Using helioseismic oscillations to characterise the Sun's internal magnetic field

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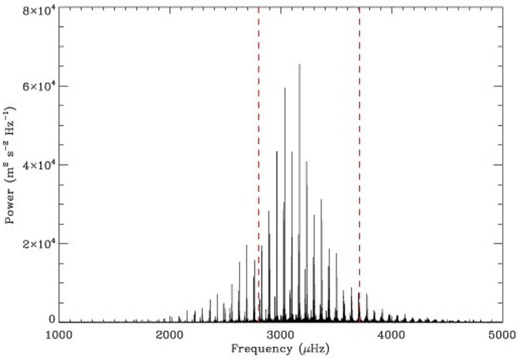
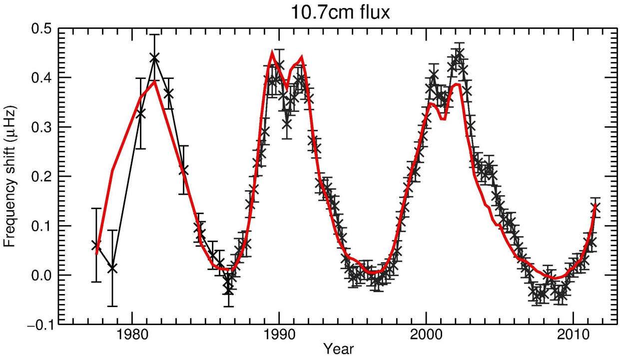
Helioseismology

- Helioseismology allows conditions beneath the solar surface to be probed.
  - Each mode samples slightly different but overlapping regions of the solar interior.



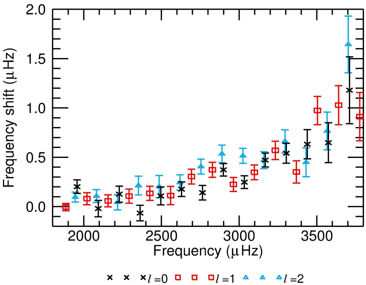
Seismic frequencies and the solar cycle

- Seismic frequencies respond to changes in the surface activity associated with the solar cycle.



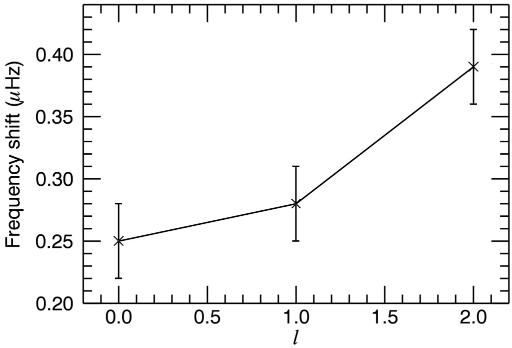
Frequency dependence of the frequency shifts

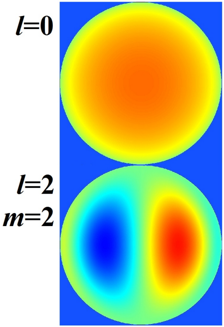
- Frequency dependence indicates changes in acoustic properties are close to surface.
  - Higher-ν modes are more sensitive to surface perturbations than low-ν modes.
- Modes below $\sim 1800\mu Hz$ experience almost no solar cycle shift $\Rightarrow$ perturbation concentrated above the upper turning points of these modes i.e $\sim 1\,\mathrm{Mm}$.



Degree-dependence of frequency shifts of Sun-as-a-star data

- Size of the shift is related to the latitudinal distribution of the solar magnetic field at the surface.

