Asymmetry in Solar Torsional Oscillation and the Sunspot Cycle

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Abstract

Solar torsional oscillations are migrating bands of slower- and faster-than-average rotation, which are strongly related to the Sun’s magnetic cycle. We perform a long-term study (16 yr) of hemispherical asymmetry in solar torsional oscillation velocity using helioseismic data for the first time. We study the north–south asymmetry in the velocity using the zonal flow velocities obtained by ring diagram analysis of the Global Oscillation Network Group (GONG) Doppler images. We find significant hemispherical asymmetry in the torsional oscillation velocity and explore its variation with respect to depth, time, and latitude. We also calculate the hemispherical asymmetry in the surface velocity measurements from the Mount Wilson Observatory and the zonal flow velocities obtained from the Helioseismic and Magnetic Imager ring diagram pipeline. These asymmetries are found to be consistent with the asymmetry obtained from GONG observations. We show that the asymmetry in near-surface torsional oscillation velocity is correlated with the asymmetry in magnetic flux and sunspot number at the solar surface, with the velocity asymmetry preceding the flux and sunspot number asymmetries. We speculate that the asymmetry in torsional oscillation velocity may help in predicting the hemispherical asymmetry in sunspot cycles.

Key words: cosmology: observations – Sun: helioseismology – Sun: rotation

1. Introduction

Solar torsional oscillations are bands of slower- and faster-than-average rotation that migrate from midlatitudes toward the equator and poles during the solar cycle. They were first discovered by Howard & Labonte (1980) using full-disk velocity measurements from the Mount Wilson Observatory 150 ft tower. Migrating zonal flow bands were clearly observed using Mount Wilson Doppler observations from 1986 (Ulrich 1998, 2001). Kosovichev & Schou (1997) were the first to observe the flow helioseismically using the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (Scherrer et al. 1995), and the migration was observed by Schou (1999). The migrating flows were also observed using the helioseismic measurements from the Global Oscillation Network Group (GONG; Harvey et al. 1996). The first radially resolved evidence of zonal flow migration using GONG was reported by Howe et al. (2000b), and Toomre et al. (2000) reported similar findings based on MDI observations. Howe et al. (2000a) concluded that the equatorward band of torsional oscillation penetrates through the convection zone. Observations by Antia & Basu (2000) also revealed that they are not just surface phenomena but have depth dependence. Antia & Basu (2001) also studied the poleward propagation of the high-latitude branch of torsional oscillation, which has higher amplitude compared to the equatorward branch. The equatorward branch of the torsional oscillations is strongly related to the Sun’s magnetic cycle, with the center of the magnetic activity belt located at the poleward boundary of the fast zone. It has been proposed that the equatorward drift of the oscillation pattern can be produced by Lorentz force due to migrating dynamo-generated fields (Schuessler 1981), thermal feedback (Spruit 2003), or magnetic quenching (Küker et al. 1999; Pipin 1999), or can be due to all three effects combined (Rempel 2007).

Global helioseismology, which uses globally coherent modes of oscillations to study large-scale flows on the Sun, cannot be used to investigate the asymmetry in zonal and meridional flows of the Sun since the splittings of global modes are not sensitive to asymmetry across the equator. The asymmetries in the flows can be studied using local helioseismology techniques (Hill 1988; Duvall et al. 1993; Lindsey & Braun 1997). Ring diagram analysis (Hill 1988; Basu & Antia 2000), which is a local helioseismology technique, considers the displacement of three-dimensional power spectra on small areas of solar disk to infer the zonal and meridional flows. We can study the north–south asymmetry using these zonal flow velocities obtained from ring diagram analysis. A drawback of the ring diagram technique is that it is constrained only to the near-surface layers because of the short-wavelength waves that are considered for the analysis. The information on the time-dependent radial and latitudinal gradient of torsional oscillation can be helpful in deducing the temporal variation of the toroidal magnetic field (Antia et al. 2008). Torsional oscillation can also provide information on the timing of the solar cycle before the appearance of new cycle magnetic activity (Howe et al. 2011). This information, along with the hemispherical variation of torsional oscillation, could be a prior indicator of the solar cycle.

