Frequency separation variations of the solar low-degree p-modes

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Abstract

Variations of frequency separations of low-degree p-modes are studied over the solar activity cycle. The separations studied are obtained from the frequencies of low-degree p-modes of the Global Oscillation Network Group (GONG). 10.7 cm radio flux is used as an index of solar activity. Small separations of the p-mode frequencies are considered to be mainly dependent on the conditions in stellar interiors. Thus they could be applied to diagnose the changes in the stellar interior. Our calculation results show that the magnitudes of variations of the mean large separations are less than 1 $\sigma$ over the solar activity cycle. Small separations show different behaviors in the ascending and descending phases of activity. In the ascending phase, variations of the small separations are less than 1 $\sigma$. However, the small separations have systematic shifts during 2004 - 2007. The shifts are roughly 1 $\sigma$ or more. The variations of the ratios of the small to large separations with time are similar to the changes of the small separations. The effects of the changes in the large separations on the ratios are negligible. The variations of the separations may be a consequence of the influence from the surface activity or systematic errors in measurements or some processes taking place in the solar interior.

Key words: star: oscillations – Sun: oscillations – Sun: activity – Sun: interior

1. Introduction

It is well-known that the solar p-mode frequencies vary with the solar cycle (Woodard & Noyes 1985; Elsworth et al. 1990; Libbrecht & Woodard 1990; Elsworth et al. 1994; Jiménez-Reyes et al. 1998; Howe et al. 1999; Chaplin et al. 2007). It has been shown that the variations of the frequencies are significantly related to magnetic activities near the solar surface (Woodard et al. 1991; Jiménez-Reyes et al. 2004; Toutain & Kosovichev 2005). However, a number of
attempts have been made to detect the relation between the frequency shifts and the variation of the solar interior. It has been proposed that the frequency shifts may relate to changes taking place in the base of the convection zone (Jiménez-Reyes et al. 1998; Serebryanskiy & Chou 2005), or in the deep core (Jiménez-Reyes et al. 1998).

Low-degree p-modes can be used to study the solar core because they can penetrate the deep interior (Dziembowski & Goode 1997). However, even these modes are primarily sensitive to the solar envelope structure. Thus frequency separations are proposed for a diagnostic tool. The frequency separations of low-degree p-modes in solar-like stars often proposed for diagnostic purposes are large separations $\Delta_l(n)$ and small separations $d_{ll+2}(n)$. The large separations approximate to the characteristic frequency $\nu_0$ of a star, defined by

$$\Delta_l(n) \equiv \nu_{n,l} - \nu_{n-1,l} \simeq \nu_0,$$

where

$$\nu_0 = (2 \int_0^R \frac{dr}{r} / c)^{-1},$$

in which $c$ is sound speed at radius $r$ and $R$ is some fiducial radius of the star. The small separations are sensitive to the structure of stellar core (Gough & Novotny 1990), defined by

$$d_{ll+2}(n) \equiv \nu_{n,l} - \nu_{n-1,l+2} = \frac{\varphi_{l+2} - \varphi_l}{\pi} \nu_0,$$

where $\varphi_l$ is the internal phase shift. For the low-degree p-modes, the $\varphi_l$ is mainly dependent on conditions in the stellar core and is almost independent of those outside the core (Roxburgh & Vorontsov 2003). These frequency separations have been extensively investigated by many authors (Christensen-Dalsgaard 1984; Ulrich 1986; Ulrich 1988; Gough 1987; Gough 1990; Gough 2003; Gough & Novotny 1990; Roxburgh & Vorontsov 2003; Audard & Provost 1994; Roxburgh 2005; Otí Floranes et al. 2005). Additionally Roxburgh (1993) defines differences $d_{01}(n)$ as

$$d_{01}(n) \equiv \frac{-\nu_{n,1} + 2\nu_{n,0} - \nu_{n-1,1}}{2} = \frac{\varphi_0 - \varphi_1}{\pi} \nu_0,$$

and Yang & Bi (2007) define differences $\sigma_{l-1l+1}(n)$ of low-degree p-modes as

$$\sigma_{l-1l+1}(n) \equiv -\nu_{n,l-1} + 2\nu_{n,l} - \nu_{n,l+1} = \frac{\varphi_{l+1} - \varphi_{l-1} - 2\varphi_1}{\pi} \nu_0.$$

The differences $\sigma_{02}(n)$ are similar to the scaled small separations $d_{ll+2}(n)/(2l+3)$ in some cases and are mainly sensitive to conditions in stellar core. The difference $\sigma_{02}$ averaged over $n$ is, however, more sensitive to changes in the central hydrogen abundance of solar-like stars than the scaled small separations (Yang & Bi 2007).

