The Potential for Ambient Plasma Wave Propulsion

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Outline

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      • Ex.: Jupiter
   B. Wave Propagation
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   C. Antenna System
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Justification

• Robust space exploration will ultimately require “living off the land”

• In-Situ propellants and propulsion will reduce launch needs
  – “Near Term” advanced propulsion (chemical, nuclear thermal, NEP) require IMLEO ~ 300 – 1000 mT
  – Feasibility of launching such masses on a regular basis is small

• Need to examine potential extraterrestrial sources for propulsion
• Utilize onboard power to couple to environment through plasma waves
  – First look: Alfven waves
    • Observed naturally in astrophysics
    • Postulated as mechanisms for heating and particle acceleration
• Radiate wave energy directionally to produce motion
  – Antennae designed to couple to correct wave and direction
  – Thrust ~ Wave field energy \( \frac{\partial B^2}{2\mu_0} \)
Analysis Approach

• Develop physical models for wave production/propulsion
• Assess possible environments
• Model wave propagation in relevant environments (Ray tracing)
• Use propagation results in system design (ANTENA rf plasma code)
  – Antenna size
  – Antenna loading (power)
  – Thrust
Alfven Wave Physics

- Low frequency waves in magnetized plasmas

- 3 modes:
  - Shear (|| B)
  - Compressional (isotropic)
  - Magnetoacoustic (⊥ B)

- Observed in terrestrial, Jovian, and Solar magnetospheres
  - Offered as possible explanation for coronal heating, acceleration of solar wind, Io plasma torus interactions

\[ \omega = k \cos(\theta)V_A \]
\[ \omega = k V_A \]
\[ \omega^2 = k^2 (V_A^2 + c_s^2) \]
\[ V_A = \sqrt{\frac{B_0^2}{\rho \mu_0}} \]
\[ c_s = \sqrt{\frac{T_e}{M_i}} \]
Ray Tracing Approach

- Dispersion relation gives wavelength and frequency as functions of environment (B, \( \rho \))

\[
(\omega^2 - k_z^2 V_A^2)(\omega^4 - \omega^2 k^2 (V_A^2 + c_s^2) + c_s^2 V_A^2 k^2 k_z^2) = 0
\]

\[
\vec{V}_A(x,y,z) = \frac{\vec{B}(x,y,z)}{\mu_0 \rho(x,y,z)}
\]

\[
c_s = \sqrt{\frac{kT_e}{M_i}}
\]

\[
k = \sqrt{k_z^2 + k^2}
\]

- Wavelength (k) depends on position through magnet and density fields
- Ray tracing follows wave energy as it propagates in magnetosphere
- Requires representative initial conditions
  - (x,y,z), (kx, ky, kz)
Establish Potential Environments

- First approximation Magnetospheres
  - Dipole magnetic field
  - Axisymmetric density
  - Uniform $T_e$
- Calculate simplified local $k$ for ray tracing
- Assess ray propagation in spatially varying fields
Jovian Magnetosphere

- Dipole strength ~ 4 nG Rj³
- Plasma density curve fit from literature
- Using a simplified dispersion relation, calculate ω, and k for initial conditions
- Use full fields model for ray tracing
Antenna Modeling

- Antennas determine the dominant axial and perpendicular wavelengths launched
  - Antenna design determines types of fields
    - E, B - Axial, radial, azimuthal
  - Antenna dimensions determine dominant wavelengths
- The desired wavelengths are determined from local B and density values
**ANTENA Code**

- Warm plasma cylindrical wave code
- Originally designed for fusion wave heating applications
  - Radial profiles of $n_e$, $T_e$ (not self consistent)
  - Axially uniform $B_0$, $n_e$
  - Uses real antenna designs/wavelength spectra
  - Calculates radiated power, antenna/plasma coupling
- Can apply ANTENA to the calculated local plasma parameters to determine best antenna size, design for the wave propulsion application
Example Antenna - Nagoya III

- Originally designed for ICRH heating in tokamaks
- Launches symmetric, left hand and right handed waves (m= 0, -1, 1)
- Antenna Length L gives peak coupling at wavelengths $\lambda \sim 2L$
RESULTS
Magnetosphere Models

- Standardized simplified model for dipole fields allows calculation structure to be applied to multiple environments
  - Jovian and Terrestrial environments described to date
Ray Tracing Analysis

- Ray tracing analysis generated from first principles in Mathematica
- Initial conditions generated for multiple Alfven modes throughout Jovian magnetosphere
  - Fast modes also depend on $k_\perp$ - assumed to be $\approx k_z$ for initial calculations
- Wave propagation has been examined throughout the Jupiter magnetosphere
  - Parallel and perpendicular waves observed
  - Currently examining results for resonance absorption and reflections
Ray tracing initial conditions

- Spatial locations span a range of conditions
  - \((2 \, \text{Rj} < r < 25 \, \text{Rj})\)
- Corresponding wavelengths \((k_z, k_{\perp})\) calculated as function of position
Ray Tracing for Jovian Magnetosphere

• Initial $\omega, k_z, k_\perp$ determined from position
• Ray propagation adjusts with changing plasma and B parameters
• Parallel and perpendicular modes can appear.
• Some indications of resonance absorption
Antenna System

• Initial conditions indicate large antenna dimensions, \( \sim 10 - 100\,\text{\textquotesingle}s\,\text{km} \)
• Some representative antenna in that size range have been modeled in the ANTENA code, using Jupiter magnetospheric B and density values
• Currently examining the effects of antenna size on coupling
Preliminary Antenna Length studies

- Assumes
  - Nagoya III antenna
  - Fixed diameter: 20 m

- Vary length from 10 – 1000 km, examine antenna loading, power deposition with $k_z$
Early Observations

- Higher impedance occurs at small $k_z$
- Impedance inversely dependent on antenna length (fixed $k_\perp$)
  - Better coupling at $10 \text{ km} < L < 100 \text{ km}$
  - $100 \text{ km}$ length gives $10 \times$ better coupling for Alfvén waves
- Further optimization of $k_\perp$ to be done
Summary of Results

• Magnetosphere models have been developed
  – Jupiter, Earth
  – Solar requires modification to pure dipole model

• Ray tracing tool has been developed
  – Currently being applied to Jovian case
  – Results thus far are similar to previous analyses in the literature

• Antenna modeling tool is operating
  – Initial antenna sizing, loading is being conducted in parallel with ray tracing results
Future Work

- Conclude Jupiter case
  - Finalize wave propagation requirements
  - Find representative antenna designs and power requirements

- Repeat for Earth, Sun
  - Modify dipole for solar magnetic field model

- Estimate system performance
  - Thrust, Thrust vectoring, power

- Assess non-linear wave option