Basu & Antia (2003) studied the asymmetry in rotation for nine Carrington rotations by applying ring diagram analysis on MDI data and concluded that the antisymmetric component becomes significant above 0.98 R⊙, and errors are large below this radius to infer any asymmetry. Zaatri et al. (2006) also studied the north–south asymmetry in zonal flow for the declining phase of cycle 23 (2001–2004) using the velocities obtained by the ring diagram analysis of GONG Doppler measurements. They investigated the temporal, latitudinal, and radial variation of zonal flow for both hemispheres and its variation with respect to the magnetic cycle. Howe et al. (2011)
and Komm et al. (2014), using ring diagram results from GONG, reported the hemispherical asymmetry in zonal flow and proposed that the flow pattern can be a precursor of magnetic activity. Zhao et al. (2014) and Zhao (2016), using time–distance analysis of Helioseismic and Magnetic Imager (HMI) Doppler measurements, also reported the existence of hemispherical asymmetry in torsional oscillation.

Howard & Labonte (1983) used 16 yr of Mount Wilson full-disk velocity measurements and Javaraiah & Gokhale (1997) used rotation data obtained from sunspot tracers to study the temporal variation in the north–south asymmetries of solar differential rotation. Gigolashvili et al. (2005), using the rotation of Hα filaments, confirmed the existence of north–south asymmetry in solar rotation and proposed a relation with asymmetry in solar activity.

The aim of this work is to look into the long-term variation in the north–south asymmetry of solar torsional oscillations. We use the zonal flow velocities obtained from the ring diagram analysis of GONG Dopplergrams for a period of 16 yr (2001 July to 2017 March), which are made available from the GONG ring diagram analysis pipeline. We study the variation in the hemispherical asymmetry of torsional oscillations with time, latitude, and depth. We also calculate the velocity asymmetry near the solar surface considering surface velocity measurements from the Mount Wilson Observatory made using the Babcock magnetograph. We compare this with the asymmetry at the near-surface layer obtained from GONG observations. The asymmetry calculated from the zonal flow velocities obtained from the ring diagram analysis of GONG ring diagram pipeline on board the Solar Dynamics Observatory (SDO) is also used for comparison. We find these to be qualitatively consistent. The migration of zonal flow and active region magnetic flux are strongly related. Motivated by this, we perform a correlation analysis of the hemispherical asymmetry in torsional oscillation with the asymmetry in sunspot flux and number. We discover that the asymmetry in velocity precedes the asymmetries in the sunspot cycle and there exists a significant correlation between the two.

2. Data

We use the zonal flow velocity data obtained from GONG ring diagram analysis pipeline for the period 2001 July to 2017 March. Ring diagram analysis is performed using the dense pack technique as described by Haber et al. (2002). The daily Dopplergrams from different GONG sites are merged and remapped into 189 overlapping patches. Each patch is circularly apodized with a diameter of 15° with centers separated by 7.5° in latitude and longitude. The latitudinal extent and the longitudinal extent from central meridian are −52.5° to 52.5°, respectively. Each patch is tracked at the Snodgrass rate for 1664 minutes to remove the differential rotation effect. Three-dimensional power spectra are calculated for each patch, and these form rings in the (k, ρ) plane. These rings get distorted in the presence of flows, and they are fitted and inverted to obtain the zonal flow and meridional flow velocities as a function of depth. The ring diagram analysis procedure is explained in detail by Corbard et al. (2003) and is implemented in the ring diagram pipeline as explained by Hill et al. (2003). The systematic effects due to the variation in B₀ angle are corrected, following the procedure mentioned by Komm et al. (2015). The data are then smoothed over 1 yr to remove random fluctuations in the data, which remain even after the B-angle correction. A 11 yr average over each latitude and depth is subtracted from the zonal flow velocity at the same latitude and depth to obtain the residual rotation rate. Figure 1(a) is the contour plot of the torsional oscillation velocity as a function of latitude and time, at a depth of 2 Mm from the surface, obtained from GONG observations. Figure 1(b) is the contour plot of the torsional oscillation velocity obtained by the inversions of global modes obtained from the GONG data (Antia et al. 2008).

