The Earth’s Ionosphere

Ryuho Kataoka (RIKEN)
Ionospheric plasma?

- Solar UV/X rays impinge on the earth, and ionize a portion of the neutral constituent.
  - Polar regions are also bombarded by auroral, radiation-belt, and solar energetic particles.
- Partially ionized (n/N<0.1%) collisional plasma
  - that envelopes the earth and forms the interface between the atmosphere and space.
- HF radio waves (~10 MHz) are reflected.
  - Edward V. Appleton was awarded a Nobel Prize in 1947 for his confirmation in 1927 of the existence of the ionosphere.
  - Ionospheric current was predicted by Balfur Stewart in 1882 based on daily geomagnetic field variations.
Contents

1. Where is the ionosphere?
   – Fundamental plasma parameters
2. What is different from MHD?
   – Hall and Pedersen effects
3. How to model the ionosphere?
   – Hall and Pedersen conductivities
4. Interesting phenomena?
   – Dynamo, SAPS, IAR, etc.
1. Where is the ionosphere?

• Aurora
  – Aurora itself is the polar ionosphere - visible interface between atmosphere and space.

• International Space Station
  – Human activities in space at middle-to-low latitudes – satellites operations etc.

• Airglow and thermosphere
  – Coexistence with upper neutral atmosphere. In-situ measurements by rockets are possible.
1. Where is the ionosphere?
1. Where is the ionosphere?

Earth's ionosphere and thermosphere

1. Dissociative recombination (molecular, fast): $\text{NO}^+ + e^- \rightarrow \text{N} + \text{O}$
2. Radiative recombination (atomic, slow): $\text{O}^+ + e^- \rightarrow \text{O} + \text{photon}$
1. Where is the ionosphere?

### Useful formulae

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Formula</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{pe} )</td>
<td>( 9.0 \times 10^3 \sqrt{n} )</td>
<td>Hz</td>
<td>2.8 MHz</td>
</tr>
<tr>
<td>( f_{pi} )</td>
<td>( 2.1 \times 10^2 \sqrt{n} )</td>
<td>Hz</td>
<td>66 kHz</td>
</tr>
<tr>
<td>( f_{ce} )</td>
<td>( 2.8 \times 10^1 B )</td>
<td>Hz</td>
<td>280 kHz</td>
</tr>
<tr>
<td>( f_{ci} )</td>
<td>( 1.5 \times 10^{-2} B )</td>
<td>Hz</td>
<td>150 Hz</td>
</tr>
<tr>
<td>( r_e )</td>
<td>( 3.1 \times 10^1 \sqrt{T_e / B} )</td>
<td>km</td>
<td>9.8 cm</td>
</tr>
<tr>
<td>( r_i )</td>
<td>( 1.3 \times 10^2 \sqrt{T_i / B} )</td>
<td>km</td>
<td>4.0 m</td>
</tr>
<tr>
<td>( \lambda_e )</td>
<td>( 5.3 \times 10^0 \sqrt{1/n} )</td>
<td>km</td>
<td>17 m</td>
</tr>
<tr>
<td>( \lambda_i )</td>
<td>( 2.3 \times 10^2 \sqrt{1/n} )</td>
<td>km</td>
<td>0.72 km</td>
</tr>
<tr>
<td>( \lambda_D )</td>
<td>( 6.9 \times 10^1 \sqrt{T_e / n} )</td>
<td>km</td>
<td>6.9 m</td>
</tr>
<tr>
<td>( v_e )</td>
<td>( 3.9 \times 10^3 \sqrt{T_e} )</td>
<td>km/s</td>
<td>120 km/s</td>
</tr>
<tr>
<td>( v_i )</td>
<td>( 9.1 \times 10^1 \sqrt{T_i} )</td>
<td>km/s</td>
<td>2.9 km/s</td>
</tr>
<tr>
<td>( v_E )</td>
<td>( 1.0 \times 10^3 E / B )</td>
<td>km/s</td>
<td>1.0 km/s</td>
</tr>
<tr>
<td>( v_A )</td>
<td>( 2.2 \times 10^1 B / \sqrt{n} )</td>
<td>km/s</td>
<td>700 km/s</td>
</tr>
<tr>
<td>( \beta )</td>
<td>( 3.5 \times 10^{-1} nT / B^2 )</td>
<td></td>
<td>3.5e-7</td>
</tr>
</tbody>
</table>

#### Typical values of ionosphere

- \( n \sim 10^5 \text{ cm}^{-3} \)
- \( T \sim 10^{-3} \text{ MK} \)
- \( W \sim 10^{-4} \text{ keV} \)
- \( B \sim 10^4 \text{ nT} \)
- \( E \sim 10 \text{ mV/m} \)

**no shocks**

**HF communications**

- Where is the ionosphere?
1. Where is the ionosphere?

