Sun-as-a-star Helioseismic Observations from SoHO over a 22-year Magnetic Cycle

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First detection of solar oscillations (Leighton, Noyes & Simon, 1962)

Start of an observing network for low-degree modes

Sun-as-a-star Helioseismic Observations: A background

Sunspot number record

Source: WDC-SILSO, Royal Observatory of Belgium, Brussels
Un-interrupted Helioseismic Observations: Sun-as-a-star (Unresolved)

Instruments onboard SDO

1600 Å and 1700 Å Continuum intensity

Integrated light

Ground-based Networks

Instruments onboard SoHO


Birmingham Solar Oscillations Network (BiSON)

Global Oscillations at Low Frequencies (GOLF)

Variability of IRradiance and Gravity Oscillations (VIRGO)

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Un-interrupted Helioseismic Observations: Resolved Disk

Global Oscillations Network Group (GONG) 1995 -

SoHO / Michaelson Doppler Imager (MDI) 1996 - 2011

SDO / Helioseismic and Magnetic Imager (HMI) 2010 -

Space Missions
Plan

✓ Sun-as-a-star observations - Some basics
✓ Why are these observations important?
✓ Results
✓ Summary
Sun-as-a-star Observations: Propagating modes

Lower turning point

\[ r_t = \frac{c(r_t) \sqrt{l(l+1)}}{2\pi \nu} \]

Upper turning point (Acoustic cutoff frequency)

\[ \nu_{ac} = \nu \]
Sun-as-a-star Observations: Why are these important?

Variability of the solar interior

Model the solar core

Search for g modes - Rotation of the core

Tested methods are laying paths for asteroseismic studies

as inferred from the acoustic mode frequencies and compare with disk-resolved mode frequencies
Sun-as-a-star observations - Temporal Variation

1860 \mu Hz \leq \nu \leq 3450 \mu Hz; \ell = 0 - 3

Common modes in individual data sets.
Sun-as-a-star observations - Temporal Variation

$1860 \mu Hz \leq \nu \leq 3450 \mu Hz; \ell = 0 - 3$

Common modes in all 3 data sets.
Quasi-biennial Periodicity - A Hint for the Second Dynamo

Unresolved observations: Low-degree Modes (0 ≤ ℓ ≤ 2)

Broomhall et al. (2011) JPCS
Quasi-biennial Periodicity - A Hint for the Second Dynamo

Unresolved observations from GOLF
Low-degree Modes ($0 \leq \ell \leq 2$)

Resolved observations from GONG
$0 \leq \ell \leq 120$

Broomhall et al. (2011) JPCS
Quasi-biennial Periodicity - A Hint for the Second Dynamo

Unresolved observations from GOLF
Low-degree Modes (0 ≤ ℓ ≤ 2)

High-\nu range
Low -\nu range
All data

Resolved observations from GONG
0 ≤ ℓ ≤ 120

\( \delta \nu \)
11-year signal
Residual \( \delta \nu \)

Grouped on the basis of lower-turning points

Broomhall et al. (2011) JPCS

Temporal Variations - Based on Upper Turning Points

Acoustic cutoff frequency as a function of radius.

Low-frequency range: $1860 \, \mu\text{Hz} < \nu \leq 2400 \, \mu\text{Hz}$
Mid-frequency range: $2400 \, \mu\text{Hz} < \nu \leq 2920 \, \mu\text{Hz}$
High-frequency range 1: $2920 \, \mu\text{Hz} < \nu \leq 3450 \, \mu\text{Hz}$
High-frequency range 2: $3450 \, \mu\text{Hz} < \nu \leq 4250 \, \mu\text{Hz}$

Temporal Variations - Based on Upper Turning Points: Contemporaneous Data

Jain et al. (2018), Proc. IAU Symposium 340
Temporal Variations - Based on Upper Turning Points: Contemporaneous Data