Moreover, the ratios $d_{ll+2}/\Delta_l$ are considered to be essentially independent of the structure of the outer layers of a star and determined by interior structures (Ulrich 1986; Roxburgh & Vorontsov 2003; Roxburgh 2005; Otí Floranes et al. 2005). The ratios $d_{01}/\Delta_0$ and $\sigma_{02}/\Delta_0$ also...
mainly rely on the interior structures (Roxburgh & Vorontsov 2003; Yang & Bi 2007). Thus changes in stellar interior could be indicated by the variations in these separation ratios.

However frequency variations with solar activity are relative to the angular \((l)\) degree, the azimuthal \((m)\) degree, and the order \(n\). The \(m\)-dependence is attributed to the solar near-surface activity (Jiménez-Reyes et al. 2004; Toutain & Kosovichev 2005) and could be removed by using the frequency centroids which incorporate all the \(m\) components of a mode (Chaplin et al. 2005). For the low-degree \(p\)-modes, centroid shifts can be regarded as being \(l\)-independent (Chaplin et al. 2005). Thus separations of frequency centroids of low-degree \(p\)-modes should be insensitive to effects of surface activity. Using the \(p\)-modes of the Birmingham Solar-Oscillations Network (BiSON) collecting data using a Sun-as-a-star technique, Chaplin et al. (2005) studied the impact of the solar activity cycle on the frequency separation ratios and found that the ratios change with the shifting level of global solar activity. Chaplin et al. (2005) pointed out that some \(m\) components are suppressed in the Sun-as-a-star observations and hence the ratios are expected to be affected by the surface activity. In this paper, we investigate the variations of frequency separations of low-degree \(p\)-modes as solar activity cycle proceeds using data collected by the resolved-Sun observations. In Section 2 we present our data and results. Then discussion and conclusion are represented in Section 3.

2. Data and results

In this work, we used the solar \(p\)-mode frequencies of the GONG (Harvey et al. 1996) to study the separations. The GONG was planned for measurements of medium and high spherical degrees, but low-degree \(p\)-modes can be measured too. Gavryusev & Gavryuseva (1999) showed that the low-\(l\) \(p\)-modes of the GONG are in good agreement with that of the Michelson Doppler Imager (MDI) and the Global Oscillations at Low Frequency (GOLF). The raw data of GONG are measured in a time series of 36 days labeled a GONG month. A 108-day time series is constructed by concatenating 3 consecutive GONG-month time series. GONG Month Mode Frequencies (GMFs) were then estimated from the 108-day spectra (Anderson et al. 1990; Hill et al. 1998; Komm et al. 1999; Howe et al. 1999). In the observation of GONG, the solar disk is imaged onto many pixels. The obtained images can then be decomposed into their constituent spherical harmonics. For each degree \(l\) and overtone \(n\), this imaging strategy provides access to all \(2l+1\) components with each being tagged by an azimuthal degree \(m\) (Chaplin et al. 2004).

The frequencies, \(\nu_{n,l,m}\), extracted from resolved-Sun observations are usually represented by

\[
\nu_{n,l,m} = \nu_{n,l} + \sum_{j=1}^{2l} a_j(n,l) l P^j_l(m),
\]

where \(P^j_l(m)\) are polynomials related to Clebsch-Gordan coefficients (Ritzwoller & Lavely 1991;
Fig. 1. Differences between the averages obtained using equation (7) and the centroids estimated by the GONG team. Circles represent the differences of frequencies of the GONG months 8, 9, and 10 (low activity), while crosses correspond to the differences of frequencies of the GONG months 58, 59, and 60 (high activity). Triangles show the errors of GONG centroids of month 8.

