicular wavelength ~ ρ_{i},
Long period



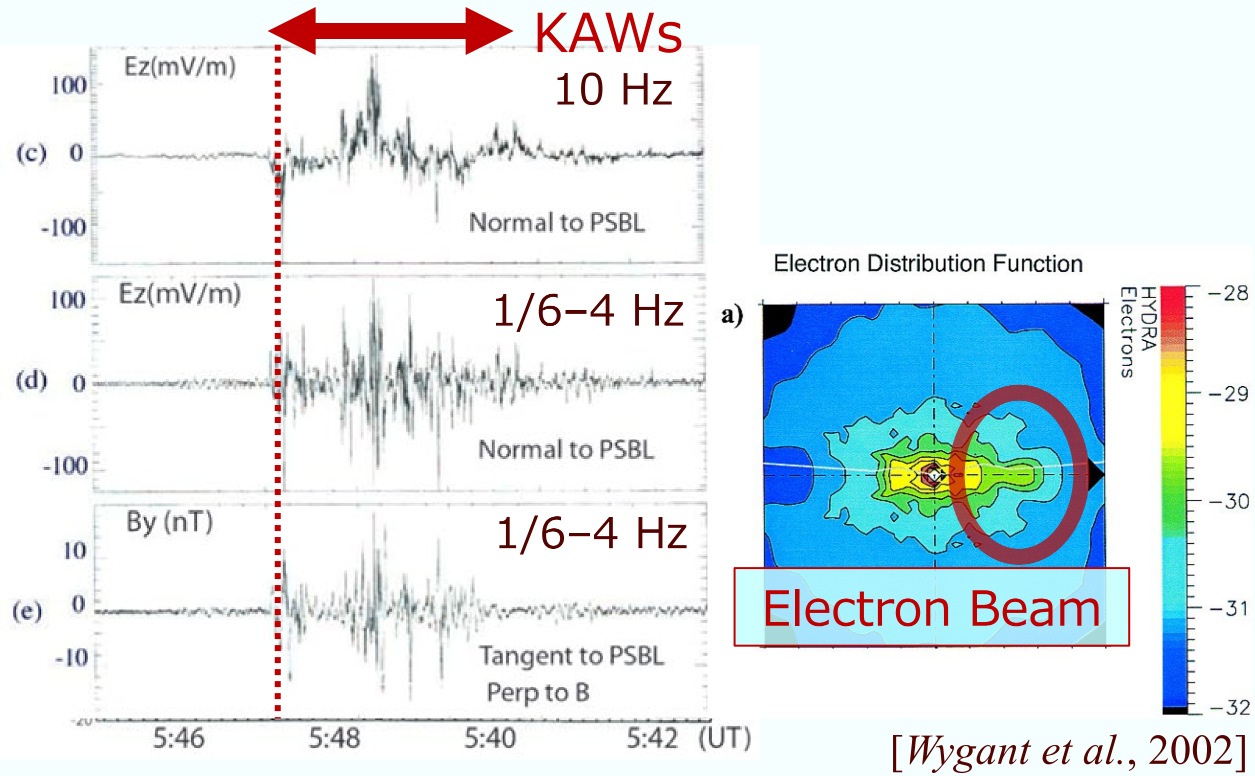
[Credit: NASA/Goddard/Aaron Kaase]

Phenomena related to KAWs → Auroras

KAWs
- transport the large parallel Poynting flux to the ionosphere,
- carry $\delta E_{\parallel}$,
- accelerates electron beams to a few keV with low pitch angle.

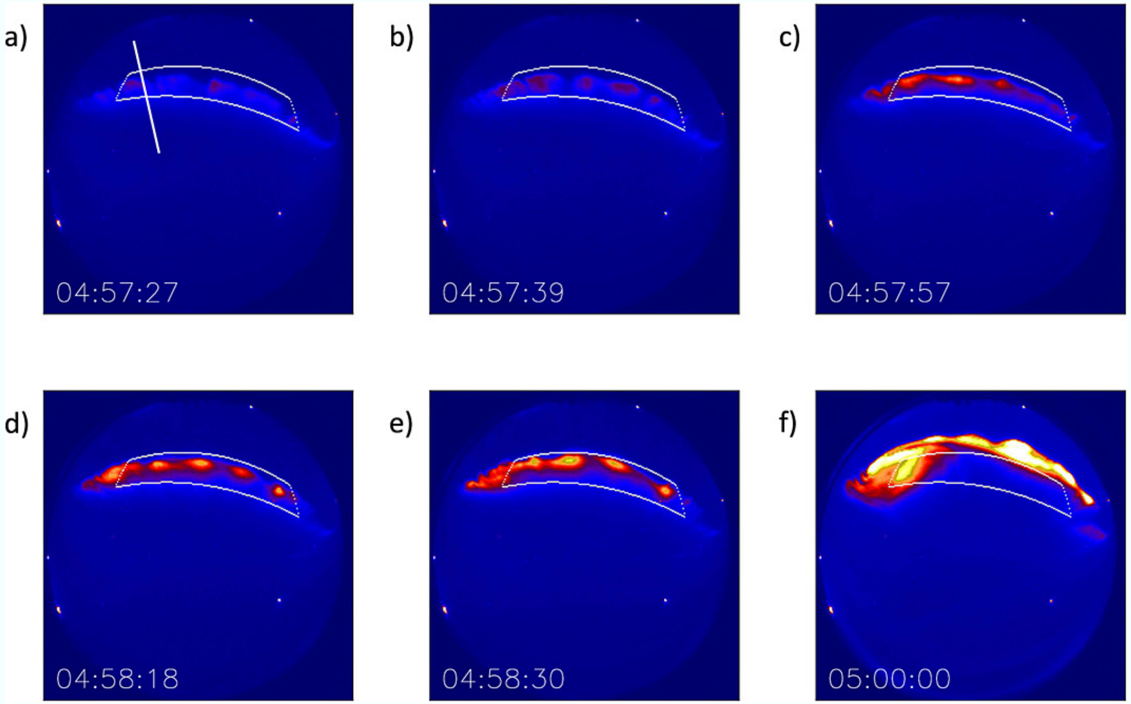
⇨ generates diffuse aurora and auroral beads.

