ULF Waves in the Hermean Magnetosphere

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ULF Waves in the Terrestrial Magnetosphere

- Ultra low frequency (ULF) waves transfer of energy, momentum and information around the planet's magnetic environment.

- ULF waves at Earth are standing waves on field lines anchored to the ionosphere with frequencies (~mHz).

- Waves are characterised by polarisation:

  Toroidal Mode:
  - Azimuthal perturbation of $\mathbf{B}$.
  - Large (global) scale size.
  - Driven by external sources.

  Poloidal Mode:
  - Meridional/radial perturbation of $\mathbf{B}$.
  - Small scale size.
  - Usually driven by internal sources.

- Toroidal mode waves are shear Alfvén waves at Earth: field line resonances (FLRs) with discrete eigenfrequencies which can be used to estimate plasma mass densities, $\rho$, given the Alfvén velocity, $v_A$, and field line length, $l$, using a simple time-of-flight calculation:

$$T = \sum_i \frac{l_i}{v_{Ai}}, \text{ where } v_{Ai} = \frac{B_i}{\sqrt{\mu_0 \rho}} \Rightarrow T = \sqrt{\mu_0 \rho} \sum_i \frac{l_i}{B_i}$$
ULF Waves at Mercury

- ULF waves observed using Mariner 10 (~2s period) was theorised to be 4\textsuperscript{th} harmonic field line resonances by Russell, [1989].

- Later Southwood, [1997] suggested that these waves are not pure FLRs as they have a compressional component.

- ULF waves at Mercury are typically of the same order as local ion gyrofrequencies (~1 Hz) which complicates things compared to at Earth.

- More likely wave modes are ion cyclotron waves (ICWs), ion-ion hybrid (IIH) resonances, ion Bernstein waves and kinetic Alfvén waves.

- IIH resonances exist between the gyrofrequencies of the main constituents of the plasma, their frequency can be used to make an estimate of relative ion concentrations Othmer et al, [1999].

- FLRs are still likely to exist in some form at Mercury, and are a useful tool in diagnosing plasma densities and relative ion concentrations.
MESSENGER MAG Data

- MESSENGER was able to sample large parts of Mercury's magnetosphere for ULF wave activity due to its orbital configuration.

- We use all of the Magnetometer data from MESSENGER to study the waves.

- MAG typically sampled data at a rate of 20 Hz (Anderson et al., [2007]) – This is very useful for studying higher frequency wave activity, allowing us to detect frequencies up to 10 Hz.
KT14 Field Model

- The KT14 magnetic field model for Mercury (Korth et al, [2015]) confines the magnetic field within a magnetopause with the functional form defined by Shue et al, [1997].

- The model for Mercury is a simplified version of the Tsyganenko models for Earth, taking into account magnetic field contributions from only the magnetopause, Mercury's intrinsic field, a disk current sheet and a Quasi-Harris sheet.
KT14 Field Model

- MESSENGER's position can be mapped to a location in the magnetic equatorial plane, the planetary surface, or to a virtual surface centred upon Mercury's dipole.

- Virtual surface used to compare events which trace to northern or southern hemispheres.

- The magnetospheric model can be used to rotate the field vectors into a coordinate system based on the local ambient field.
Wave Detection

- Wave activity can be detected using dynamic Fourier analysis of the rotated magnetometer data with a sliding time window 120s in length – A compromise between being able to detect ULF waves and spatial/temporal ambiguity.

- The spectra were split in to two frequency bands, this talk focuses on low frequency wave activity up to 0.5 Hz.

