Alfvén Waves Around Us

The Science of ULF Waves (Since 1859)

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7th July 2008

First Observations

The first published observations of ULF waves were made in 1859.
Recorded at Kew Observatory, during space weather events triggered by the first solar flare to be observed (Carrington; Hodgson).
In an article in 1861, Samuel Balfour reports of magnetic readings,

> *"...there were superimposed smaller waves whose period might be perhaps only a few minutes, or even less."*

Theory

For almost a century, the observational effort was on cataloguing and classifying different types of ULF wave.

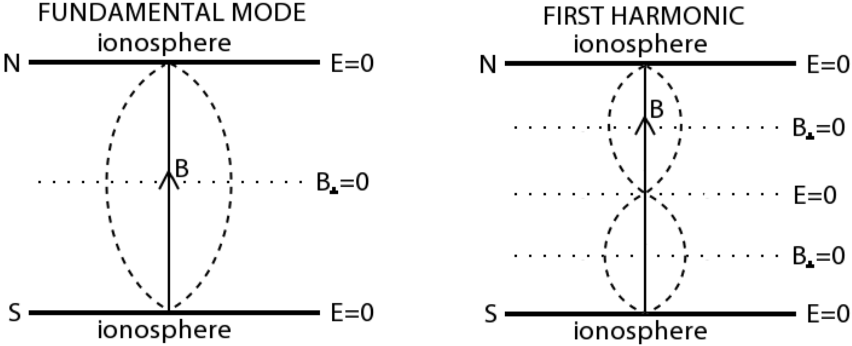
The theoretical explanation of these waves was offered after two key pieces of work:

- Alfvén, 1942: "Existence of electomagnetic-hydrodynamic waves".
- Storey, 1953: "An investigation of whistling atmospherics" shows electron density in the magnetosphere is much greater than anticipated.

Following these, Dungey (1954) deduced existence of standing Alfvén waves in the magnetosphere, using these to explain measurements of ULF waves on the ground.

Structure of Standing Alfvén Waves

Alfvén waves displace magnetic field lines as energy travels along them.
Boundary condition of fixed endpoints ($E = 0$) produces standing waves.



Electric and magnetic field perturbations are 90° out of phase.

Observation Verification

Dungey's theory of standing Alfvén waves makes predictions which were verified by later observations.

- Both ends of a field line are disturbed by a ULF wave.
  - Sugiura 1961.
- Cycles at both ends of a field line match.
  - Nagata et al. 1963.
- Waves are observed in space as well as on the ground.
  - Patel 1965.
- Realistic plasma parameters allow numerical integration of equations for field line eigenfrequencies.
  - Cummings et al. 1969.
- Electric and magnetic field oscillations are 90° out of phase.
  - Singer et al. 1982 (also improved on eigenfrequencies).

Changes with Latitude

- Dungey's idea was well established by the 1970s and research shifted to the excitation of ULF waves.
- As an observer moves to higher latitude (polewards), they move to longer field lines with lower natural frequencies.
- For the lowest frequency class of ULF waves (Pc5; period $>$ 150s) observe large waves at just a few frequencies (each wave is monochromatic).
- Maximum amplitude of each signal is at corresponding field line, but has finite width.

Explanation

Southwood (1974) and Chen & Hasegawa (1974) independently explained the favoured excitation of some latitudes:

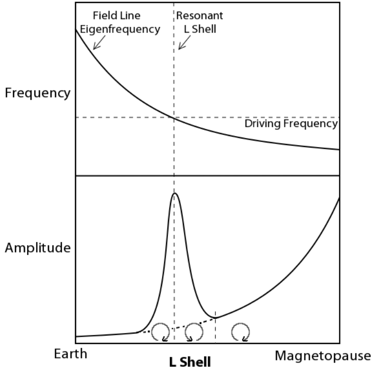
- Requires existence of monchromatic fast waves in the magnetosphere.
- These couple to standing Alfvén waves when the driving frequency matches the field line eigenfrequency.

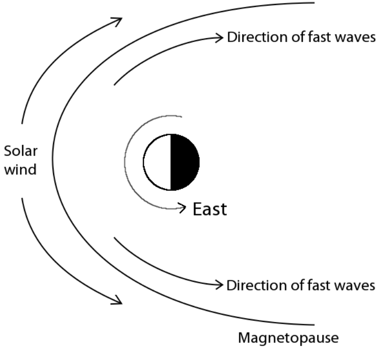
Provided a monochromatic source is found, explains favoured frequencies and finite widths of resonances.

Also explains measured switches in polarization (observed by Samson et al. 1971).

Amplitude and Polarization of ULF Waves

Observations by Samson et al. 1971 show polarisation switches at resonant latitude and at high latitude.
Also saw a switch at 12 noon (instruments under nose of magnetosphere).





Reproduced by theory if fast waves propogate tailwards.

Sources of Monochromatic Fast Waves

Later work focused on confirming the source of monochromatic fast waves.

- Kelvin-Helmholtz (wind over water) instability
  - Magnetopause ‘flaps’ as solar wind rushes by.
  - Suggested as energy source in Dungey’s 1954 work.
  - Observed phase speeds of resonances often too fast.
- Cavity/Waveguide modes
  - Suggested by Kivelson et al. 1984.
  - Magnetosphere ‘rings like a bell’.
  - Cause is buffeting by variations in solar wind and sporadic magnetic reconnection.

Both sources believed to act under different conditions (Wright 1999).

Summary

Timeline:

- 1859 First published observations of ULF waves (Balfour).
- 1954 Explanation of ULF waves in terms of standing Alfvén waves (Dungey).
- 1957 Sputnik 1 starts space era.
- 1961-82 Confirmation of theory from structure and frequencies of waves, using ground and space data.
- 1974 Explanation of excitation and polarisation of ULF waves (Southwood; Chen & Hasegawa).
- 1984 Theory of cavity modes (Kivelson et al.).