The surface velocity measurements obtained from the Mount Wilson 150 ft tower using the Babcock magnetograph (Babcock 1953) are used for calculating the hemispherical asymmetry at the solar surface and are compared with the near-surface torsional oscillation velocity asymmetry obtained from the GONG observations. The preparation of this data set is explained by Ulrich (2001). The data consist of 34 latitude points with a separation of 4° (−68° to 68°) and have a temporal resolution of 1.5 days from Carrington rotation 1617 to 2121, with each Carrington rotation divided into 18 intervals. Here we consider the data only for the GONG observing period. For our analysis, we further average the data and interpolate the data for GONG latitudes. The zonal flow derived from the ring diagram analysis of data obtained from HMI is also used for our analysis. B-angle correction is applied for these data also, following the procedure suggested by Komm et al. (2015), and further smoothed over 1 yr. The data we consider here start from 2010 August and cover a period of about 7 yr with latitude coverage of −62.5° to 62.5°.

The sunspot area data compiled by the Royal Greenwich Observatory (RGO) and the United States Air Force/US National Oceanic and Atmospheric Administration (USAF/NOAA) are used for calculating the sunspot flux used in this study. We consider the maximum area (A) of each active region in units of microhemispheres and convert it to magnetic flux by using the empirical relation Φ(A) = 7.0 × 10¹⁹ × A Mx (Sheeley 1966; Dikpati et al. 2006). We calculate the magnetic flux for both the hemispheres separately for the period from 2001 July to 2016 September. To check for the relatedness of various proxies for the sunspot cycle, we performed a correlation analysis between this calculated magnetic flux and the flux obtained from the synoptic magnetograms of MDI and HMI combined together for the same period. A correlation coefficient of 0.88 (99.9% confidence) is obtained, which justifies the use of flux obtained from sunspot proxy for our analysis.

3. Results

Asymmetry in torsional oscillation velocity across the equator is clearly observed in Figure 1(a), which is derived from the ring diagram analysis of GONG data. The contour plot of velocity obtained from global modes (Figure 1(b)), which assumes symmetry across the equator, is included for comparison. Figure 2 is the plot of temporal variation of torsional oscillation velocity for northern (blue) and southern (red) hemispheres at different depths and latitudes obtained from GONG observations. Here we plot the velocities at latitudes 7°, 22°, 30°, 37.6°, and 45°. This latitude range corresponds to the equatorward migrating branch of torsional oscillation. Local helioseismology restricts the velocity information to shallow depths from the surface. We consider the velocity at radial distances of 0.980, 0.990, and 0.997 R⊙. The time series for the torsional oscillation velocity at 0.990 R⊙ obtained from global modes at different latitudes is plotted.
along with the north and south velocities in the respective panels for comparison. Representative error bars (mean) are also shown along with the plots. The error values mentioned here are the mean of standard errors (δ) in velocity values. These are obtained from the standard deviations (σ) of the velocity values from the mean velocity of each year (δ = σ/√N, where N is the number of data points). Our observations cover the declining phase of cycle 23 and rising phase of cycle 24. It is observed that the magnitude of velocity increases with depth in both the hemispheres. Also the velocity amplitude decreases with latitude. It is clear from the figure that an asymmetry exists in velocity between the hemispheres at all depths and latitudes. The velocities appear to be more asymmetric beyond 2011. Also, the asymmetry appears to be high for higher latitudes. We quantify asymmetry as the difference of the velocity in the southern hemisphere from that in the northern hemisphere for each latitude and depth. The comparison with global mode velocity shows that the velocities obtained from both local and global techniques follow the same trend, with local modes providing hemispherical variation and global measurements providing lower errors. Our analysis is restricted above 0.980 \( R_e \) because the scatter in the data increases significantly below this depth (the mean standard error of 0.970 \( R_e \) is 3.81 m s\(^{-1}\), which is two times the error at 0.980 \( R_e \) of 1.72 m s\(^{-1}\)). The standard error is nearly the same for the three depths that are used for our analysis.