[*Akasofu*, 1964; *Kalmoni et al.*, 2015, 2017, 2018]



[*Wygant et al.*, 2002]

Auroral beads along the onset arc during the auroral substorm

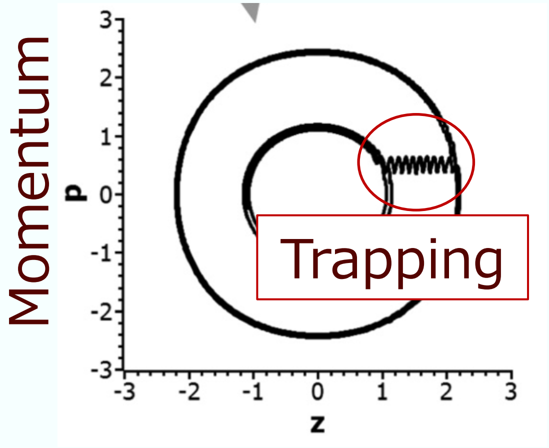


[*Kalmoni et al.*, 2015]

Electron Acceleration Processes → Landau Resonance

3 types of Landau Resonance

1. Scattering process $v_{\parallel} = V_{ph\parallel}$



[*Artemyev et al.*, 2017a]

2. Trapping process

[e.g., *Hasegawa*, 1976]

Trap e^- in the potential well, transport, and accelerate to $V_{ph\parallel}$

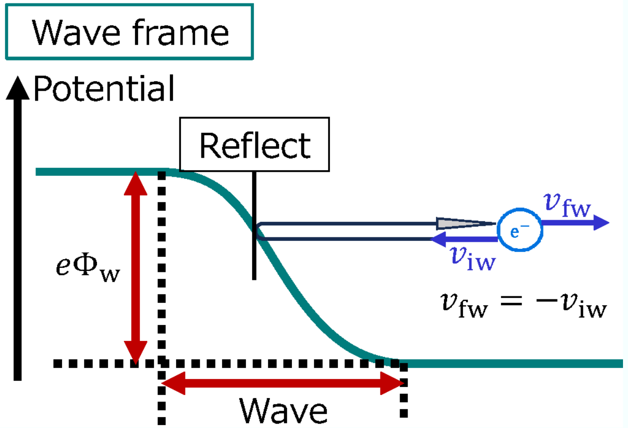
$$V_{ph\parallel} - V_{tr} \leq v_{\parallel} \leq V_{ph\parallel} + V_{tr}$$

3. Reflection process

[*Kletzing*, 1994]

The wave reflects and accelerates e^- to $2V_{ph\parallel} - v_{\parallel}$.

$$V_{ph\parallel} - V_{tr} \leq v_{\parallel} < V_{ph\parallel}$$



$V_{tr} \propto \sqrt{\Phi_E}$: trapping speed

Broadened the resonance condition by the wave potential Φ_E

Recent numerical studies

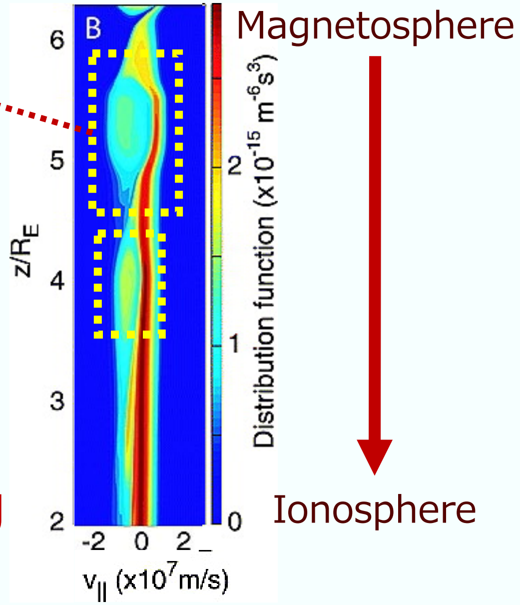
e^- trapping is important in the e^- acceleration processes.

[*Artemyev et al.*, 2015; *Damiano et al.*, 2015, 2016; *Watt and Rankin*, 2009, 2010]

Trapping Island

Transporting toward the ionosphere

Energy source for auroral brightening



[*Watt and Rankin*, 2010]

The physical process of e^- acceleration by KAWs with a large Φ_E is not well understood.

2nd-order Resonance Theory / Purpose

2nd-order resonance theory

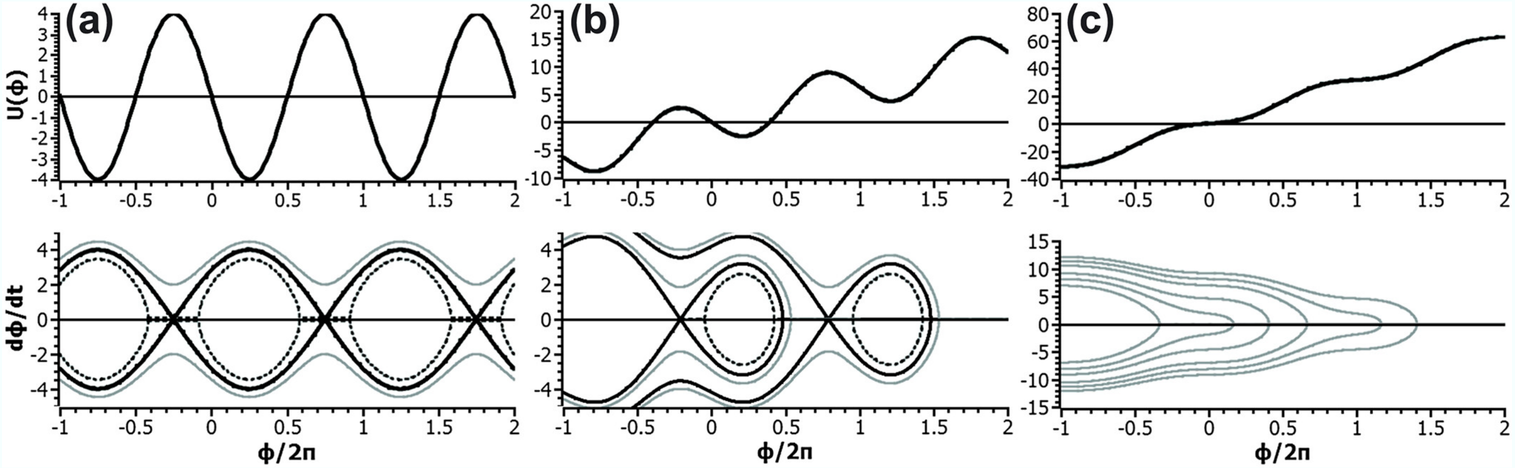
One of the way to understand the particle motion in waves
[e.g., *Matsumoto and Omura*, 1981]

$$\begin{cases} \dfrac{d\psi}{dt} = k_{\parallel}(v_{\parallel} - V_{ph\parallel}) \equiv \theta \\ \dfrac{d\theta}{dt} = -\omega_t^2(\sin\psi + S) \end{cases}$$

Simple harmonic motion of ψ
+
Inhomogeneity factor S

S obstructs the trapping process.