**Typical quantity of state**

<table>
<thead>
<tr>
<th>Plasma type</th>
<th>N (/cc)</th>
<th>ne (/cc)</th>
<th>T (eV)</th>
<th>B (G)</th>
<th>V (km/s)</th>
<th>( V_A (\text{km/s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionosphere (E)</td>
<td>10⁹</td>
<td>10⁵</td>
<td>10⁻¹</td>
<td>10⁻¹</td>
<td>1</td>
<td>10³</td>
</tr>
<tr>
<td>Ionosphere (J)</td>
<td>10¹³</td>
<td>10⁶</td>
<td>10⁻¹</td>
<td>10</td>
<td>1</td>
<td>10⁷</td>
</tr>
<tr>
<td>Chromosphere</td>
<td>10¹⁴</td>
<td>10¹¹</td>
<td>1</td>
<td>10²</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Photosphere</td>
<td>10¹⁷</td>
<td>10¹³</td>
<td>1</td>
<td>10³</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

Shocks: \( V/V_A > 1 \)

Alfven resonator: large \( \Sigma_P / \Sigma_A \), and large \( \text{grad} \Sigma_A \)

<table>
<thead>
<tr>
<th>Plasma type</th>
<th>( J (\text{A/km}) )</th>
<th>( \Sigma_P \text{ (mho)} )</th>
<th>( \Sigma_A \text{ (mho)} )</th>
<th>( E (\text{V/km}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionosphere (E)</td>
<td>10²</td>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Ionosphere (J)</td>
<td>10³</td>
<td>1</td>
<td>0.01</td>
<td>10³</td>
</tr>
<tr>
<td>Chromosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Q: Whether \( J = \Sigma E \) is important or not in the Sun?
2. What is different from MHD?

- Partially ionized plasma (3-comp. gas)
  - Neutral component represents the principal mass density (m<<M, n<<N)

\[ NM \frac{d\mathbf{v}_n}{dt} = -\nabla p + nM v_{in} (\mathbf{v}_i - \mathbf{v}_n) + nmv_{en} (\mathbf{v}_e - \mathbf{v}_n) + Nf_n \]

\[ nM \frac{d\mathbf{v}_i}{dt} = -\nabla p_i + ne (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - nM v_{in} (\mathbf{v}_i - \mathbf{v}_n) - nmv_{ie} (\mathbf{v}_i - \mathbf{v}_e) + nf_i \]

\[ nm \frac{d\mathbf{v}_e}{dt} = -\nabla p_e - ne (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - nmv_{en} (\mathbf{v}_e - \mathbf{v}_n) + nmv_{ie} (\mathbf{v}_i - \mathbf{v}_e) + nf_e \]
2. What is different from MHD?

Hall & Pedersen effects

This expression is “basic”, neglecting the inertia, pressure, and external forces.

\[ E = -v_n \times B + \eta \nabla \times B + \alpha (\nabla \times B) \times B - \beta \left[ (\nabla \times B) \times B \right] \times B \]

1. MHD induction
2. Ohmic resistive diffusion effect
3. Hall effect
4. Pedersen effect (ambipolar diffusion)

The 2nd 3rd and 4th terms involve rot B, which is smaller by O(1/L) than the 1st term, where L is the characteristic large scale of variation of B.

This is a possible modification from frozen-in MHD formulations, and the “Hall MHD” may be useful to understand the current carrier in M-I system.
2. What is different from MHD?

**Hall & Pedersen effects**

This expression is more “physical”, and more accurate than the “basic” one.

\[
E = -v_n \times B + \eta \nabla \times B + \frac{1}{ne} \left[ -\nabla p_e + (\nabla \times B) \times B \right] - (v_i - v_n) \times B \tag{6}
\]

The third term can be derived from collisionless electron gas without the inertia:

The **Hall effect** arises from the electric field required to hold very fast electrons in the company of the massive sluggish ions. In this approximation, the Hall effect is independent of the collisions.

The fourth term can be derived from momentum equations of ions and electrons assuming \( u \) and \( w \) are equal, while their slight difference provides the current:

The **Pedersen effect (ambipolar diffusion)** arises from all of the pressure gradients, the Lorentz force, and other forces, driving the ions and electrons through the neutral gas. The forced slippage of the ions and electrons relative to the neutral gas is opposed by the friction, with collision times \( \tau_i \) and \( \tau_e \).
3. How to model the ionosphere?

Ionospheric convection observed by SuperDARN
Research interest

- Magnetosphere-Ionosphere (M-I) coupling
  - The physics of M-I coupling enhances our knowledge about auroral substorms, geomagnetic storms, and many other interesting processes of the solar wind energy transfer into the atmosphere.
  - Partially ionized plasma contacting with MHD plasma naturally create feedbacks, instabilities, and equilibria via the self-consistent conductivity variations.
    - SAPS, IAR/IFI, GDI/FAI, and aurora acceleration
  - For a robust global MHD modeling of planetary power system, it is crucial to model the ionosphere self-consistently, especially during storm time.

3. How to model the ionosphere?
3. How to model the ionosphere?

Classical logic of M-I coupling

We did not know how to self-consistently couple M-I system for a long time.
3. How to model the ionosphere?

Self-consistent logic of M-I coupling

We are understanding how to self-consistently couple M-I system.
3. How to model the ionosphere?

**Hall & Pedersen conductivities**

We usually do not solve the Hall MHD eqs. because of fixed ambient B field. In the reference frame of zero neutral wind with magnetic field coordinates, the most important physical relationship in the ionosphere is the Ohm’s law.

\[
\mathbf{j} = \sigma_p \mathbf{E}_\perp - \sigma_H (\mathbf{E}_\perp \times \mathbf{b}) + \sigma_o \mathbf{E}_\parallel
\]

\[
\sigma_p = ne \left( \frac{b_i}{1 + \kappa_i^2} - \frac{b_e}{1 + \kappa_e^2} \right)
\]

**Pedersen conductivity**

\[
\sigma_H = \frac{ne}{B} \left( \frac{\kappa_e^2}{1 + \kappa_e^2} - \frac{\kappa_i^2}{1 + \kappa_i^2} \right)
\]