Figure 3 is the plot of hemispherical asymmetry in torsional oscillation velocity \((U_{\text{North}} - U_{\text{South}})\) at different depths and latitudes as a function of time. The positive value of asymmetry implies that the velocity of torsional oscillation in the northern hemisphere is greater than that in the southern hemisphere at the same time, depth, and latitude. It is observed that the
The solar magnetic cycle and torsional oscillation have similar migrating patterns. Thus, one may expect some correlation between the hemispherical asymmetry in torsional oscillations and magnetic flux. We average the near-surface torsional oscillation velocity (at 0.997 \( R_\odot \)) obtained from GONG observations over latitude depending on the location of magnetic features. The data are averaged over 7°.5–15° for the time interval 2002.2–2008, 15°–30° for 2008–2013, and 7°.5–22°.5 for 2013–2016.8 in both hemispheres. The latitude range for each interval is chosen depending on the location of active regions within that interval, such that the averaged velocity encompasses the active latitude. Hemispherical asymmetry is calculated from this averaged velocity over the whole observing period. We calculate the asymmetry in the magnetic flux and sunspot number (SSN) between the hemispheres obtained from RGO and USAF/NOAA sunspot data. Sunspot flux and SSN asymmetries are quantified in the same way as the velocity asymmetry. Figure 5 is the plot of this hemispherical asymmetry in velocity as a function of time, along with the asymmetry in sunspot flux scaled by 0.75 \( \times 10^{22} \) and SSN for the same period. We observe that the asymmetries in flux and number appear to be correlated with asymmetry in velocity over time with a time delay. The asymmetry in velocity is observed to be preceding the asymmetry in flux and SSN. We generate 1000 random sample sets of velocity asymmetry, flux, and SSN asymmetries based on their mean value and standard error at each time stamp. We do a correlation analysis of this random set of velocity asymmetry with the randomly generated sets of flux and SSN asymmetries for a range of time delays from 0 to 2.25 yr, with the asymmetry in velocity preceding the flux and SSN asymmetries. We obtain 1000 time delay values corresponding to the peak value of the Pearson correlation coefficient for each
A mean time delay of 1.41 ± 0.38 yr is obtained with a correlation coefficient of 0.72 (99.9% confidence) for the correlation between velocity and flux asymmetries. A correlation coefficient of 0.78 (99.9% confidence) is obtained for a mean time delay of 1.18 ± 0.23 yr between the velocity asymmetry and SSN asymmetry.

Next, we try to relate the asymmetry in velocity with the asymmetry in flux and SSN. The top panel of Figure 6 is a scatter plot of the asymmetry in flux versus asymmetry in torsional oscillation velocity with a time delay of 1.41 yr, with the latter preceding the former. This scatter plot is fitted with a straight line \( p_1 x + p_2 \) with coefficients \( p_1 = 8.47 \times 10^{21} \) Mx s\(^{-1}\) and \( p_2 = -6.37 \times 10^{21} \) Mx within 95% confidence bounds given by \( 7.16 \times 10^{21} \) Mx s\(^{-1}\), \( 9.77 \times 10^{21} \) Mx s\(^{-1}\) and \( -1.00 \times 10^{22} \) Mx, \( -2.70 \times 10^{21} \) Mx, respectively. The bottom panel is the scatter plot of asymmetry in sunspot number as a function of asymmetry in torsional oscillation with the velocity asymmetry preceding by 1.18 yr. The coefficients of the fitted line are \( p_1 = 0.99 \) s\(^{-1}\) and \( p_2 = -0.71 \) within 95% confidence bounds given by \( 0.87 \) s\(^{-1}\), \( 1.12 \) s\(^{-1}\) and \( -1.06, -0.36 \), respectively.

4. Conclusions

We report an asymmetry between the torsional oscillation velocities of the northern and southern hemispheres at all depths and latitudes. Basu & Antia (2003) studied asymmetry in solar rotation for nine Carrington rotations, but any definite
temporal variation in the asymmetry component was not observed. However, our study, using data for 16 yr, shows that there is temporal variation in the asymmetry and that it tends to be zero near the solar minima. There is an increase in asymmetry beyond 2012 at higher latitudes (Figure 3). A faster-than-average velocity region appeared at high latitudes around 2012–2014 in the southern hemisphere and around 2015–2016 in the northern hemisphere. The increase in asymmetry is because of the delay in the appearance of this region in the northern hemisphere. We speculate that these regions correspond to the poleward-migrating branches of the next sunspot cycle. For lower latitudes, the time of appearance of maximum asymmetry is delayed, and this delay corresponds to the migration of bands from higher to lower latitudes. Also the northern branch is observed to be migrating faster than the southern branch. A similar observation was made by Komm et al. (2014). It was observed from the time–distance analysis of HMI data by Zhao et al. (2014) and Zhao (2016) that the faster band of the equatorward-migrating branch of torsional oscillation in the northern hemisphere is closer to the equator than its southern hemisphere counterpart for the present cycle.

