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Solar Cycle Variation in GONG and MDI Data: 1995-2002

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Abstract. Both GONG and MDI projects have measured p-mode frequencies of the Sun for more than 7 years. Here we review what we have learnt from the temporal variation of the oscillation frequencies and splitting coefficients.

1. Introduction

Helioseismology has now been accepted as a powerful diagnostic tool to carry information from inside the sun at different depths. The basic data which enables to infer this information are the global oscillation modes which are characterised by the eigenfrequencies. During the solar cycle 21, it was observed that mode frequencies change with the evolution of the solar cycle (Woodard and Noyce, 1985; Libbrecht and Woodard, 1989; Elsworth et al., 1990) which suggested that these changes are manifestation of the variation of the magnetic field with solar cycle. During the early stages of the current solar cycle 23, the frequency variation has also been shown to be strongly correlated with many other activity indices at the solar surface (e.g. Bhatnagar, Jain and Tripathy, 1999). With nearly 7 years of co-temporal helioseismic data from two different instruments from two different platforms, we are now in a stronger position to study the time variation of p-mode frequencies with changes in the levels of solar activity.

The frequencies of modes of oscillations are typically represented in terms of mean frequencies ($\nu_{n\ell}$) for each multiplet (n, ℓ), n being the radial order, ℓ the spheical harmonic degree, and frequency splittings $\nu_{n\ell m} - \nu_{n\ell}$ according to the azimuthal order m (see Ritzwoller and Lavely, 1991 for details). The odd coefficients are used to calculate the solar rotation while the even coefficients sense spherically asymmetric properties e.g. local variation in the sound speed, asphericity, the magnetic field strength etc.

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2. Analysis and Results

For the present study, we consider 68 overlapping GONG data sets (GONG month 2-69) derived from 108 day long time series but spaced in an interval of 36 days. These data sets cover a period from May 7, 1995 to March 30, 2002 and were produced through the standard GONG pipeline (Hill et al., 1996). Each set yields about 60,000 useful frequencies for individual n, ℓ, m modes for $\ell = 0$ to 150 in about 1600 multiplets. Central frequencies $\nu_{n\ell}$ and a coefficients up to a_9 are derived from these multiplets. The MDI data consists of 31 non-overlapping data sets starting on May 1, 1996 and ending on November 1, 2002 with interuptions between June 16 and October 22, 1998 due to the loss of contact with SOHO. All these data sets are 72 days long except those immediately before and after the break, which are shorter. Each data set consist of centroid p-mode frequencies up to $\ell \approx 200$ and a-coefficients up to a_{18} (Schou, 1999).

2.1 Frequency shifts

The mean shift $\delta\nu$ for a given ℓ and n is calculated from the relation

$$\delta\nu(t) = \sum_{n,\ell} \frac{\delta\nu_{n,\ell}(t)}{\sigma^2_{n,\ell}} \Bigg/ \sum_{n,\ell} \frac{1}{\sigma^2_{n,\ell}}, \tag{1}$$

where $\delta\nu_{n,\ell}(t)$ is the change in measured frequency for a given ℓ and n and $\sigma_{n,\ell}$ is the error in the observed frequency. Since the solar activity changes over the cycle, we have defined the change $\delta\nu_{n,\ell}(t) = \nu_{n,\ell}(t) - < \nu_{n,\ell} >$ where the average $< \nu_{n,\ell} >$ is calculated separately for GONG and MDI data sets.

The frequency shift is well known to have a strong dependence on frequency and for a meaningful analysis, we have considered only those p-modes which are present in all GONG and MDI data sets in the frequency range of 1500–3500 μHz. Figure 1(a) shows the temporal variation of mean frequency shift for MDI and non-overlapping GONG data sets and we clearly note that there is a systematic offset between the two shifts. This may have been caused either due to different analysis technique to derive the mode frequencies or because of the different time series lengths over which avearges are taken to compute the frequency shifts (Jain and Bhatnagar, 2003). The mean frequency shift is correlated with various activity indices representing photospheric, chromospheric and coronal activities (for details see Jain et al., 2000). In panel (b), we show the frequency shifts calculated from the overlapping GONG data sets along with the scaled activity index represented by 10.7 cm radio flux. It is evident that the change in frequency follows the change in solar activity very closely, the proximity being marginally higher during the ascending phase of the solar cycle. A similar result for the low degree p-mode frequencies were reported by Chaplin et al. (2001). For a detailed investigation, we calculate the mean frequency shifts corresponding to four different frequency bins of 500 μHz. The offset between GONG and MDI data sets is quite apparent in lower frequency bands and slowly decreases for higher frequency ranges. For the highest frequency band (3000-3500 μHz), the offset is seen only when the activity