**Hall conductivity**

\[
\sigma_o = ne(b_i - b_e)
\]

\[
\kappa_j = \frac{\omega_{je}}{\nu_{jn}} = \frac{q_j B}{M_j \nu_{jn}} = B b_j
\]

**mobility coefficient**
3. How to model the ionosphere?

- Electrons always drift ($k_e > 1$)

---

**0827 UT, 12 August, 1991**

**a) Frequencies**
- $v_i$, $v_e$, $\Omega_i$, $\Omega_e$

**b) Mobility coefficients**
- $k_i$, $k_e$

**c) Conductivities**
- $\sigma_i$, $\sigma_p$, $\sigma_e$
3. How to model the ionosphere?

**Hall & Pedersen currents**

Pederssen currents basically connect to field-aligned currents (FACs) \( j_\parallel \). Hall currents basically close (circulate along ExB drift) in the ionosphere.

\[
\mathbf{j}_\perp = \sigma_P \mathbf{E}_\perp - \sigma_H (\mathbf{E}_\perp \times \mathbf{b})
\]

\[
\nabla \cdot \mathbf{j}_\perp = 0 \text{ with uniform conductivities}
\]

\[
\frac{\partial j_\parallel}{\partial Z} = -\sigma_P \nabla \cdot \mathbf{E}_\perp + \sigma_H \nabla \cdot (\mathbf{E}_\perp \times \mathbf{b})
\]

Height integrate

\[
j_\parallel = -\Sigma_P \nabla \cdot \mathbf{E}_\perp + \Sigma_H \nabla \cdot (\mathbf{E}_\perp \times \mathbf{b})
\]

Incompressible convection

\[
j_\parallel = -\Sigma_P \nabla \cdot \mathbf{E}_\perp
\]
3. How to model the ionosphere?

The Earth’s M-I current system

図5: 磁気圏・電離圏結合系における沿磁力線電流のクロージャを模式的に示した図.
4. Interesting phenomena?

• Neutral-ion coupling
  – Neutral wind dynamo, Jupiter M-I system

• Feedback 1: conductivity decrease
  – Density trough, subauroral polarization stream
    • ion chemistry, gradient drift instability

• Feedback 2: conductivity increase
  – Alfven resonator, feedback instability
    • kilometric radiation, ion outflow, Alfvenon
4. Interesting phenomena?

**Neutral Wind Dynamo**

Sq current system (Chapman and Bartels, 1949)

\[
\frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial J}{\partial \theta} \right) + \frac{1}{\sin \theta} \frac{\partial^2 J}{\partial \phi^2} = 2B_0 \Sigma_C \left[ \frac{\partial}{\partial \theta} \left( \sin \theta \cos \theta \frac{\partial \Psi}{\partial \theta} \right) + \cot \theta \frac{\partial^2 \Psi}{\partial \phi^2} \right]
\]

- \( J \): Stream function of horizontal dynamo current
- \( \Psi \): Stream function of neutral gas flow
- \( \Sigma_C = \Sigma_P + \frac{\Sigma_H^2}{\Sigma_P} \): Cowling conductivity

Effect of polarization E field:
No FAC & all currents close in the dynamo current layer.

neutral wind U  
E=UxB  
J_{dynamo}
Neutral-ion coupling at Jupiter

Torque transportation from planet to the magnetospheric plasma

M-I coupling via FAC

Neutral wind

Io

Angular momentum

Thermosphere/Ionosphere largely affected by the coupling system

Magnetospheric plasma

Electron precipitation

Magnetosphere

Acceleration

Neutral wind

Ionospheric plasma

Without M-I coupling

M-sphere acceleration

Total power

Joule heating

Ion drag

Interesting phenomena? Tao et al. (JGR 2009, in press)
Density trough during storms

4. Interesting phenomena?: Feedback 1: conductivity decrease

Low conductivity $\Sigma$ $\Rightarrow$ Stronger E-field

more frictional heating $\Rightarrow$ Lower conductivity

Possible feedback

$E = I_0 / \Sigma$
4. Interesting phenomena?: Feedback 1: conductivity decrease

**Atmospheric ion chemistry**

1. Dissociative recombination (molecular, fast): \( \text{NO}^+ + \text{e}^- \rightarrow \text{N} + \text{O} \)
2. Radiative recombination (atomic, slow): \( \text{O}^+ + \text{e}^- \rightarrow \text{O} + \text{photon} \)

\[
\kappa \times \text{eff} \times \text{N} \times \frac{m}{n} = \frac{m}{m+n} \left( \frac{m_i U^2}{3k_B} + T_i - T_n \right) + T_n
\]

\[
T_i = T_n + \frac{m_a U^2}{3k_B}
\]

\[
\alpha = \frac{\delta[O^+]}{[O^+]} = \left\{ k(T_{\text{eff}}) - k(T_n) \right\} [N_2] \delta t
\]

Reaction rate \( \kappa \) as a function of \( T_{\text{eff}} \)

St.Maurice and Laneville (1998)

Ion temperature due to ion frictional heating above 200 km

Schunk et al. (1975)

Density depression rate: significantly large when \( U > 1 \) km/s

Kataoka et al. (2003)
4. Interesting phenomena?: Feedback 1: conductivity decrease

Subauroral polarization stream (SAPS)

Magnetosphere (ring current) and ionosphere (trough) interaction to produce very strong electric field.

Kataoka et al. (GRL 2007)

Fig. 4. Latitudinal extent of westward flow enhancement. Empirical SAPS locations as estimated by Huang and Foster (2002) and Wang et al. (2008) are also shown as a function of $D_{st}$. Horizontal solid and dotted lines show the low-latitude boundaries of auroral electron precipitation and trapped ring current protons.