$S = 0$ $\quad 0 < |S| < 1$ $\quad |S| \geq 1$



[*Artemyev et al.*, 2017b]

This theory has not been applied to the e^- acceleration process of KAWs.

Purpose

To understand the physical process of electron acceleration by KAWs with the large scalar potential and the spatial variation of wave phase, which are unique to KAWs

- Obtain the pendulum equations and S by introducing the 2nd-order resonance theory
- Investigate the detailed characteristics of e^- acceleration processes by KAWs

Equations for 2nd-order Resonance Theory

Kinetic Alfvén waves (KAWs)

Dispersion Relation (ERMHD)

$$\omega = k_\perp \rho_i k_\parallel v_A \sqrt{\frac{1+\tau}{\beta_i(1+\tau)+2\tau}} \quad (\tau \coloneqq T_i/T_e)$$

[*Schekochihin et al.*, 2009]

Assumption $k_\perp \rho_i = 2\pi$

Wave phase $$\psi = \int_0^z k_\parallel \, dz' - \omega t + \psi_0$$

Scalar potential $$\varphi = \varphi_0 \cos\psi$$

Electric field $$\delta E_\parallel = k_\parallel \varphi_0 \left(2 + \frac{1}{\tau}\right) \sin\psi = k_\parallel \Phi_E \sin\psi$$

Equations of Motion

$$\frac{dv_\parallel}{dt} = -\frac{\mu}{m_e}\frac{dB_0}{dz} - \frac{e}{m_e}\delta E_\parallel$$

Mirror force vs. $\delta E_\parallel$

$$\frac{d\mu}{dt} = 0$$

μ conservation

Material derivative of wave phase ψ

1st-order $$\frac{d\psi}{dt} = k_\parallel (v_\parallel - V_{ph\parallel}) \equiv \theta$$

2nd-order $$\frac{d\theta}{dt} = -\omega_t^2(\sin\psi + S)$$

Pendulum equations

Parallel wave phase speed: $V_{ph\parallel} \coloneqq \frac{\omega}{k_\parallel}$

Trapping frequency: $\omega_t \coloneqq k_\parallel \sqrt{\frac{K_E}{m_e}}$ $K_E \coloneqq e\Phi_E$

Inhomogeneity factor:

$$S \coloneqq \frac{K}{K_E}(1 + \Gamma\cos^2\alpha)\delta_1$$

Pitch angle coefficient: $\Gamma \coloneqq 1 + \frac{2\beta_i(1+\tau)}{\beta_i(1+\tau)+2\tau} \sim 1$

Magnetic field gradient scale:

$$\delta_1 \coloneqq \frac{1}{k_\parallel B_0}\frac{dB_0}{dz}$$

Types of Electron States in KAWs

Pendulum equations

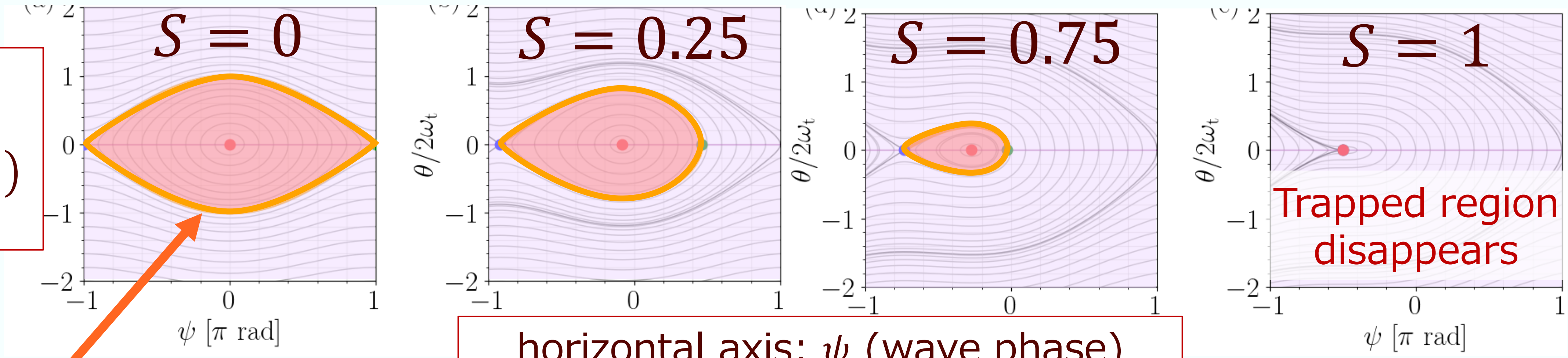
$$\begin{cases} \dfrac{\mathrm{d}\psi}{\mathrm{d}t} = k_\parallel (v_\parallel - V_{\mathrm{ph}\parallel}) \equiv \theta \\ \dfrac{\mathrm{d}\theta}{\mathrm{d}t} = -\omega_\mathrm{t}^2 (\sin\psi + S) \end{cases}$$

$\omega_\mathrm{t} = \text{const.}$
$S = \text{const.}$

$$\frac{m_\mathrm{e}}{2K_\mathrm{E}} (v_\parallel - V_{\mathrm{ph}\parallel})^2 - (\cos\psi - S\psi) = \text{const.}$$

plots

$S = S(K, \alpha, \lambda)$



vertical axis

$$\frac{1}{2}\sqrt{\frac{m_\mathrm{e}}{K_\mathrm{E}}} (v_\parallel - V_{\mathrm{ph}\parallel})$$

horizontal axis: ψ (wave phase)