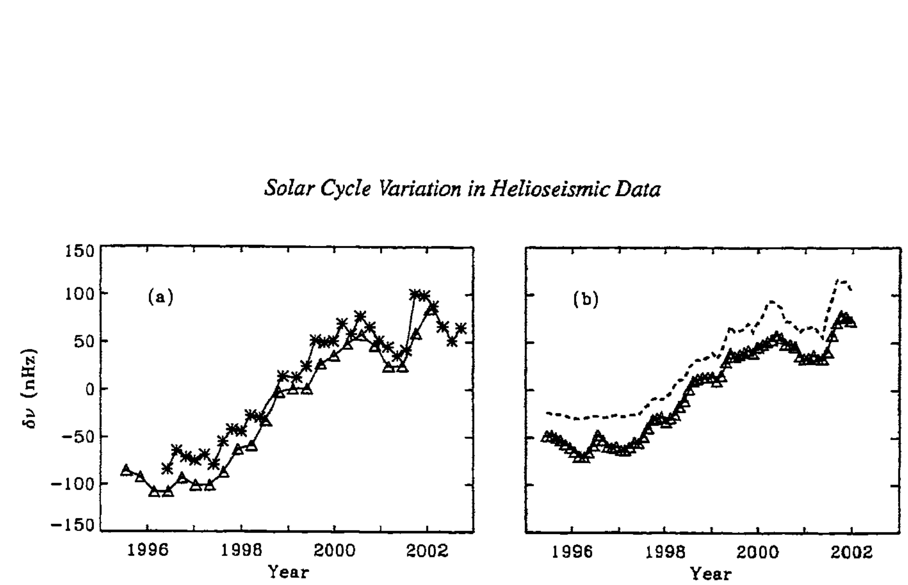

Figure 1. The change in mean frequency for the period 1995-2002. In panel (a), the triangles represent the shifts calculated from non-overlapping GONG data sets while the stars represent the shifts from MDI data. Panel (b) shows the frequency shifts of the overlapping GONG data sets along with the scaled activity level represented by 10.7 cm radio flux (dashed line).

level is high. In low frequency bands, deviations from the simple activity dependence is observed during the activity minimum period.

Since both GONG and MDI frequencies are obtained from time series spanning over few months, these can be used to study the temporal evolution of a single (n,ℓ) multiplet. The variation of the central frequency of two multiplets for $n = 6$ and $n = 9$ corresponding to $\ell = 60$, along with the scaled activity index is shown in Figure 2. It is remarkable that even the frequency of a single mode of oscillation closely follows the changes in activity level. As mentioned earlier, a small offset between the absolute values for GONG and MDI frequencies at lower n values corresponding to lower frequency range is clearly seen. However, the sensitivity to the activity level appears independent of the data sets used.

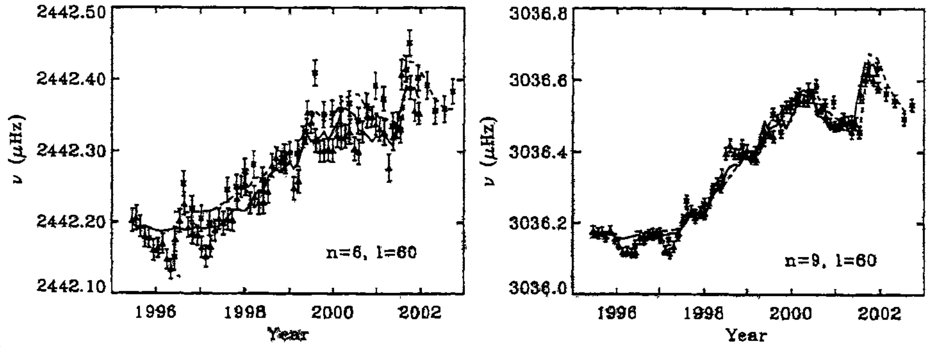

Figure 2. Temporal variation of centroid frequency for two different values of n corresponding to same value of ℓ for GONG (triangles) and MDI (stars) data sets. The 1 σ errors are also shown. The continuous curves represent 10.7 cm radio flux, scaled by the best fit to GONG (solid line) and MDI (dashed line) data.

2.2 Variation in solar structure

The study of temporal variation have not shown any significant changes in the solar interior structure. Specifically, no changes have been detected in the depth of the convection zone (Basu, 2002). Similarly, no systematic temporal change in the sound speed has been determined within the 1 σ error limits (Basu, 2002; Vorontsov, 2002), although discrepancies in the derived sound speed are noticed between the GONG and MDI data sets (Basu et al., 2003).