Kataoka et al. (AnGeo 2009)
4. Interesting phenomena?

Small-scale density irregularities are necessary for HF coherent backscatters of ~10 MHz (15m).

Ionospheric convection observed by SuperDARN
Gradient drift instability (GDI)

GDI occurs when the direction of the plasma drift is parallel to background density gradient. The linear growth rate is

$$\gamma_{\text{GDI}} = \nu \frac{\nabla n}{n}$$

GDI is a plausible candidate for the generation of field-aligned irregularities (FAI), which is necessary for HF coherent backscatters of ~10 MHz (15m).

The current convective instability (CCI), 3D version of GDI, is caused by the upward field aligned current (Ossakow and Chaturvedi, 1979).
4. Interesting phenomena?: Localized FAI production due to isolated convection vorties.

Transient F-region irregularities

Kataoka et al. (AnGeo 2003)
4. Interesting phenomena?: Feedback 2: conductivity increase

Ionospheric Alfven Resonator

Alfven waves resonate between the conductive ionosphere and sharp $V_A$ gradient.

Fig. 2. Alfven speed profiles for the numerical runs described in the text. The solid curve refers to the exponential Alfven speed profile shown in Figures 3-5. The dotted curve is for the exponential density profile whose spectrum is shown in Figure 6. The dashed curve refers to the density model which consists of an exponential plus a power law described in Figure 7.

Figure 1. The Alfven velocity in units of the speed of light, c, along the Jupiter-Io magnetic flux tube.

Lysak (JGR 1988)  Ergun et al. (JGR 2006)
4. Interesting phenomena?

Earth During Substorm

Ergun et al. (JGR 2006)

Jupiter-Io

Alfvén Waves

"S-Bursts"

AKR

Upward and Downward Currents

Reconnection Region

Plasma Sheet

Jupiter-Io

Alfvén Waves

S-Bursts Alfvén wave-dominated region.

DAM

Io

Near steady-state current systems.
4. Interesting phenomena?: Feedback 2: conductivity increase

**Ionospheric Alfven Resonator**

Ionosphere as a wave amplifier.

\[ f_0 = \frac{V_{AI}}{2\pi h} \]

Q: How about the solar atmosphere?

**Fig. 1.**—Coronal Alfven speed as a function of heliocentric distance. The three curves are calculated using a magnetic field of \( B = 1.7 \left( \frac{R_\odot}{R} \right)^3 + 1.3 \left( \frac{R_\odot}{R} \right)^2 \) G and the density models of Saito et al. (1977) (solid curve), Sittler & Guhathakurta (1999) (dashed curve), and Newkirk (1967) (dot-dashed curve).

**Fig. 2.**—Alfven speed profiles for the numerical runs described in the text. The solid curve refers to the exponential Alfven speed profile shown in Figures 3-5. The dotted curve is for the exponential density profile whose spectrum in shown in Figure 6. The dashed curve refers to the density model which consists of an exponential plus a power law described in Figure 7.

4. Interesting phenomena?: Feedback 2: conductivity increase

**Ionospheric feedback instability**

*Lysak and Song (JGR 2002)*

**Ionosphere**

\[ j_z = -\nabla \cdot (\Sigma P E_\perp - \Sigma H E_\perp \times \mathbf{b}) \]

\[ S_P = f(j_z) \]

feedback when more \( \Sigma P \), more \( j_z \)

\[ \frac{\partial \Sigma P}{\partial t} + (u_E \cdot \nabla) \Sigma P = S_P - R_P (\Sigma P^2 - \Sigma P_0^2) \]

**Magnetosphere**

\[ Z_{\text{pure}} = \frac{1}{\Sigma_A} \]

\[ Z_{\text{resonator}} \sim \frac{iJ_0 (2 \omega / V_{AI})}{\Sigma_{AI} iJ_1 (2 \omega / V_{AI})} \]

holds if \( V_{AI} / V_{AM} \ll 1 \)

\[ \delta j_z = -\frac{\Sigma_A}{\Sigma_A + \Sigma P_0} \mathbf{I}_\perp \cdot \nabla \frac{\delta n}{n_0} \]

week feedback in the limit \( \Sigma_A / \Sigma P_0 \ll 1 \)
4. Interesting phenomena?: Feedback 2: conductivity increase

**Ionospheric feedback instability**

Lysak and Song (JGR 2002)

The ionospheric feedback instability (IFI) can excite eigenmodes of both field line resonance (FLR) and IAR, producing narrow-scale structures.

The free energy for instability comes from the reduction of Joule heating due to self-consistent changes in ionization of Alfvénic perturbations.

Necessary condition for instability is

\[
\frac{\gamma k_\perp \cdot u_d}{V_{AI} / 2h} > 2.4
\]

scale height above the ionosphere

\[
\Sigma_{P,H} = n e \Delta z \mu_{P,H}
\]

ionosphere height

relative drift velocity between electrons and ions

\[
u_d = \mu_p E_\perp - \mu_H E_\perp \times \hat{b}
\]

number of electron-ion pairs produced per incident electron

\[
\gamma = 1 + e \Phi || / E_0
\]
4. Interesting phenomena?: Feedback 2: conductivity increase

**Ionospheric Alfven Resonator**

Potential role of IAR + feedback instability for substorm triggering??

very fast growth rate of ~10sec

![Image of THEMIS ASI images showing a substorm auroral breakup on February 22, 2006.](image)

**Figure 1.** A sequence of THEMIS ASI images showing a substorm auroral breakup on February 22, 2006.

Liang et al. (GRL 2008)
4. Interesting phenomena?
- ionospheric role for plasma explosion -

E// production when \( v_d > v_{\text{critical}} \)

Figure 8. (a) Altitude distribution of field-aligned electric field derived from magnetic mirror process by Chiu and Schulz [1978]. (b) Altitude profile of drift velocity of FAC electron [Morioka et al., 2005]. (c) Altitude profile of Alfvén velocity. Curves (b) and (c) are based on the empirical electron density model along the \( L = 7 \) field line.