Chaplin et al. (2004) and \( \nu_{c}^{n,l} \) is the so-called central frequency of the multiplet (i.e. frequency centroid). Using the polynomials \( P_{j}^{l}(m) \) given by Chaplin et al. (2004) and equation (6), one can get the central frequency of low-degree p-modes of the resolved-Sun observations,

\[
\nu_{c}^{n,l} = \sum_{m=-l}^{l} \frac{\nu_{n,l,m}}{2l+1}.
\]  

(7)

The central frequencies are sensitive to the spherically symmetric component of the internal structure of a star and are usually used as inputs to inversions of the internal structure (Chaplin et al. 2004; Chaplin et al. 2005).

In order to study the variations of frequency separations with the solar activity cycle, we used the GMFs observed between 1996 and 2007. Centroids \( \nu_{n,l} \) and individual frequencies \( \nu_{n,l,m} \) of the GMFs were published by the GONG team\(^1\). Some centroids \( \nu_{n,l} \) published are inconsecutive in the order \( n \), especially for the modes with \( l = 1 \), but the frequencies \( \nu_{n,l,m} \) are consecutive. In order to obtain separations, we used the averages \( \nu_{c}^{n,l} \) of all \( 2l+1 \) components of each mode instead of the centroids \( \nu_{n,l} \). In figure 1, we compared the averages obtained using equation (7) with the available centroids estimated by the GONG team. The differences between the frequencies obtained using equation (7) and the available GONG centroids are almost much less than the errors of the GONG centroids in the range of \( 2400 \ \mu\text{Hz} < \nu < 3500 \ \mu\text{Hz} \) except a few modes, whose differences are close to the errors of the GONG centroids. In this range, the averages obtained using equation (7) are good consistent with the centroids estimated by the GONG team. All the following frequency separations are obtained from the averages.

Figure 2 shows fractional changes of the separation ratios in two sets of GMFs, one at

\(^{1}\) ftp://gong2.nso.edu/MFS/
Fig. 2. Fractional changes between the separations ratios in two GMFs, one at a high level (2001) and one at a low level of activity (1996) (the differences are in the sense "high data - low data").

Table 1. Results of linear fits between separations and time. Left panel for the ascending phase of solar activity, while right panel for the during ∼ 2004 to 2007 except for the large separations.

| Separation | Ascending phase | From ∼ 2004 to 2007 |
|------------|----------------|---------------------|
|            | Slope (nHz/year) | χ² | R | Slope (nHz/year) | χ² | R |
| < d₀₂ >    | - 6.9 ± 5.1     | 0.228 | 0.177 | - 35.4 ± 7.6 | 0.019 | 0.697 |
| < d₀₁ >    | 1.1 ± 5.3       | 0.244 | 0.027 | - 76.9 ± 13.4 | 0.058 | 0.768 |
| < σ₀₂ >    | - 9.9 ± 7.1     | 0.446 | 0.184 | 108 ± 23   | 0.179 | 0.692 |
| < d₁₃ >    | - 8.6 ± 3.3     | 0.092 | 0.327 | 43.0 ± 9.0 | 0.029 | 0.691 |
| < Δ₀ >     | 11.8 ± 2.8      | 0.072 | 0.485 | - 14.7 ± 2.3ᵇ | 0.041 | 0.654 |
| < Δ₁ >     | 5.2 ± 2.2       | 0.041 | 0.303 | - 11.4 ± 1.3ᵇ | 0.012 | 0.771 |
| < d₀₂/3Δ₀ >| - (1.9 ± 1.2)×10⁻⁵ | 1.3×10⁻⁶ | 0.205 | - (8.8 ± 1.9)×10⁻⁵ | 1.2×10⁻⁷ | 0.698 |
| < d₀₁/Δ₀ > | (5.6 ± 3.9)×10⁻⁵ | 1.3×10⁻⁵ | 0.019 | - (5.7 ± 1.0)×10⁻⁴ | 3.2×10⁻⁶ | 0.766 |
| < σ₀₂/Δ₀ > | - (7.5 ± 5.3)×10⁻⁶ | 2.5×10⁻⁵ | 0.188 | (8.0 ± 1.7)×10⁻⁴ | 9.8×10⁻⁶ | 0.694 |
| < d₁₃/5Δ₁ >| - (1.4 ± 0.5)×10⁻⁵ | 2.0×10⁻⁷ | 0.348 | (6.5 ± 1.4)×10⁻⁵ | 6.2×10⁻⁸ | 0.699 |

a. Not for ratios.