Orange line: trapped–scattered boundary

INSIDE
Phase-trapped state

Detrapped →
← Trapped

OUTSIDE
Phase-scattered state

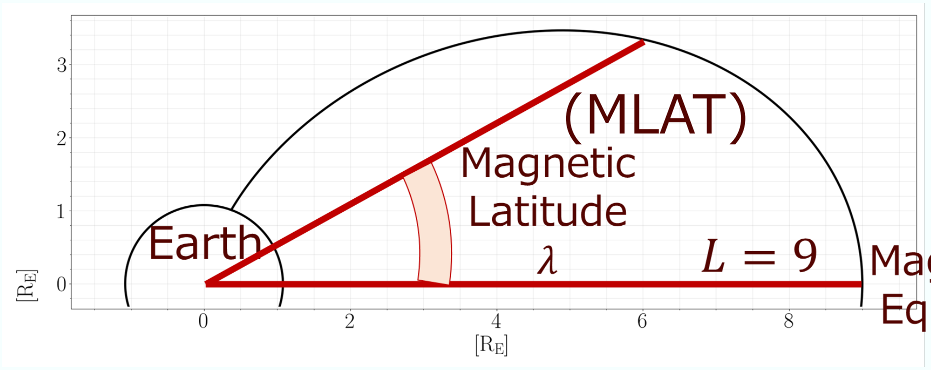
S variation

Method of Test Particle Simulations

Settings

Earth's dipole magnetic field line at $L = 9$

$$n = 1\,\mathrm{cm}^{-3}, T_\mathrm{i} = 1\,\mathrm{keV}, T_\mathrm{e} = 100\,\mathrm{eV}, f_\mathrm{KAW} = \frac{\omega}{2\pi} = 0.15\,\mathrm{Hz}, k_\perp \rho_\mathrm{i} = 2\pi, \varphi_0 = 2\,\mathrm{kV}$$



Particle Calculation Method

4th-order Runge–Kutta method

Time step: $10^{-3}\,\mathrm{s} = 1.5 \times 10^{-4}\, f_\mathrm{KAW}^{-1}$

Equations:

3+1 dimensions $(\psi, v_\parallel, \lambda, t)$

$$\begin{cases} \dfrac{\mathrm{d}\psi}{\mathrm{d}t} = k_\parallel(\lambda)\, v_\parallel - \omega \\ \dfrac{\mathrm{d}v_\parallel}{\mathrm{d}t} = -k_\parallel(\lambda) \dfrac{B_0(\lambda)\,\mu}{m_\mathrm{e}} \delta_1(\lambda) - k_\parallel(\lambda) \dfrac{K_\mathrm{E}}{m_\mathrm{e}} \sin\psi \\ \dfrac{\mathrm{d}\lambda}{\mathrm{d}t} = \dfrac{v_\parallel}{R_\mathrm{E} L} \dfrac{1}{\cos\lambda \sqrt{1 + 3\sin^2\lambda}} \end{cases}$$