Morioka et al. (JGR 2008)
4. Interesting phenomena?: Ionosphere as plasma source

**AKR and upflowing ions**

Kumamoto et al. (JGR 2003)

Upflowing ions from ionosphere changes the ambient temperature and density, and control the unstable conditions of plasma waves for aurora accelerations.
4. Interesting phenomena?: contribution for setting a powerful acceleration system.

Alfvenon


- Powerful 1-step acceleration
  - aurora inverted V (ion inertia)
  - arc element (electron inertia)
- Fast-mode alfvenon
  - negative potential is capable of keV aurora & 100 keV flares.
- Slow-mode alfvenon
  - positive potential creates 300-800 km/s solar wind ions.

Q: They assumed the existence of this U-shape potential (zero potential across B). Highly conductive chromosphere??, or particular current closure in the Sun??
4. Interesting phenomena?

K. Stasiewicz and J. Ekeberg. Alfvénons and dispersive MHD waves

**Fig. 3.** Electric field, $E_x/V_A B_0$, and positive potential, $\Phi/\Phi_A$, for a slow alfvenon obtained by integration of nonlinear equations for $\beta=10^{-4}$, $\gamma=5/3$, $M=8 \times 10^{-4}$, $\cos \alpha=0.03$.

**Table 1.** Characteristic potential $\Phi_A = B_0 V_A \lambda_i$ [kV] for plasma conditions above the auroral region.

<table>
<thead>
<tr>
<th>$N$ [cm$^{-3}$]</th>
<th>$B_0$ [nT]</th>
<th>$E_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^3$</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>$10^2$</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>$10^1$</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>$10^0$</td>
<td>5000</td>
<td>50</td>
</tr>
</tbody>
</table>

**Fig. 4.** A sequence of two fast alfvenons (convergent electric field structures) obtained by integration of nonlinear equations for $M=0.95$, $R_m=0$ (other parameters as in Fig. 3). Such alfvenons could correspond to multiple auroral arcs.

**Table 2.** Characteristic potential $\Phi_A$ [kV] for plasma conditions in the solar corona.

<table>
<thead>
<tr>
<th>$N$ [cm$^{-3}$]</th>
<th>$B_0$ [G]</th>
<th>$E_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{11}$</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>$10^{10}$</td>
<td>5000</td>
<td>50</td>
</tr>
<tr>
<td>$10^{09}$</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>$10^{08}$</td>
<td>5000</td>
<td>50</td>
</tr>
</tbody>
</table>
One-step acceleration by $E_{//}$

• Within the two-fluid model, $E_{//}$ can easily be obtained from generalized Ohm’s law

$$E_{//} = \eta J_{//} - \frac{\nabla_{//} p_{//}^e}{N_e} - \left( \frac{p_{\perp e} - p_{//}^e}{N_e} \right) \frac{(\nabla B)_{//}}{B} + \frac{m_e}{N e^2} \left[ \nabla \cdot (V_{//} J_{//} + J_{//} V_{//}) + \frac{\partial J_{//}}{\partial t} \right]$$

– anomalous resistivity
– electron pressure gradient along B
– magnetic mirror force on anisotropic Pe
– electron inertial effect

4. Interesting phenomena?
Summary

• The Earth’s ionosphere is introduced in terms of M-I coupling power system.
  – Fundamental formulations, parameters, etc.
  – Interesting phenomena such as neutral-ion coupling, conductivity feedbacks, etc.

• Many questions arise for today.
  – Neutral-ion coupling in other stars?
  – SAPS, IAR, and E// in other stars?
Appendix 1

Equations (cgs) of Parker (2007): “Conversations on electric and magnetic fields in the cosmos”
Weakly ionized plasma

- Three-component gas approximation
  - Neutral component represents the principal mass density \(m<<M, n<<N\)

\[
NM \frac{dv}{dt} = -\nabla p + \frac{nM(w-v)}{\tau_i} + \frac{nm(u-v)}{\tau_e} + NF \tag{1}
\]

\[
nM \frac{dw}{dt} = -\nabla p_i + ne \left( E + \frac{w \times B}{c} \right) - \frac{nM(w-v)}{\tau_i} - \frac{nm(w-u)}{\tau} + nf_i \tag{2}
\]

\[
nm \frac{du}{dt} = -\nabla p_e - ne \left( E + \frac{u \times B}{c} \right) - \frac{nm(u-v)}{\tau_e} + \frac{nm(w-u)}{\tau} + nf_e \tag{3}
\]
Hall/Pedersen effects

This expression is “basic”, neglecting the inertia, pressure, and external forces.

\[
E = \frac{B}{c} (-v \times b + \eta \nabla \times b + \alpha L - \beta L \times b)
\]  

(4)

\[
L = \frac{(\nabla \times b) \times b}{4\pi}
\]

Lorenz force

(5)

\[
\alpha = cB \frac{M / \tau_i - m / \tau_e}{4\pi neQ}
\]