Figure 4. Asymmetry in torsional oscillation at a depth of 2 Mm obtained from the GONG observations (red), Mount Wilson surface velocity measurements (blue), and HMI observations at 2 Mm (green) for different latitudes as a function of time. The asymmetries are considered only for the GONG observing period. Error bars (mean) are given in respective panels.

Figure 5. Asymmetry in torsional oscillation (red) at 2 Mm, obtained by taking the latitudinal average of velocity for both hemispheres. Latitudinal average is done depending on the position of active regions at different epochs. The asymmetries in sunspot flux (blue) and sunspot number (green) are also plotted as a function of time.
The feedback of magnetic forces on flows can impact the velocities obtained by feature tracking, while these do not directly affect Doppler measurements. The difference in the asymmetries obtained from GONG and Mount Wilson velocities at low latitudes can be due to this reason. The absence of magnetic features at higher latitudes can affect the velocity measurements by feature tracking, and hence the Mount Wilson velocities show larger variations from the GONG measurements at these latitudes since the former are based on tracking the migration of magnetic features. The asymmetry derived from GONG observations is well correlated with that derived from HMI observations at all latitudes. Fluctuations and hence errors are high for GONG observations at higher latitudes. The variation between all three asymmetries at higher latitudes can also be due to projection effects.

Sunspots appear on the poleward boundary of the faster-rotating branch, and the equator moving bands are associated with the magnetic activity. The northern hemisphere attains peak velocity before the southern hemisphere because of the faster migration of the northern band within this time frame. Interestingly, observations show that the northern hemisphere attains maximum magnetic flux before the southern hemisphere. Howard & Labonte (1983) combined the torsional oscillation velocities for the northern and southern hemispheres and showed that the torsional oscillation precedes magnetic activity, increasing by ~1 yr before the total magnetic flux. We observe that the asymmetry in torsional oscillation appears to precede the asymmetry in magnetic flux by $1.41 \pm 0.38$ yr and sunspot number asymmetry by $1.18 \pm 0.23$ yr on average and that they are well correlated. We derive empirical relations connecting the asymmetry in velocity with flux and sunspot number. We speculate on the possibility of predicting the hemispherical asymmetry in magnetic cycle using the torsional oscillation asymmetry. Gigolashvili et al. (2005) suggest that the asymmetry in solar activity can be responsible for north-south asymmetry in solar differential rotation. But the time delay between the asymmetries, with velocity preceding the magnetic activity, and their strong correlation from our observations point to the possibility that the asymmetry in magnetic flux can be a consequence of asymmetry in torsional oscillations. Alternatively, the asymmetry in the deep-seated magnetic flux belt of a sunspot cycle before they are manifested at the surface may also generate an early asymmetry in near-surface torsional oscillation through a nonlocal (e.g., thermal shadow) effect. Further work with more accurate deep flow diagnostics and magnetohydrodynamic simulations is necessary to conclusively establish the physical process at play.

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Figure 6. Top panel: asymmetry in sunspot flux (t yr) vs. the asymmetry in torsional oscillation velocity (t−1.41 yr), fitted with a straight line of slope $8.47 \times 10^{-5}$ Mx s m$^{-1}$ and intercept $-6.37 \times 10^{-5}$ Mx. Bottom panel: asymmetry in sunspot number (t yr) vs. the asymmetry in torsional oscillation velocity (t−1.18 yr), fitted with a straight line of slope $0.99$ m s$^{-1}$ and intercept $-0.71$. The mean standard errors in the sunspot flux and number are shown in the respective panels.
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