Mirror Force

$\delta E_\parallel$

wave phase

Equation of Motion

$$\frac{\mathrm{d}z}{\mathrm{d}t} = v_\parallel$$

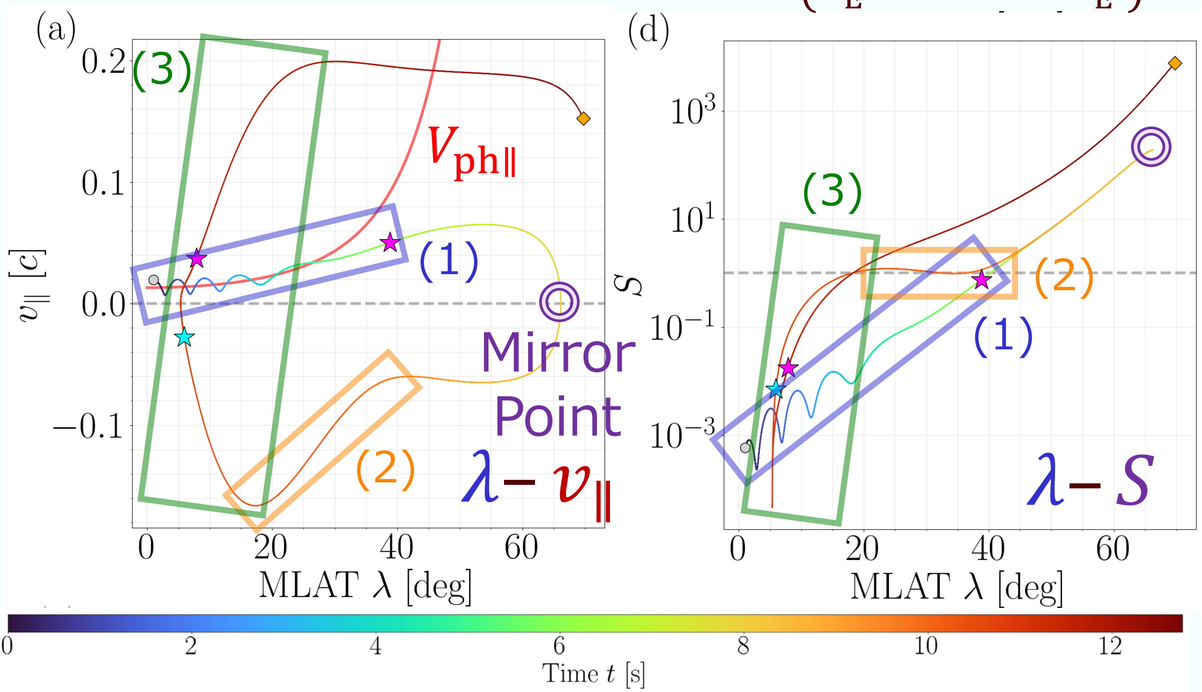
Analysis of Electron Trajectories

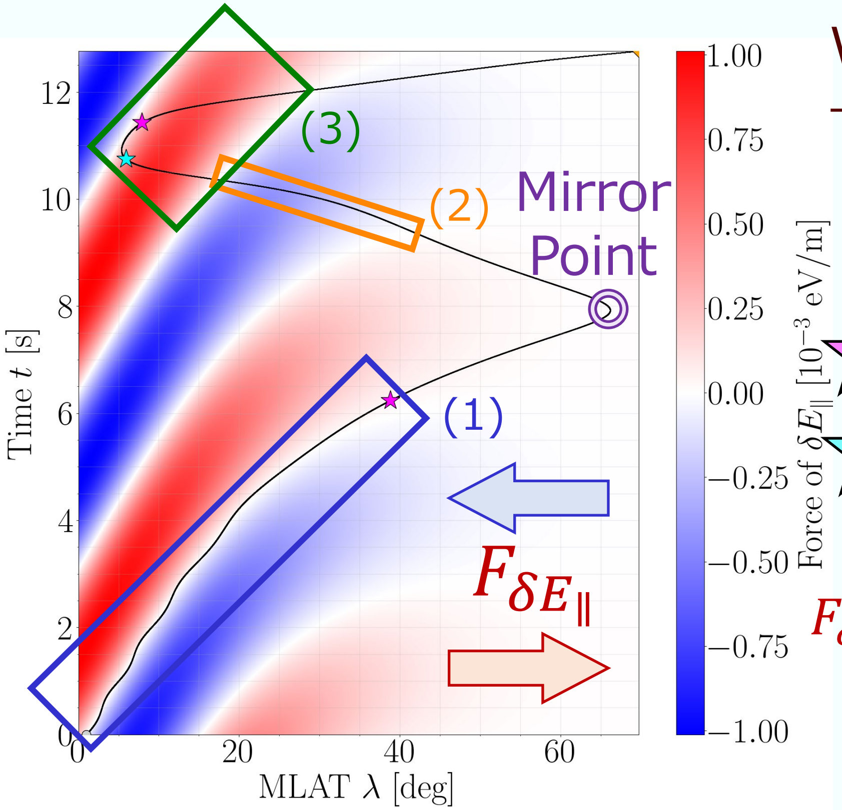
★ (1) e^- is trapped and transported toward the ionosphere while $v_\parallel$ increases and decreases around $v_\parallel = V_{\mathrm{ph}\parallel}$ and $\psi = 0$.

(2) When e^- moves back to lower MLATs, e^- is negatively accelerated at $v_\parallel < 0$.

(3) e^- is reflected by the KAW and accelerated enough to precipitate the ionosphere.

$$S = \left\{ \frac{K_\parallel}{K_\mathrm{E}} (1 + \Gamma) + \frac{B_0 \mu}{K_\mathrm{E}} \right\} \delta_1$$





Wave Period: 6.67 s
→ ≤ 2 periods

★ Detrapped Point
★ Trapped Point

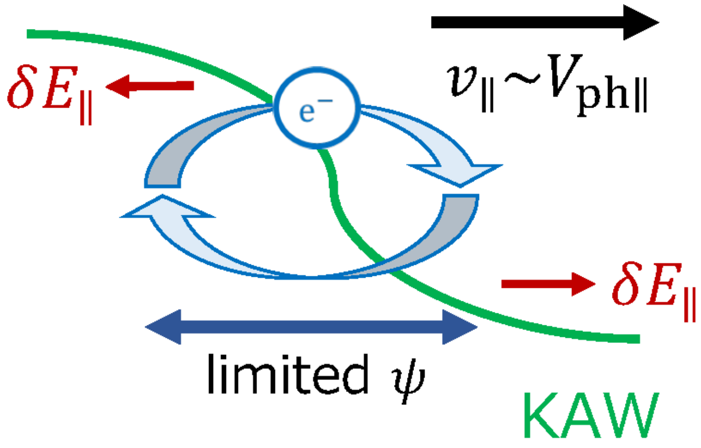
$$F_{\delta E_\parallel} = -e\, \delta E_\parallel = -k_\parallel(\lambda)\, K_\mathrm{E} \sin\psi$$

Initial condition: $K_\mathrm{i} = 100$ eV, $\alpha_\mathrm{i} = 10°$, $\psi_\mathrm{i} = 0$, $\lambda_\mathrm{i} = 1°$

There are 3 processes where KAWs accelerate electrons.

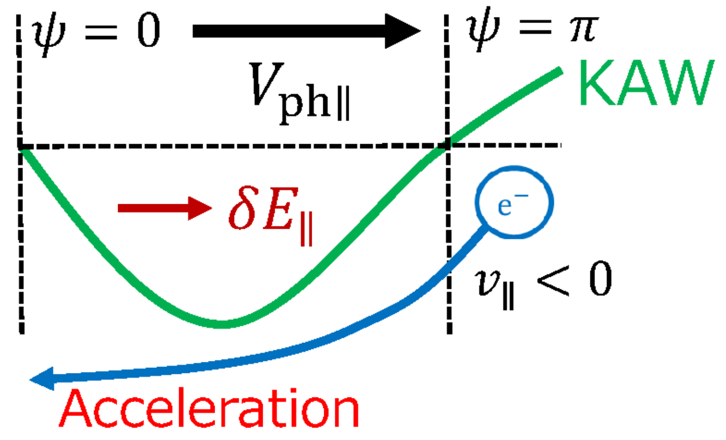
(1)

Transporting process of a phase-trapped electron



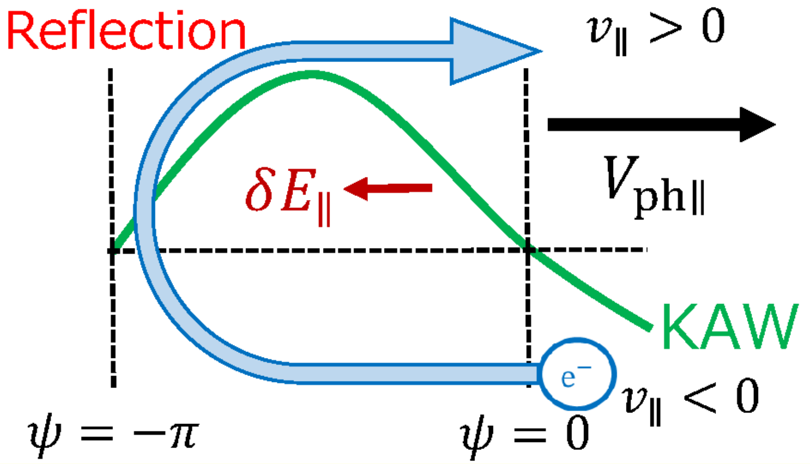
(2)

Negative acceleration process of a phase-scattered electron



(3)

