Field Line Resonant Wave Activity in the Hermean Magnetosphere

M. K. James, S. M. Imber, T. K. Yeoman and E. J. Bunce

Radio and Space Plasma Physics Group, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK.
Terrestrial ULF Waves

- ULF waves transfer of energy, momentum and information around the planet's magnetic environment.
- ULF waves at Earth stand on field lines anchored to the ionosphere.
- Terrestrial ULF wave frequencies ~mHz,
- Waves are characterised by predominant transverse polarisation:

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

**Poloidal Mode:**
- Meridional/radial perturbation of $B$.
- Small scale size.
- Usually driven by internal sources.
Toroidal Mode Waves

- A pure toroidal mode wave is a shear Alfvén wave, with no compressional component and would oscillate globally around an entire L-shell.

- This large-scale mode may be driven by buffeting of the solar wind on the magnetopause, or the Kelvin-Helmholtz instability on the magnetopause flanks.

- The frequency of a toroidal resonance is a function of the Alfvén speed along the field line:

\[ f = \left[ \int_0^L \frac{2}{nV_A} \, dl \right]^{-1} \]

where \( V_A = \frac{B}{\sqrt{\mu_0 \rho}} \)

- Plasma mass density can be estimated using the fundamental frequency of an Alfvén wave using a field model and some assumption of how the plasma mass is distributed along the field line:

\[ \frac{1}{f} = 2 \int_0^L \frac{1}{V_A} \, dl \approx 2 \sum_i \frac{l_i \sqrt{\mu_0 \rho_i}}{B_i} \]
ULF Waves at Mercury

- First ULF waves observed by Mariner 10 (~2s period), thought to be $4^{th}$ 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 to be ion cyclotron waves (ICWs), ion-ion hybrid (IIH) resonances, ion Bernstein waves or kinetic Alfvén waves.

- IIH resonances exist between the gyrofrequencies of main plasma constituents, frequency is related to 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.

[Russell, 1989]
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

- KT14 magnetic field model [Korth et al., 2015] is based on Tsyganenko models for Earth.
- Magnetosphere confined by magnetopause with the functional form defined by Shue et al., [1997].
- The size of the magnetosphere is scaled by distance from the Sun: 
  \[ R'_{ss}[R_M] = 1.9372 \times (r_{Sun}[AU])^{\frac{1}{3}} \]
KT14 Magnetic Footprints and Field Orientation

- MESSENGER is mapped to magnetic footprints on:
  - magnetic equatorial plane (pink)
  - planetary surface (red)
  - “invariant latitude” surface centered on magnetic dipole (blue)

- Magnetic field vectors are rotated into a coordinate system based on the local ambient field with components:
  - $B_{\parallel}$ – parallel (compressional)
  - $B_p$ – poloidal
  - $B_\varphi$ – toroidal (azimuthal)
ULF Wave Detection

- Fourier analysis performed using a sliding time window 120s in length.
- Each spectrum is associated with a magnetic equatorial footprint and surface footprints.
- Only waves with a frequency less than the local sodium gyrofrequency were used, to remove cyclotron and IIH wave activity.
- Each spectral peak has a corresponding wave phase, power, polarization and frequency.
Mean Wave Power

- Wave power is detected throughout entire magnetosphere.
- Power is concentrated near dayside magnetopause and near the nightside of the planet.
- Dawn-dusk asymmetry present – more wave power near dawn.
- Wave power appears to define polar cap boundary – lack of wave power in polar cap.
Toroidal Wave Power

- Toroidal waves are most likely to represent shear Alfvén waves, the toroidal field line resonances seen at Earth.
- Most of the toroidal wave power is found close to the dayside magnetopause.
- The peak in toroidal power maps to mid-latitudes on the dayside surface of Mercury.
Transverse Component Comparison

- Removed compressionally dominant waves, showing mean $R_{\phi p}$.
- Transverse waves on the dayside and near the flanks are predominantly toroidal.
- Poloidal power dominates the magnetotail, similar to the poloidal oscillations observed at Earth's nightside.

Magnetic Equatorial Footprints

Mercury "Surface" Footprints
Transverse Wave Polarizations

- The most circularly polarized transverse waves appear closest to the magnetopause and become much more eccentric further into the magnetosphere.
- Transverse waves exhibit a polarization highly suggestive of being driven by an anti-sunward moving source, with a reversal in handedness slightly after noon in local time.
- This suggests a large number of waves are externally driven – possibly by K-H.
The handedness of the K-H driven waves is derived from the flow of the solar wind past the magnetopause.

Fast mode waves propagating planetward from the magnetopause become evanescent at the turning point $X_T$ with a reversal in polarization.

Wave resonates with local toroidal eigenfrequency at $X_R$ with another reversal in polarization and a peak in wave amplitude.
Contour map shows the locations of right (red) and left (green) hand polarized transverse wave populations in invariant latitude and local time.