- Each spectrum is associated with a magnetic equatorial footprint and surface footprints.
Derived Wave Properties

- Wave frequency, $f$, and powers, $P_P$, $P_\phi$ and $P_\parallel$.
- Azimuthal and poloidal power may be combined to give transverse wave power, $P_\perp$.
- Poloidal and parallel components can also be combined to form a non-azimuthal wave power, $P_C$.
- Three ratios, $R_{\phi C}$, $R_{\parallel \perp}$ and $R_{\phi P}$, to compare the three wave power components:
  \[ R_{\phi C} = \frac{\text{Azimuthal}}{\text{Non-Azimuthal}} \]
  \[ R_{\parallel \perp} = \frac{\text{Parallel}}{\text{Transverse}} \]
  \[ R_{\phi P} = \frac{\text{Azimuthal}}{\text{Poloidal}} \]
- Transverse polarisation parameters: eccentricity and handedness.
- Wave propagation vector, $k$. 

[Image of derived wave properties with diagrams showing various components and ratios.]
Wave Power (All Components)

- Wave power is detected throughout entire magnetosphere – it is important to have high resolution magnetometer data all of the time in order to detect such waves.
- Power is concentrated near dayside magnetopause and near the nightside of the planet.
- Dawn-dusk asymmetry present – more wave power near dawn.
Azimuthal Wave Power

- Azimuthally oscillating waves are most likely to represent shear Alfvén waves, the toroidal field line resonances seen at Earth.
- Most of the azimuthal wave power is found close to the dayside magnetopause.
- The peak in azimuthal power maps to mid-latitudes on the virtual surface of mercury.
Parallel Wave Power

- Parallel compressional wave power is most abundant in the nightside magnetosphere, within ~2 RM of Mercury's surface.
- Polar cap boundary defined by parallel waves at ~65° latitude on the dayside and ~30° on the nightside.
- Parallel power peaks the nightside and around noon and is more powerful near dawn than dusk.
Comparison of Azimuthal and Non-Azimuthal Waves

- Non-azimuthal waves dominate the majority of the magnetosphere.
- Azimuthal oscillations dominate the late-morning and afternoon sectors close to Mercury – this is where we may be most likely to expect FLRs and therefore be able to estimate plasma mass density.
Comparison of Parallel and Transverse Waves

- The parallel component is usually dominant in the magnetotail.
- Transverse oscillations dominate on the dayside and near to the magnetopause – some of the transverse oscillations could be IIH resonances.
Comparison of Transverse Components ($\log_{10} R_{||\perp} < 0$)

- Most of the transverse waves on the dayside and near the flanks have a dominant azimuthal component – again these could be FLRs.
- Poloidal power dominates the magnetotail, similar to the large numbers of poloidal oscillations observed at Earth's nightside.
Transverse Wave Polarisations

- Majority of detected transverse waves exhibit a nearly-linear polarisation – an indicator of possible resonance.
- The more elliptical/circular waves ($0 \leq e \leq 0.5$) change handedness near noon similar to at Earth – possibly related to K-H vortices near the magnetopause.
BepiColombo

- Magnetometers on both orbiters will be great for extending the study of ULF wave activity at Mercury – ideally these would provide high frequency data at all times during the mission.

- The orbits of the planetary and magnetospheric orbiters are such that they are likely to exist on the same field lines at certain times which could be useful for studying the properties of (possibly) standing waves.

- When the magnetospheric orbiter has its apoapsis outside of the magnetosphere, it may be possible to see what effects upstream waves have on magnetospheric wave activity.

- Particle instruments will be important for studying plasma properties and particle distribution functions related to wave activity – distribution function data would be ideally sampled every few seconds.
Wave activity appears everywhere within the Hermean magnetosphere.

Azimuthal waves which may represent field line resonances could be used to provide an estimate of local plasma densities.

Compressional wave activity traced to Mercury's surface defines a likely average polar cap boundary location.

Linearly polarised transverse waves which could represent local ion-ion hybrid resonances are common and may be used to estimate ion concentration ratios.

Transverse wave polarisation reverses handedness around noon, with left-handed waves dominating the dawnside and right-handed waves dominating the duskside magnetosphere – similar to what is observed at Earth.

BepiColombo will provide a great opportunity to extend the study of ULF waves using a multi-spacecraft approach.