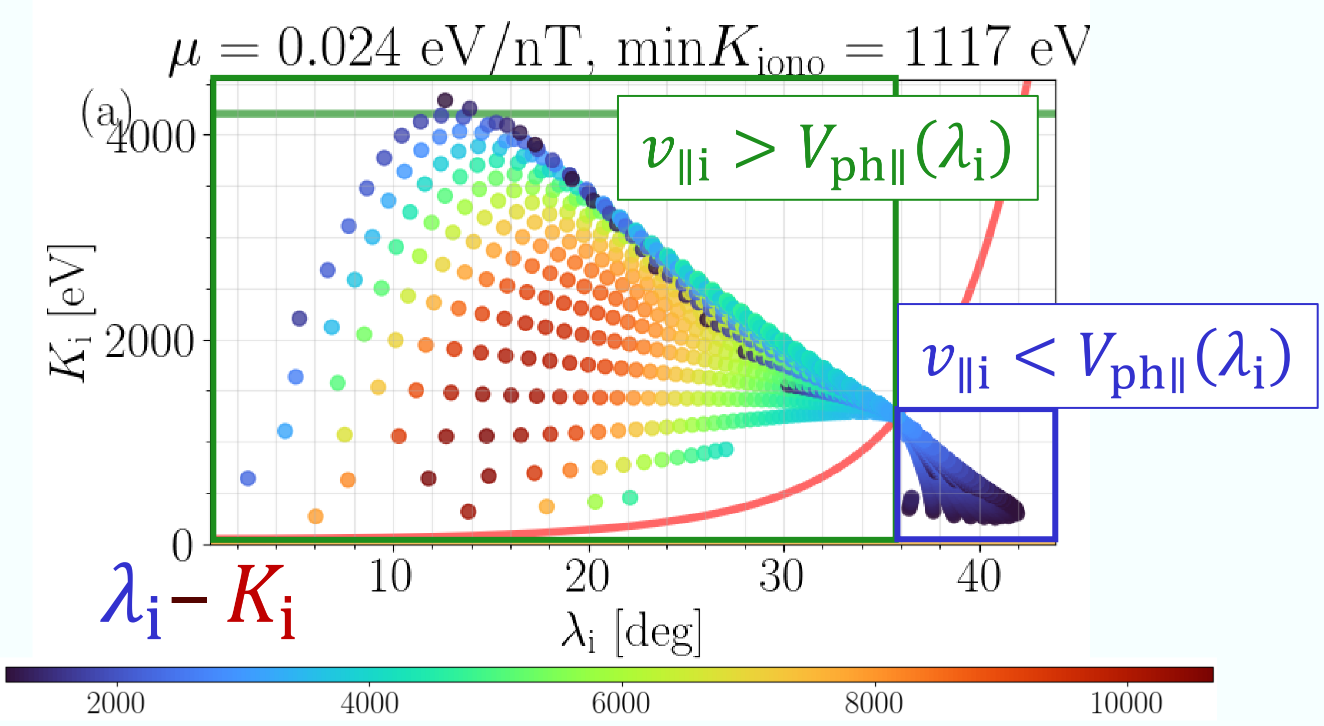
Reflection process of an electron with a large circle trajectory



Differences between Trapping and Reflection Processes (1)

Precipitating e^- toward the ionosphere

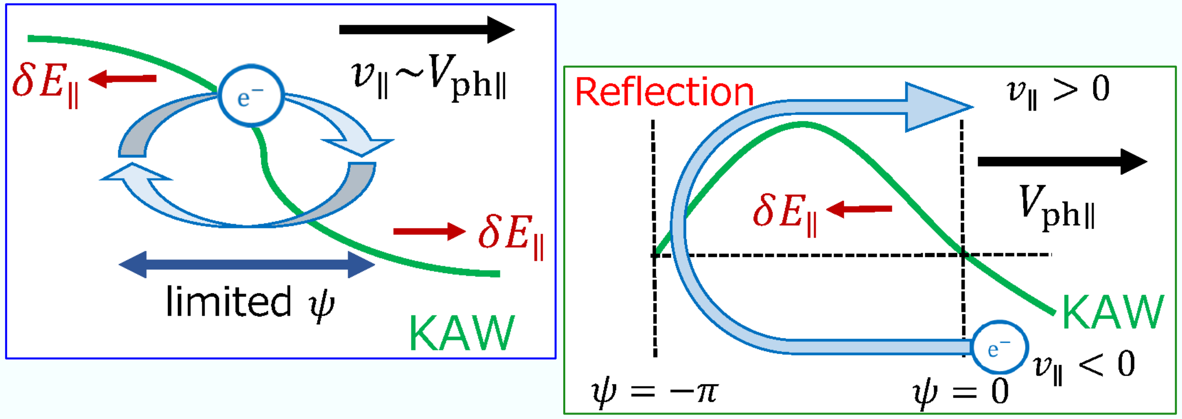
Detrapped point vs. Energy at Ionosphere



Kinetic energy at the ionosphere $K(\lambda_{iono})$ [eV]

1. TRAPPING process

When $v_{\parallel i} < V_{ph\parallel}$, i.e., e^- are detrapped by not being able to keep up with the KAW, e^- are accelerated into a monoenergetic.



3. REFLECTION process

When $v_{\parallel i} > V_{ph\parallel}$, i.e., e^- are detrapped due to overtaking the KAW, e^- are accelerated into a broadband.

$$v_\parallel, \quad K_\parallel = \frac{1}{2} m_e v_\parallel^2, \quad S = \frac{K_\parallel}{K_E}(1+\Gamma)\delta_1(\lambda) + \frac{B_0(\lambda)\,\mu}{K_E}\delta_1(\lambda)$$

from $\mathrm{d}k_\parallel/\mathrm{d}t$ | from mirror force

TRAPPING

small $v_\parallel$ oscillation around low $V_{\mathrm{ph}\parallel}$ at low MLAT