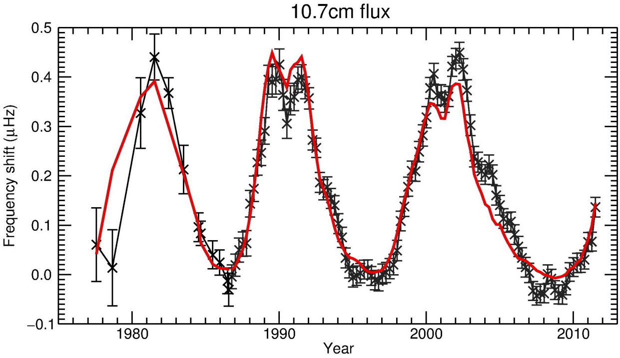




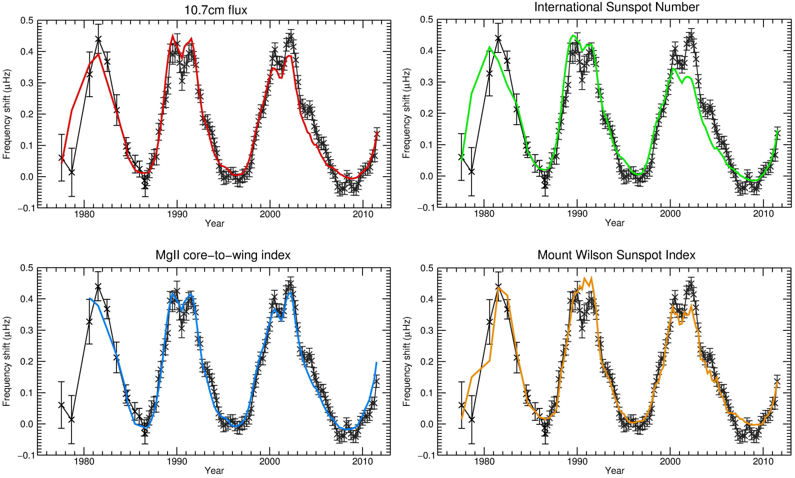
Courtesy of G. Davies and K. Goss

Returning to the seismic frequencies and the solar cycle

- Discrepancies between frequency shifts and 10.7cm flux are observed.

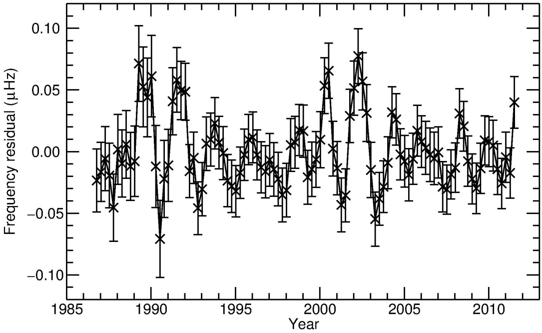


Seismic frequencies and proxies of the solar cycle



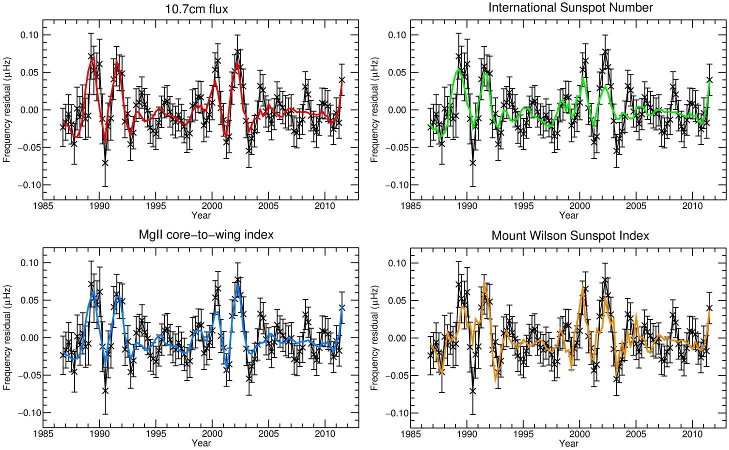
Shorter term variations in the seismic frequencies

- Persistent shorter term variations are visible in frequency shifts.



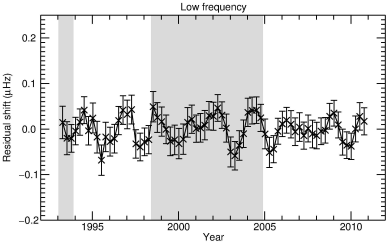
Shorter term variations in the solar cycle proxies

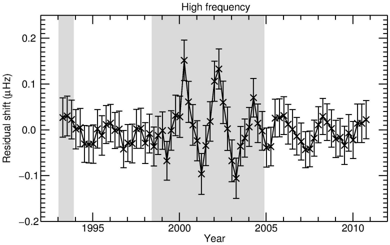
- In the proxies the shorter term signal is only present close to solar maximum.



Difficult to characterize the field

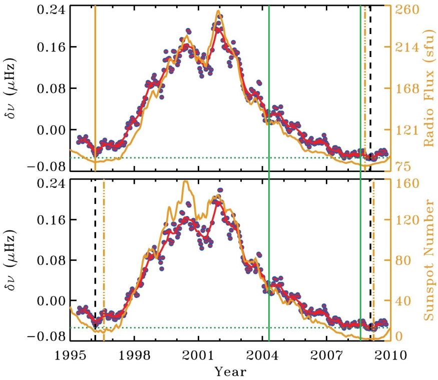
- There is some evidence that the frequency dependence of the quasi-biennial signal is weaker than 11-yr signal $\Rightarrow$ magnetic field is deeper in the solar interior.
- Hard to characterize the l dependence with Sun-as-a-star data.





Use higher-degree modes

- Can we use higher-l modes to help characterize the field?
  - Some evidence for double minima, depending on which l and ν are considered.



From Jain, Tripathy, and Hill, 2011, ApJ, 739, 6

Summary

- Internal acoustic oscillations are affected by solar magnetic field.
- Characteristics of the observed changes in the oscillations can be used the characterize the internal magnetic field.
- Quasi-biennial signal also visible in p-mode frequencies.
- Possibly use higher-l modes to characterize field responsible for this signal.
- Quasi-biennial signal persists in p-mode frequencies throughout recent unusual solar minimum
    - Unlike that observed in surface proxies.
- Implies the field continues to exist in the solar interior even during times of solar minimum.