2.3 Variation in even order splitting coefficients

Similar to the mean frequency shifts, the mean even order splitting coefficients are well correlated with the corresponding component of the magnetic flux (Antia et al., 2001; Howe, Komm and Hill, 2002). Assuming that the even a coefficients arise from aspherical sound speed distribution, these coefficients were inverted to deduce the latitudinal distribution of the sound speed. But no significant temporal variation in the asphericity of the sound speed was found (Antia et al., 2001) emphasizing that the temporal variation seen in each a coefficients arise from changes localised near the surface layers. On the other hand, one can assume that the changes in the even coefficients are due to the magnetic field and it is possible to infer the magnetic field in the solar interior as a function of radial distance and latitude. However, due to the fairly small values of the coefficients, no definitive magnetic field strength has been confirmed. Dziembowski and Goode (1989) claimed to find evidence for a mega gauss field while Antia (2002) reported a field strength of 300 kG as an upper limit near the base of the convection zone.

2.4 Variation in solar dynamics

Helioseismic results have confirmed that the surface differential rotation detected with Doppler Observations persists throughout the convection zone (e.g. Schou et al., 2002). There appears to be very little, if any, variation of the rotation rate with latitude in the outer radiative zone, while at the base of the convection zone, a shear layer (the tachocline) separates the radiative interior which rotates almost like a solid body. However, accurate determination of the rotation rate in the solar core is yet to be achieved as it requires very fine low degree frequency splittings. A recent study (Eff-Darwich et al., 2002) rule out any departure of the rotation rate in the deep solar interior by more than 20% of the surface rotation rate at mid-latitude. In addition, one does not find any significant change in the location of the tachocline although there is some hint that the tachocline itself may consist of two-components (Basu and Antia, 2003).

In solar dynamo theories, it is generally believed that the rotation stretches the poloidal field lines near the tachocline and creates the toroidal fields, hence it is important to look for possible variations in rotation rate with time. Surface observations have indeed indicated the existence of such time varying rotation rate in the form of zonal bands of slow and fast rotation (Howard and LaBonte, 1980) and are believed to arise from the nonlinear interactions between magnetic

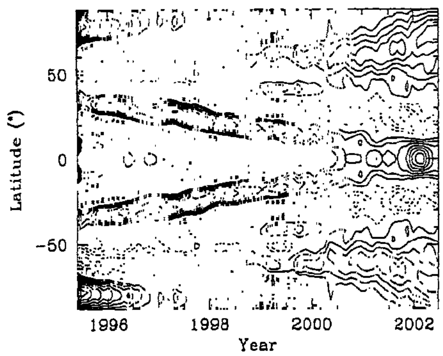

Figure 3. Contour diagrams of constant rotation velocity residuals at $r = 0.98\ R_\odot$ obtained using two-dimensional RLS inversion of the GONG data. The continuous contours are for positive δv_ϕ, while dotted contours denote negative values. The contours are drawn at interval of 1 m/s. Zero contours are not shown.

fields and differential rotation. Figure 3 shows the rotation residuals obtained by subtracting the temporal mean of the rotation rate using GONG data. The figure actually shows the linear velocity corresponding to the residual in rotation rate i.e. $\delta v_\phi = \delta\Omega r \cos\theta$, where θ is the latitude. It can be seen that there are distinct bands of faster and slower than average rotation rate and at low latitudes these move towards the equator with time as is well known from earlier studies (Schou, 1999; Antia and Basu, 2000). At high latitudes, the bands seem to move toward the poles (Antia and Basu, 2001; Ulrich, 2001). The transition between these movement takes place around a latitude of 50^0. It has also been reported that these flows penetrate to a depth of about $0.1R_\odot$ (Basu and Antia, 2003). Solar meridional flow velocity also shows a clear temporal variation and its magnitude appear to decrease with increase in the solar activity (Haber et al., 2002; Basu and Antia, 2003). It is expected that the temporal variation in the rotation rate and meridional flow would provide constraints on solar dynamo models (e.g. Nandy and Choudhuri, 2002).

3. Conclusions

We have analysed the p-mode oscillation frequencies obtained from GONG and MDI instruments covering a period of seven years which includes the descending phase of solar cycle 22 and ascending phase of cycle 23. The frequencies show an increase with solar activity and changes are found to be well correlated with activity indices. No significant temporal variation is seen in the solar structure in the interior while in the outer layers, the rotation rate shows the chracterestic zonal bands. At low latitudes, these bands move towards the equator and at high latitudes, they appear to move towards the pole.

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