The Giant Planets as Unique Laboratories for Space Plasma Processes

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Credit: NASA
Auroras of the giant planets

Jupiter
Saturn
Uranus

Earth-based telescopes
Spacecraft
Why do we care about the auroras of the giant planets?

**Magnetospheres and Atmospheres**

- The aurora provides the essential context to understand the dynamics of magnetospheres

**"Energy Crisis"**

- Jupiter’s upper atmosphere is ~ 700 K or ~4.5× hotter than predicted by solar radiation models
- Saturn, Uranus, and Neptune are ~2.5×, ~5.8×, and ~4.5× hotter than predicted
- The upper atmosphere is predominantly heated by the redistribution of auroral energy

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Seiff et al., 1997

O’Donoghue et al., 2021
Juno’s Unique View of Jupiter’s Aurora

Credit: HST
The Magnetosphere of Jupiter

Credit: Szalay, Smith & Smith
Electron Acceleration Mechanism (Peaked)

Electric Potentials (theorized as cause of peaked distributions via electrostatic acceleration)

• Quasi-static potential structures accelerate auroral particles parallel to the magnetic field. Each electron gains the same amount of energy $q\Phi$
• These potential structures develop when there are not enough charge carriers (i.e., low electron density)
• Strong electric fields accelerate electrons to compensate for their scarcity, in order to balance $\nabla \times B$ imposed by the magnetosphere

Recent statistics have shown that broadband distributions are much more common than monoenergetic distributions on main auroral field lines

Cannot be explained by a quasi-static energization mechanism

Electrostatic (inverted V) and time-dependent (broadband) acceleration over Jupiter’s upward auroral zone (Zone-I) [Mauk et al., 2020]
A Brief Introduction to Plasma Waves

- Due to the presence of long-range forces, various types of waves can exist in a plasma that have no counterpart in ordinary gases or dielectric media
  - In the absence of collisions, this is by virtue of electric and magnetic fields, as well as various charged particle species supported by a plasma
- One of the most fundamental plasma waves is the electron plasma frequency, $\omega_{pe}$ (the Langmuir wave)
  - When electrons are displaced relative to the ions, an electric field is set up to restore charge neutrality
  - The inertia means the response of the system is harmonic
  - The electric field is therefore oscillating, with a natural frequency, $\omega_{pe}$ that is proportional to the square root of electron number density, $\sqrt{n_e}$
  - Therefore, $n_e$ can be inferred by simply measuring the frequency of the oscillating electric field

- The properties of a given plasma wave is encoded in its dispersion relation. This requires that a relationship between frequency, wavelength, and direction must be satisfied for a wave to exist. For example, a propagating Langmuir wave has a dispersion relation given by $\omega^2 = \omega_p^2 + 3k^2v_{th}^2$

Linear response of the plasma to small perturbations
Basic Principles of Wave-Particle Interaction (1)

- The collisionless nature of space plasmas would imply that there is virtually no dissipation.
- Wave-particle interactions introduce finite dissipation in a collisionless plasma.
- They are thought to be play an important role in the dynamics of the radiation belts, auroral acceleration regions, magnetopause boundary layers, shock heating, etc.

- Wave-particle interaction becomes possible when a wave frequency felt by a particle is Doppler shifted by the velocity of the particle. Resonance occurs when the Doppler-shifted frequency is at the cyclotron frequency, or its harmonics, i.e., \( \omega - k_{\|}v_{\|} = n\omega_c \).
  - A special case is Landau resonance, where \( n = 0 \).

Maxwellian plasma.  
Wave will always suffer damping.

Beam-plasma system.  
Resonance possible.
Another special case worth noting is **cyclotron resonance**, where \( n = \pm 1 \)

Normal cyclotron resonance \((n = +1)\) occurs when an ion/electron interacts with a left/right-handed wave, i.e., the particle gyrates in the same sense as the wave’s oscillating electric field.

Anomalous cyclotron resonance \((n = -1)\) occurs when an ion/electron interactions with a right/left-handed wave, i.e., the particle gyrates in the opposite sense as the wave’s oscillating electric field.