⇩

small and slow S variation

REFLECTION

large and rapid $v_\parallel$ variation

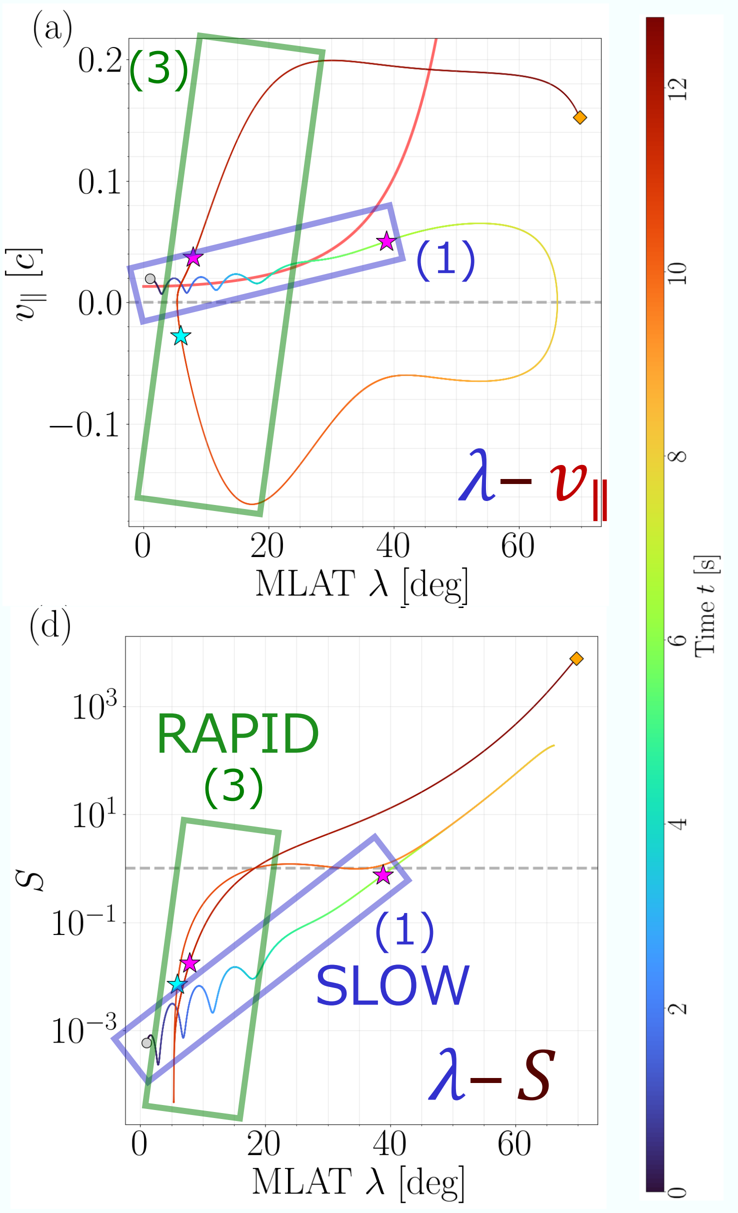
⇩

large and rapid S variation and be detrapped

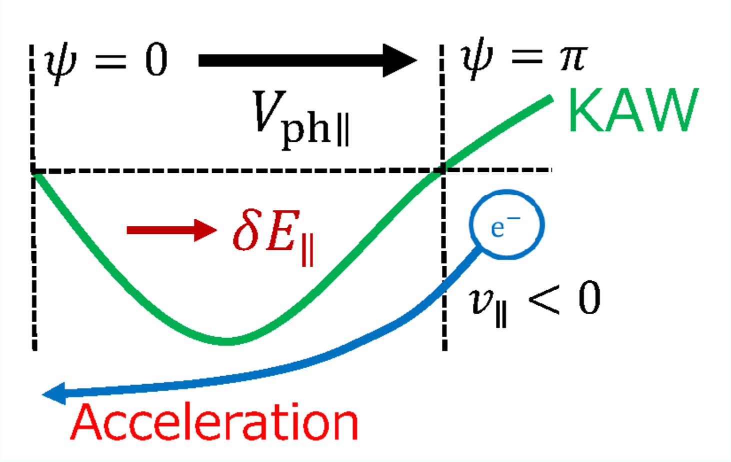
When the time variation of S is large, the reflection process is promoted rather than the trapping process.

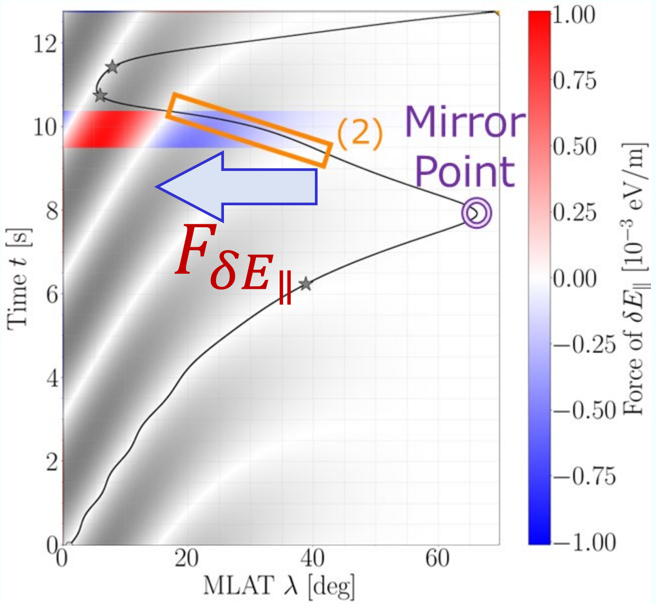
When K_E is large, temporal structure in energy spectra is broken due to the overlap of accelerated e^- from different ψ.

[*Watt and Rankin*, 2010]



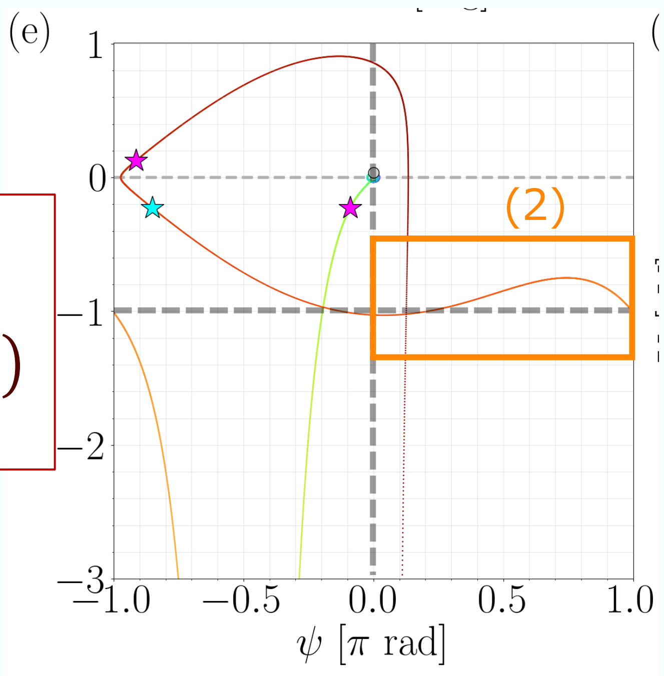
2. NEGATIVE ACCELERATION process





vertical axis

$$\frac{1}{2}\sqrt{\frac{m_e}{K_E}}\left(v_{\parallel} - V_{\mathrm{ph}\parallel}\right)$$



$v_{\parallel} \to V_{\mathrm{ph}\parallel} - V_{\mathrm{tr}}$ at $\psi = 0$

$V_{\mathrm{tr}} = 2\sqrt{\frac{K_E}{m_e}}$: trapping speed

And the trajectory becomes a large circle.