Hall coefficient, where \( Q = \frac{M}{\tau_i} + \frac{m}{\tau_e} \)

\[
\beta = \frac{B^2}{4\pi nQ}
\]

Pedersen coefficient (ambipolar diffusion)

\[
\eta = \frac{c^2}{4\pi ne^2} \left[ \frac{m}{\tau} + \frac{(m / \tau_e)(M / \tau_i)}{Q} \right]
\]

Ohmic resistive diffusion coefficient
Hall/Pedersen effects

This expression is “physical”, and more accurate than “basic”.

\[
E = -\frac{v \times B}{c} + \eta \nabla \times B + \frac{1}{ne} \left[ -\nabla p_e + \frac{(\nabla \times B) \times B}{4\pi} \right] - \frac{(w - v) \times B}{c}
\]  

(6)

The third term can be derived from collisionless electron gas without the inertia:

The **Hall effect** arises from the electric field required to hold very fast electrons in the company of the massive sluggish ions. In this approximation, the Hall effect is independent of the collisions.

The fourth term can be derived from (2)+(3) assuming \( u \) and \( w \) are equal, while their slight difference provides the current:

The **Pedersen effect (ambipolar diffusion)** arises from all of the pressure gradients, the Lorentz force, and other forces, driving the ions and electrons through the neutral gas. The forced slippage of the ions and electrons relative to the neutral gas is opposed by the friction, with collision times \( \tau_i \) and \( \tau_e \).
Appendix 2

IAR materials

Ergun et al. (JGR 2006)
Hirano, Fukunishi, Kataoka et al. (JGR 2005)
Hasunuma, Nagatsuma, Kataoka et al. (JGR 2009)
Figure 2. Observation of electron acceleration associated with an the ionospheric Alfvén resonator. (a) The measured magnetic field, minus the Earth’s model field, perpendicular to the Earth’s model field at ~5 Hz frequency band. (b) Antiearthward (150° to 210° in pitch angle) electron energy flux versus energy and time at 79 ms resolution. (c) earthward (−30° to 30° in pitch angle) electron energy flux versus energy and time at 79 ms resolution.
Meso-scale FAC

Figure 3. Polar distributions of mesoscale FACs in (left) summer, (middle) equinox, and (right) winter. The format and the data period used for statistical analysis are the same as those used in Figure 2.

Figure 6. Polar distributions of mesoscale FACs for three ranges of altitude: (left) 3000–6000 km, (middle) 6000–8000 km, and (right) 8000–10,500 km. The format is the same as that used in Figure 4.
Figure 11. Statistical Alfvén velocity profiles and plasma density profiles in the region of 70°–80° in ILAT and 0600–0900 in MLT obtained from Akebono PWS data for the period from April 1989 to March 1992. The left plot shows the Alfvén velocity profiles, while the right plot shows the plasma density profile with the data number. Red lines show the profiles under the sunlit condition (solar zenith angle < 75°), while blue lines show those under the dark condition (solar zenith angle > 105°). Error bars show the standard deviation (1σ) of the statistical data.
Appendix 3

Alfvenon

Stasiewicz and Ekeberg

Linear dispersion equation within the two-fluid model

\[ k^2 \lambda_i^2 = \frac{(AM_{||}^{-2} - D_M)(A + R_a M_{||}^2 \sin^2 \alpha)}{R_m(2A - M_{||}^2 D_M) - 1} \]

\[ A = M_{||}^2 - 1, \quad D_M = \sin^2 \alpha / (M^2 - \gamma \beta / 2) \]

\[ M = \omega / kV_A, \quad M_{||} = M / \cos \alpha \]

Branches: Alfvén, kinetic Alfvén, electron inertial Alfvén, magnetoacoustic, acoustic, ion cyclotron, lower hybrid, whistler waves
Fig. 1. Wave modes in a cold two-fluid plasma with $\beta=10^{-5}$, $\gamma=5/3$, $R_m=1/1836$, $R_e=0$ obtained with Eq. (35). The upper part shows the color coded logarithm of inverse wavelength $\lambda_i/\lambda$ with marked wavelengths $\lambda_i$ (magenta), and $\lambda_e$ (black).

Fig. 2. Wave modes in a warm two-fluid plasma with $\beta=10^{-2}$ obtained with Eq. (35). Other parameters as in Fig. 1. The crossover position with kinetic modes ($A^+, IC^+, S^+$) is at $\cos^2\alpha=\gamma\beta/2$. 
Fig. 6. An example of bursty ion flows measured by Cluster in the magnetotail at \((-16.7, -9.6, -1.8)\) $R_E$ GSE (geocentric solar ecliptic) coordinates. These flows can produce magneto sonic and Alfvén waves carrying Poynting flux toward the ionosphere with power sufficient to drive auroral phenomena.
Appendix 4

Jupiter satellites’ parameters
Kivelson et al.
## Table 21.1: Physical properties of the Galilean satellites and surrounding plasma.