Distortions in particle distribution functions are unstable to plasma waves. Plasma waves act to smear out the distortions. This could be via heating (spreading out in velocity space), accelerating, and/or pitch angle scattering (reducing anisotropy).
**Cassini’s and Juno’s plasma wave instruments**

- E-fields over a frequency range up to 16 MHz
- B-fields over a frequency range up to 12 kHz

Gurnett et al. (2005), *Science*

- E-fields over a frequency range up to 41 MHz
- B-fields over a frequency range up to 20 kHz

Definition: Jupiter’s Auroral Zones

- The various auroral zones of Jupiter were first explicitly defined from energetic electron spectra (Mauk et al., 2020)
  - Diffuse aurora:
    - Most equatorward and broadest in latitude
    - Electron intensities greater outside the loss cone (trapped) than inside the loss cone
    - Electron intensities within the loss cone are predominantly downward (precipitating)
  - Zone-I
    - Intermediate and narrow in latitude
    - Brightest in UV
    - Electron intensities greatest in the downward loss cone
  - Zone-II
    - Poleward and narrow in latitude
    - Bright in UV (by contrast with “black” aurora at Earth and Saturn)
    - Electron intensities comparable in both upward and downward loss cones

General Plasma Properties (low altitude)

\[
\begin{align*}
|B| & \sim O(10^5) \text{nT} \\
\nu_e & \sim O(10^{-3} - 10^{-2}) \text{ cm}^3 \\
T_e & \sim O(10^3 - 10^4) \text{ eV} \\
f_{ce} & \sim O(10^6) \text{ Hz and } f_{ci} \sim O(10^5) \text{ Hz} \\
f_{pe} & \sim O(10^3 - 10^4) \text{ Hz} \\
\lambda_e & \sim O(1 - 10) \text{ km} \\
v_A & \rightarrow \epsilon
\end{align*}
\]
Electron Acceleration Mechanisms (Broadband)

- Broadband energization calls upon a time-dependent/stochastic mechanism
- Broadband acceleration of electrons requires that the parallel electric field vary over the time it takes the electrons to pass through the acceleration region

1. Alfvén waves
   - Alfvén waves develop a $E_{\parallel}$ when electron mass is accounted for, which serves to accelerate electrons
   - Jupiter’s magnetosphere is full of disturbances that propagate in the form of Alfvén waves and these travel along magnetic field lines to higher latitudes where they can accelerate electrons

2. Whistler-mode waves
   - Whistler-mode waves grow and then undergo damping as they accelerate electrons
   - Whistler-mode waves are commonly observed in auroral regions of planetary magnetospheres

Propagation and dissipation of Alfvén waves in Jupiter's magnetosphere [Saur et al., 2003; 2018]

Growth and damping of whistler-mode waves in Jupiter's auroral zones [Elliott et al., 2018]
Density depletions above the aurora

Ordinary (O) mode waves have a low-frequency cutoff at the electron plasma frequency, 

\[ f_{pe} [\text{Hz}] = 8980 \sqrt{n_e} [\text{cm}^{-3}] \]
Density depletions above the aurora

The whistler mode cannot propagate above $f_{pe}$, leaving Alfvén waves as the leading candidate for broadband acceleration.

However, strong observational evidence for Alfvénic acceleration remains premature.

Sulaiman et al., 2022
Fields and Particles in Zone I

- **O-mode**
- **ICW (H+)**
- **ICW (H3+)**
- **Alfvénic fluctuations**
- **Upward FAC**
- **Downward FAC**

**Images and Graphs:**
- Diagram showing spatial distribution with labels for diffuse, Z-I, Z-II, and PC.
- Graphs illustrating spectral analysis with frequency and energy flux plots.
Electron acceleration: More on Alfvén Waves

Development of $E_\parallel$ due to the electron inertial effect. For a plane wave

$$\frac{E_\parallel}{E_\perp} = \frac{k_\parallel k_\perp \lambda_e^2}{1 + k_\perp^2 \lambda_e^2}$$

This parallel electric field increases with $k_\perp \lambda_e$

- Low $n_e$ increases $\lambda_e (= c/2\pi f_{pe})$
- $k_\perp$ increases due to plasma turbulence cascading energy from larger to smaller scales (e.g., Saur et al., 2003; 2018)
- Phase mixing due to gradients in the Alfvén speed can lead to smaller wavelengths thus increasing $k_\perp$ (Lysak et al., 2021)

The conditions are ripe for the development of a large parallel electric field. The wave can interact with electrons resonantly or non-resonantly.