Overall polarization reversal occurs at around 13:00 MLT – similar to that in Samson et al., 1971 for Earth.

Small numbers of LH (RH) polarized waves cross into the RH (LH) polarized region.

Could the outliers represent the evanescent waves in the region between the turning point and the resonant L shell?

If so – this region may not be very obvious given the highly dynamic nature of the Hermean magnetosphere.

[Samson et al., 1971]
Finding Resonances and Turning Points

- Data from spectral peaks adjacent in time and close in frequency were stitched together to form a time series for a number of waves (a very large number).
- For each wave time series: wave power and polarization parameters are compared between consecutive spectra to determine if MESSENGER had crossed through a resonant region or a possible turning point.

### Resonances:
- Transverse component is dominant over compressional component.
- There is a peak in azimuthal (toroidal) wave power.
- There is a reversal in handedness in the appropriate direction depending on spacecraft direction and local time.

### Turning Points:
- Transverse component is dominant over compressional component.
- There is **not** a peak in wave power.
- There is a reversal in polarization handedness in the opposite sense to what would be appropriate for a resonance.
An Example Field Line Resonance Event

- Example of Messenger after entering dawn-side magnetopause.
- Wave frequency is significantly lower than $f_{cNa^+}$ at $\sim 15$ mHz – higher than the 2-7 mHz expected for terrestrial FLRs.
- Passes through turning point at $\sim 10:30$.
- Crosses resonant region at $\sim 10:32$, where there is a significant peak in toroidal wave power.
- Wave is highly linear, predominantly toroidal and exhibits flip in handedness.
- Wave power and polarization matches the theory for terrestrial FLRs.
- Density $\sim 400$ amu cm$^{-3}$ $\equiv \sim 17$ Na$^+$ cm$^{-3}$ - possibly a bit high.
Resonant Frequencies and Densities

- Toroidal resonances mostly map to a small arc in the dayside magnetosphere.
- They mostly map to 40 – 60° invariant latitude.
- Frequencies are a bit of a mess but there is some hint that resonances closer to the planet are generally higher in frequency.
- Plasma mass density is computed assuming that there is a constant density along the resonant field line.
- Plasma mass density estimates range from 10 to 1000 amu cm⁻³, where higher densities appear closer to Mercury, at lower invariant latitudes.
Transverse Resonances

- Relaxed criteria to include any transverse resonance (poloidal or toroidal):
  - Transverse wave power must dominate over compressional wave power.
  - Peak in toroidal or poloidal wave power.
  - Polarization reversal in either direction.
- Many more events appear – most of which are still predominantly toroidal.
- Similar frequencies and density estimates to just Earth-like FLR events.
Observations and Models of Plasma Mass Density

Actual plasma measurements haven’t been able to measure the densities predicted by field line resonance:

- **Mariner 10**: 3-7 \( H^+ \) cm\(^{-3} \) \cite{Ogilvie1977}.
- **MESSENGER FIPS**:
  - 1-20 \( H^+ \) cm\(^{-3} \)
  - \( 5.1 \times 10^{-3} \) Na\(^+ \) cm\(^{-3} \) (2 cm\(^{-3} \) in the cusps)
  - \( 3.9 \times 10^{-2} \) He\(^{2+} \) cm\(^{-3} \)
  - \( 3.4 \times 10^{-4} \) He\(^+ \) cm\(^{-3} \)
  - \( 8.0 \times 10^{-4} \) O\(^+ \) cm\(^{-3} \)

\cite{Raines2011, Raines2013, Raines2014}

Models have been more optimistic:

- **Benna et al., 2010**: 8-10 \( H^+ \) cm\(^{-3} \) within a small drift belt, >10 cm\(^{-3} \) in the morning sectors and 10-100 cm\(^{-3} \) in the cusps.
- Simulations of sodium ion production predicted 10-100 Na\(^+ \) cm\(^{-3} \) (\( \sim 200 – 2000 \) amu cm\(^{-3} \)) in the dayside magnetosphere \cite{Leblanc2003, Delcourt2003, Yagi2010}.

\cite{Yagi2010}
Conclusions

- Using MESSENGER MAG data we have identified ~200 candidates for field line resonance at Mercury.
- FLRs occur mostly in the dayside magnetosphere, occasionally on the flanks.
- Plasma mass density has been estimated for each event and is typically between 10 and 1000 amu cm$^{-3}$, where the highest densities are predicted closest to the planet.
- Plasma mass density agrees with plasma models, but not with FIPS observations.
- Transverse wave polarizations show a clear reversal in handedness at ~13:00 local time, where a small number of outliers may represent evanescent waves between the turning point and the resonant field line.
- We could look into the turning points to determine where the turning point usually occurs and where evanescent waves usually exist.
- It may not even be necessary for there to be a turning point.
- It would be interesting to determine whether the majority of waves are just the ringing of the magnetosphere to noise, or whether the solar wind is driving discrete resonances.