<table>
<thead>
<tr>
<th>Symbol (units), Physical property</th>
<th>Io</th>
<th>Europa</th>
<th>Ganymede</th>
<th>Callisto</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_\phi(nT)$, jovian magnetic field, av. min (max)</td>
<td>1720 (2080)</td>
<td>370 (460)</td>
<td>64 (113)</td>
<td>4 (42)</td>
<td>1</td>
</tr>
<tr>
<td>$n_e(\text{elms cm}^{-3})$, Eq. av. (range) eln. density</td>
<td>2500 (1200-3800)</td>
<td>200 (18-250)</td>
<td>5 (1-10)</td>
<td>0.15 (0.01-0.70)</td>
<td>2</td>
</tr>
<tr>
<td>$&lt; Z &gt;$, Eq. av. (lobe) ion charge</td>
<td>1.3 (1.3)</td>
<td>1.5 (1.5)</td>
<td>1.3 (1)</td>
<td>1.5 (1)</td>
<td>3</td>
</tr>
<tr>
<td>$&lt; A &gt;$, Eq. av. (lobe) ion mass in $m_p$</td>
<td>22 (19)</td>
<td>18.5 (17)</td>
<td>14 (2)</td>
<td>16 (2)</td>
<td>3</td>
</tr>
<tr>
<td>$n_i(\text{ions cm}^{-3})$, av. (range) ion no. density</td>
<td>1920 (960-2900)</td>
<td>130 (12-170)</td>
<td>4 (1-8)</td>
<td>0.10 (0.01-0.5)</td>
<td>3</td>
</tr>
<tr>
<td>$\rho_m(\text{amu cm}^{-3})$, av. (range) ion mass density</td>
<td>42300 (18000-64300)</td>
<td>2500 (200-3000)</td>
<td>54 (2-100)</td>
<td>1.6 (0.02-7)</td>
<td>3</td>
</tr>
<tr>
<td>$\delta T_1$; (eV), equator (range) ion temperature</td>
<td>70 (20-90)</td>
<td>100 (50-400)</td>
<td>60 (10-100)</td>
<td>60 (10-100)</td>
<td>3</td>
</tr>
<tr>
<td>$\delta T_e$(eV), electron temperature</td>
<td>6</td>
<td>100</td>
<td>300</td>
<td>500</td>
<td>4</td>
</tr>
<tr>
<td>$p_{\text{th}}$(nPa), Eq. (range) pressure thermal plasma</td>
<td>22 (3-42)</td>
<td>2.1 (0.1-11)</td>
<td>0.04 (0.002-0.12)</td>
<td>0.001 (0.00-0.01)</td>
<td>3</td>
</tr>
<tr>
<td>$p_{\text{eu}}$(nPa) (20 keV-100 MeV ions)</td>
<td>10</td>
<td>12</td>
<td>3.6</td>
<td>0.37</td>
<td>5</td>
</tr>
<tr>
<td>$p_e$(nPa) (both &quot;cold&quot; and &quot;hot&quot; electrons)</td>
<td>2.4</td>
<td>3.2</td>
<td>0.2</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>$p$(nPa), Eq. (max) total pressure</td>
<td>34 (54)</td>
<td>17 (26)</td>
<td>3.8 (3.9)</td>
<td>0.38 (0.39)</td>
<td>3, 5</td>
</tr>
<tr>
<td>$v_{cr}$(km s$^{-1}$), local corotation velocity</td>
<td>74</td>
<td>117</td>
<td>187</td>
<td>328</td>
<td>6</td>
</tr>
<tr>
<td>$v_{ls}$(km s$^{-1}$), satellite orbit velocity</td>
<td>17</td>
<td>14</td>
<td>11</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>$v_{pl}$,(km s$^{-1}$) plasma azimuthal vel. (range)</td>
<td>74 (70-74)</td>
<td>90 (70-100)</td>
<td>150 (95-163)</td>
<td>200 (130-280)</td>
<td>7</td>
</tr>
<tr>
<td>$a$(km s$^{-1}$), relative velocity (range), $v_{pl}t$ $v_s$</td>
<td>57 (53-57)</td>
<td>76 (56-86)</td>
<td>139 (84-152)</td>
<td>192 (122-272)</td>
<td>6</td>
</tr>
<tr>
<td>$v_A$(km s$^{-1}$), Eq. (range) Alfven speed</td>
<td>180 (150-340)</td>
<td>160 (145-700)</td>
<td>190 (130-1700)</td>
<td>70 (30-6500)</td>
<td>8</td>
</tr>
<tr>
<td>$c_s$(km s$^{-1}$), Eq. (range) Alfvén speed</td>
<td>29 (27-53)</td>
<td>92 (76-330)</td>
<td>280 (100-1400)</td>
<td>500 (230-1400)</td>
<td>9</td>
</tr>
<tr>
<td>$P_{\phi}^{2}/2\mu_0$(nPa), Eq. (lobe) magnetic pressure</td>
<td>1200 (1700)</td>
<td>54 (84)</td>
<td>1.6 (5)</td>
<td>0.006 (0.7)</td>
<td>1</td>
</tr>
<tr>
<td>$\rho u^2$(nPa), Eq. (max) ram pressure</td>
<td>230 (350)</td>
<td>24 (38)</td>
<td>1.7 (4.1)</td>
<td>0.10 (0.90)</td>
<td></td>
</tr>
<tr>
<td>$\rho u^2$(nPa), lobe ram pressure</td>
<td>100</td>
<td>2.5</td>
<td>0.08</td>
<td>0.002</td>
<td></td>
</tr>
</tbody>
</table>
Table 21.1 - continued Physical properties of the Galilean satellites and surrounding plasma.