Black: F10 ; Color: Frequency shifts

GOLF

1860 μHz ≤ ν ≤ 2400 μHz

2920 μHz ≤ ν ≤ 3450 μHz

3450 μHz ≤ ν ≤ 4250 μHz

VIRGO

1860 μHz ≤ ν ≤ 2400 μHz

2400 μHz ≤ ν ≤ 2920 μHz

2920 μHz ≤ ν ≤ 3450 μHz

BISON

3450 μHz ≤ ν ≤ 4250 μHz

2400 μHz ≤ ν ≤ 2920 μHz

1860 μHz ≤ ν ≤ 2400 μHz

Jain et al. (2018), Proc. IAU Symposium 340
## Contemporaneous Data Sets: Quantitative Analysis

<table>
<thead>
<tr>
<th>Data Source</th>
<th>BiSON</th>
<th>GOLF</th>
<th>VIRGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Cycle</td>
<td>22-24</td>
<td>23-24</td>
<td>22 23 24</td>
</tr>
<tr>
<td>Low-ν range</td>
<td>0.66 0.56</td>
<td>0.79 0.58 0.63</td>
<td>- 0.54</td>
</tr>
<tr>
<td>Mid-ν range</td>
<td>0.94 0.95</td>
<td>0.95 0.96 0.96</td>
<td>- 0.95</td>
</tr>
<tr>
<td>High-ν range</td>
<td>0.97 0.97</td>
<td>0.97 0.97 0.97</td>
<td>- 0.96</td>
</tr>
<tr>
<td>High-ν range 2</td>
<td>0.92 0.96</td>
<td>0.87 0.96 0.95</td>
<td>- 0.95</td>
</tr>
</tbody>
</table>

**Pearson's linear correlation coefficients**

Jain et al. (2018), Proc. IAU Symposium 340
Temporal Variations - Based on Upper Turning Points

Previous Studies from BiSON

Very low-frequencies from GOLF

Pearson's linear correlation coefficients: 0.54 0.36

SOHO 29 – Nice, November 2018
Thus, the studies, based on un-interrupted Sun-as-a-star (unresolved) observations from about 3 solar cycles, suggest that

- the solar cycle-related changes in oscillation frequencies are different from cycle to cycle.

- the magnetic layer has become thinner after cycle 22 and this change is confined to shallower layers of the Sun.

If this is true, we should see similar variations in intermediate degree modes that do not travel to the solar core.
Comparison with the modes confined to convection zone

Unresolved observations Low-degree Modes ($0 \leq \ell \leq 2$)

- $3450 \mu Hz \leq \nu \leq 4250 \mu Hz$
- $2920 \mu Hz \leq \nu \leq 3450 \mu Hz$
- $2400 \mu Hz \leq \nu \leq 2920 \mu Hz$
- $1860 \mu Hz \leq \nu \leq 2400 \mu Hz$

Resolved observations from GONG

Intermediate-degree Modes
Seismic minimum between Cycles 23-24

Unresolved observations from GOLF
Low-degree Modes (0 ≤ ℓ ≤ 2)

Solar activity minimum: Late 2008

Resolved observations from GONG
Low/Intermediate-degree Modes with r_+/R ≤ 0.3

Seismic minimum: Late 2007


Adapted from Jain et al. (2011) ApJ
Seismic minimum between Cycles 23-24

Unresolved observations from GOLF
Low-degree Modes (0 ≤ ℓ ≤ 2)

Resolved observations from GONG
Low/Intermediate-degree Modes (0 ≤ ℓ ≤ 120)


These results clearly show that the modes travelling to the solar core have different sensitivity to the magnetic field observed above the surface.

Adapted from Jain et al. (2011) ApJ
Long-term simultaneous Sun-as-a-star observations from GOLF and VIRGO onboard SoHO, along with ground-based BiSON and resolved-disk observations from GONG clearly show that there are similarities as well as differences between unresolved- and resolved-disk observations.

The oscillation frequencies from all observations do vary in phase with the solar activity cycle, however the minimum sensed by the modes confined to the convection zone happened around the same time as in the solar activity indicators while the modes travelled to the core sensed minimum about a year earlier.

Based on Sun-as-a-star observations, it has been suggested that the magnetic layer of the Sun is changing gradually and has become thinner in last 2 solar cycles. Similar analysis with modes in intermediate-degree range do not support this findings.

Thus, the helioseismic observations covering all regions below the surface for several solar cycles are necessary to understand the variability of different layers in the solar interior and its link to the surface magnetic activity.