Saur et al. (2018) estimated an energization of 0.7 MeV over 1 R_j

The lack of appreciable Alfvén wave power in the low-altitude (0.6 – 1.6 R_j) auroral zones supports the possibility Landau damping at higher altitudes. This is reinforced by the presence of Alfvénic fluctuations reported at much higher altitudes (> 10 R_j) that map to the main emissions (Lorch et al., 2022)
Ion acceleration in Zone-I

Persistent ionospheric H\(^+\) accelerated over Zone-I at a rate of 1-5 kg s\(^{-1}\) [Szalay et al., 2021]

- H\(^+\) energy distributions are peaked and pitch angles are highly collimated along the magnetic field away from Jupiter
- This indicates electrostatic acceleration by electric potentials above Zone-I
- In order to be admitted into potential structures in higher altitudes, ionospheric ions must be energized to above Jupiter’s gravitation binding energy
- Presence of upward propagating H\(^+\) and H\(_3^+\) cyclotron waves (ICWs) suggest transverse heating of ionospheric ions which develop a parallel velocity via the action of mirror forces (conservation of the first adiabatic invariant)
- Electrostatic acceleration found to be suppressed when electron broadband acceleration occurs [Mauk et al., 2020]

Ionospheric H\(^+\) accelerated away from Jupiter along auroral field lines. The peak H\(^+\) outflow maps to Zone I [Szalay et al., 2021]
How are auroral density cavities maintained?

Density gradients

Incoming large-scale Alfvén waves

“Initial” shallow density gradient due to ionospheric inhomogeneity or ponderomotive effect

Density gradient steepened and auroral cavity deepens through positive feedback

Production of small-scale Alfvén and (secondary) ion cyclotron waves

Steeper density gradients

Production of small-scale Alfvén waves

Phase mixing and refraction

Quasi-neutrality required

Cold ionospheric electrons dragged out

Stimulating ion outflow via transverse heating

Positive feedback mechanism

Chaston et al., 2006
Density depletions above Zone II

Phase speed of a transverse mode in a cold unmagnetized plasma

\[ v_p = \frac{\omega}{k} = \frac{c}{\sqrt{1 - \frac{\omega_{pe}^2}{\omega^2}}} \]

Phase speed can be related to E and B fluctuations using Fourier’s representation of Faraday’s law

\[ ik \times \vec{E} = -(-i\omega)\vec{B} \]

\[ v_p = \frac{\omega}{k} = \frac{\vec{E}_z}{\vec{B}_y} \]

Sulaiman et al., 2023
Jupiter’s aurora: The present

Sulaiman et al., 2022
Shock waves in the Universe

Shock waves

Size & Strength

CME/IPS

Planets & Comets

Supernovae

Heliosphere

Heliocentric Distance
Collisionless Shock Waves (Basic Principles)

- Energetic particles
- Shock
- Kinetic energy
- Thermal energy
- Electromagnetic energy

Super-magnetosonic, $M_f > 1$

Sub-magnetosonic, $M_f < 1$
(by definition)

Irreversible "heating"
The solar wind conditions near the Gas Giants

Sulaiman et al. (2017b), Springer International Publishing
Parameter Space at Saturn

$M_A$ Parameter Space at Saturn (cont’d)


Masters et al. (2013), *Nature Physics*
Ion Reflection

Zank et al., 1996
Credit: ESA
Ion Reflection
Timescale of Specular Reflection

\[(2 \cos^2 \theta_{Bn} - 1) \frac{2\pi}{\tau} t^* + 2 \sin^2 \theta_{Bn} \sin \left( \frac{2\pi}{\tau} t^* \right) = 0\]

- \(t^*\) is the time of first re-encounter with the shock after specular reflection
- Solving numerically, for \(t^*\)
Thank you!
CMA Diagram