<table>
<thead>
<tr>
<th>Symbol (units), Physical property</th>
<th>Io</th>
<th>Europa</th>
<th>Ganymede</th>
<th>Callisto</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_z)(nT), maximum satellite surface field</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>1500</td>
<td>&lt;40</td>
<td>10</td>
</tr>
<tr>
<td>(\Sigma_A(S) = \langle \mu_0 v_A \rangle^{-1}), Alfvén cond. Eq. (range)</td>
<td>4.4 (2.4-5.4)</td>
<td>4.9 (1.1-5.5)</td>
<td>4.2 (0.5-6)</td>
<td>12 (0.1-25)</td>
<td>11</td>
</tr>
<tr>
<td>(\Sigma_D(S), \text{av. (max)}) ionsph. Pedersen cond</td>
<td>~200</td>
<td>~30</td>
<td>2</td>
<td>~1000</td>
<td>11</td>
</tr>
<tr>
<td>(\Sigma_H(S), \text{av. (max)}) ionsph. Hall cond</td>
<td>100-200 (1200)</td>
<td>~10</td>
<td>0.1</td>
<td>~&lt;10000</td>
<td>11</td>
</tr>
<tr>
<td>(M/m_i)(s^{-1}), ions per s added locally to flow</td>
<td>10^{28}</td>
<td>&lt;6 \times 10^{26}</td>
<td>&lt;6 \times 10^{26}</td>
<td>&lt;5 \times 10^{25}</td>
<td>12</td>
</tr>
</tbody>
</table>

Characteristic frequencies and gyroradii

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Io</th>
<th>Europa</th>
<th>Ganymede</th>
<th>Callisto</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_p)(kHz), av. (range) electron plasma freq.</td>
<td>450 (310-550)</td>
<td>130 (38-140)</td>
<td>20 (9-28)</td>
<td>3.5 (0.9-7.5)</td>
</tr>
<tr>
<td>(f_D)(Hz), av. (range) plasma freq. mass (m_i) ion</td>
<td>2500 (1900-5700)</td>
<td>850 (260-4300)</td>
<td>140 (150-4200)</td>
<td>25 (15-7300)</td>
</tr>
<tr>
<td>(f_{ce})(kHz), Eq. (lobe) electron cyclotron freq.</td>
<td>48 (58)</td>
<td>10 (13)</td>
<td>1.8 (3.2)</td>
<td>0.11 (1.2)</td>
</tr>
<tr>
<td>(f_{ci})(Hz), Eq. (lobe) cyclotron freq. mass (m_i) ion</td>
<td>1.5 (2.0)</td>
<td>0.5 (0.6)</td>
<td>0.08 (0.9)</td>
<td>0.01 (0.3)</td>
</tr>
<tr>
<td>(\rho_{\text{th}}) thermal ions gyroradii (km) Eq. (lobe)</td>
<td>1.8 (1.6)</td>
<td>8 (12)</td>
<td>36 (13)</td>
<td>530 (34)</td>
</tr>
<tr>
<td>(\rho_{e,pu}) pickup ions gyroradii (km) Eq. (lobe)</td>
<td>3.0 (2.5)</td>
<td>19 (15)</td>
<td>200 (110)</td>
<td>4200 (400)</td>
</tr>
</tbody>
</table>

Table 21.2. Dimensionless parameters characterizing plasma-satellite interactions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Io</th>
<th>Europa</th>
<th>Ganymede</th>
<th>Callisto</th>
<th>Titan</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_A = u/v_A) equator (range)</td>
<td>0.31 (0.16-0.39)</td>
<td>0.47 (0.08-0.59)</td>
<td>0.73 (0.05-1.1)</td>
<td>2.8 (0.62-8.5)</td>
<td>1.9</td>
</tr>
<tr>
<td>(M_s = u/c_s) (range)</td>
<td>2.0 (1.0-2.1)</td>
<td>0.9 (0.16-1.1)</td>
<td>0.5 (0.06-0.8)</td>
<td>0.4 (0.03-1.2)</td>
<td>0.57</td>
</tr>
<tr>
<td>(M_t = u/(v^2_A + c_s^2)^{1/2}) (range)</td>
<td>0.31 (0.16-0.38)</td>
<td>0.42 (0.07-0.52)</td>
<td>0.42 (0.04-0.66)</td>
<td>0.39 (0.02-1.2)</td>
<td>0.55</td>
</tr>
<tr>
<td>(v_A/v_{cr})</td>
<td>1.0</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>(\theta_A) (degrees) (range)</td>
<td>17 (9-21)</td>
<td>25 (4.5-30)</td>
<td>36 (3-48)</td>
<td>70 (1-83)</td>
<td>62</td>
</tr>
<tr>
<td>(\beta = p/(B^2/2\mu_0)) (lobe)</td>
<td>(\sim 0.32)</td>
<td>(\sim 0.32)</td>
<td>2.4 (0.8)</td>
<td>64 (0.6)</td>
<td>11</td>
</tr>
<tr>
<td>(\Sigma_p)(av.g)/(\Sigma_A)(eq)</td>
<td>(\sim 45)</td>
<td>6</td>
<td>0.5</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>(M/\rho_{\mu r_2}) (range)</td>
<td>1-3</td>
<td>1.3</td>
<td>5-500</td>
<td>4-4000</td>
<td>(&lt;600)</td>
</tr>
<tr>
<td>(B_{surf}/B_{bg}) (range)</td>
<td>&lt;0.02</td>
<td>&lt;0.15</td>
<td>13-23</td>
<td>(&lt;1-10)</td>
<td>(&lt;2.3)</td>
</tr>
<tr>
<td>(\rho_{g,pu}/r_s) (range)</td>
<td>0.0014-0.0016</td>
<td>0.010-0.012</td>
<td>0.01-0.08</td>
<td>0.16-1.73</td>
<td></td>
</tr>
</tbody>
</table>