This process adjusts the trajectory so that they are likely to take the REFLECTION process.

Summary

Purpose

To understand the physical process of electron acceleration by KAWs with the large scalar potential and the spatial variation of wave phase, which are unique to KAWs

- Obtain the pendulum equations and S by introducing the 2nd-order resonance theory
- Investigate the detailed characteristics of e^- acceleration processes by KAWs through the theoretical analysis and test particle simulations

We found the 3 electron acceleration processes.
Trapping process / Reflection process/ Negative acceleration process

Trapping process: e^- are accelerated into a monoenergetic.

Reflection process: e^- are accelerated into a broadband.

Negative acceleration process: This process promotes e^- to take the reflection process.

When the time variation of S is large,
the reflection process is promoted rather than the trapping process.

地球磁気圏 → 他の惑星磁気圏へ (木星)

KAWの働き

波のポテンシャルの大きさで、オーローラの時空間変化を変える可能性がある。

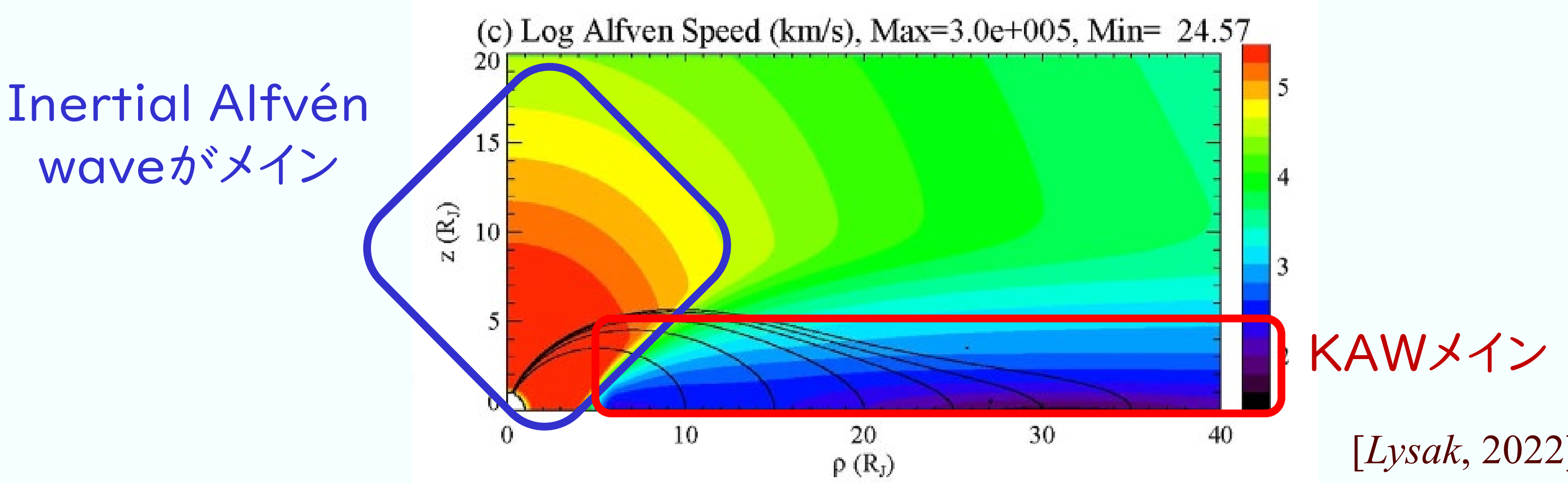
[*Watt and Rankin*, 2010]

木星

- Junoによる木星磁気圏の中高緯度における分散性Alfvén波の観測 [*Lorch et al.*, 2022]
- Junoによる幅広いエネルギー帯の電子ビームの観測とオーロラ発光の関係 [*Mauk et al.*, 2017]

JUICE mission　磁気赤道付近を主に観測する → $\beta \gg m_e/m_i$ の領域 → KAWがメイン

⇒ KAWによる電子加速の様子を観測できる可能性



[*Lysak*, 2022]

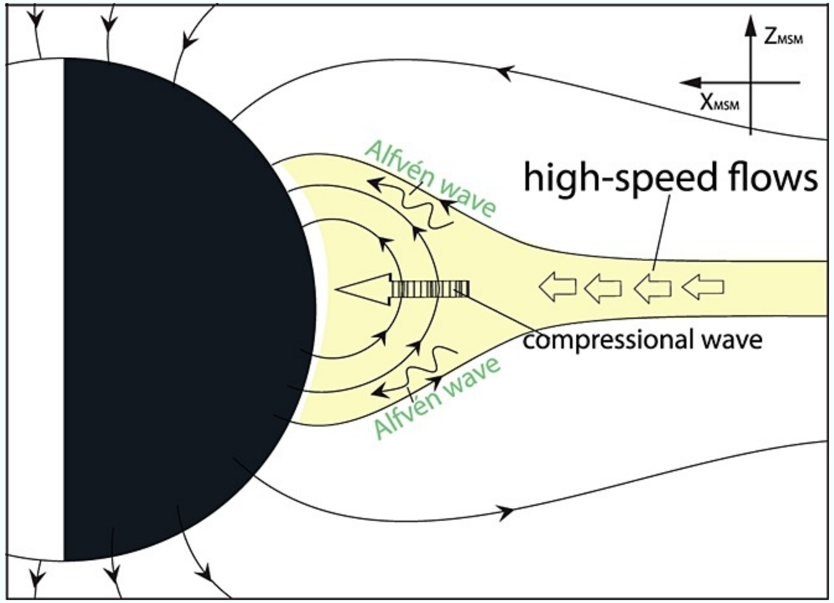
水星

MESSENGER(MAG, FIPS)によって、
サブストーム中のプラズマシートでAlfvén waveと
compressional waveが観測された。

[*Sun et al.*, 2015]

プラズマシートのプラズマベータ値$\left(\beta = \frac{2\mu_0 P}{B^2}\right)$が0.1以上

[e.g., *Glass et al.*, 2022]



[*Sun et al.*, 2015]

⇨ プラズマシートの電子/イオン加速過程で、KAWが重要になる可能性？

BepiColombo missionで、プラズマシートにおけるKAWの観測とその役割について明らかにできるか？

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