b. The results were obtained from the data between ∼ 2001 and 2007.

da low level and one at a high level of activity. The error bars indicate 1 σ errors, which were propagated from uncertainties on the individual frequencies of the GMFs. The departure of the separation ratios from the null level is within 1 σ but shows a systematic shift, which is consistent with the prediction of the 108 day spectra of Chaplin et al. 2005 (in their figure 1).

However, just as the observed shifts of ratios of the BiSON frequencies (Chaplin et al. 2005), ‘the shifts are clearly not significant for individual estimates of the ratios’. In the interest of temporal variations of separations, for each set of separations with the same degree l, we averaged the separations over n in the range of 2400 µHz < νₙ,l < 3500 µHz, which was implied by symbols <>. The frequency range is often used to obtain a mean frequency shift (Elsworth et al. 1994; Jiménez-Reyes et al. 2004).

Figure 3 shows the temporal variation of mean separations < dₙₙ+₂ >, < σ₀₂ >, < d₀₁ >,
Fig. 3. Temporal variation of separations. The error bars represent 1 σ errors. The thin lines show the linear fits between the plotted quantities in the ascending phase of the solar activity, while the thick lines indicate the linear fits in the descending phase of the solar activity. Sunspot number and 10.7 cm radio flux are plotted too. 1 SFU = $10^{-22}$ W m$^{-2}$ Hz$^{-1}$. 
Table 2. Results of linear fitting between separations and 10.7 cm radio flux.

| Separation | Ascending phase | From ~ 2004 to 2007 |
|------------|-----------------|---------------------|
|            | Slope (nHz/SFU) | χ²       | R    | Slope (nHz/SFU) | χ²       | R    |
| < d₀₂ >    | -0.34 ± 0.19    | 0.223 | 0.235 | 2.13 ± 0.69 | 0.026 | 0.542 |
| < d₀₁ >    | 0.024 ± 0.197   | 0.244 | 0.016 | 5.6 ± 1.1  | 0.068 | 0.722 |
| < σ₀₂ >    | -0.33 ± 0.27    | 0.449 | 0.162 | -8.4 ± 1.8 | 0.176 | 0.699 |
| < d₁₃ >    | -0.25 ± 0.13    | 0.096 | 0.254 | -3.2 ± 0.8 | 0.032 | 0.657 |
| < Δ₀ >     | 0.33 ± 0.11     | 0.081 | 0.361 | 0.57 ± 0.09ᵃ | 0.041 | 0.648 |
| < Δ₁ >     | 0.22 ± 0.08     | 0.040 | 0.329 | 0.45 ± 0.05ᵃ | 0.012 | 0.791 |

ᵃ. The results were obtained from the data between ~ 2001 and 2007.

< Δ₀ > and < Δ₁ >. Sunspot numbers and 10.7 cm radio flux² (F10), which are always used as an index of the solar activity, are also plotted as a function of time. The activity indices have been averaged over the same time interval covered by the GONG date. The error bars show 1 σ errors, which come from the formal errors on the frequencies. When averaging these separations from each spectrum, the correlations of neighbouring separations were considered. The lines in this figure represent the results of linear least-squares fits. The fits in the descending phase of solar activity were divided into two periods in accordance with the variations of separations: one from ~ 2001 to 2004 and one from ~ 2004 to 2007. Variations in the latter period are more obvious and systematic. The mean large separations < Δ₀ > and < Δ₁ > increase/decrease in the ascending/descending phase of solar activity and reach a maximum in 2001. However, the magnitude of the shifts of the large separations is about 0.07 µHz, which is less than 1 σ. Variations of small separations with time are more complicated than those of the large separations. In the ascending phase of solar activity, the separations < d₄₄+2 >, < σ₀₂ > and < d₀₁ > almost have no systematic shifts; the magnitudes of the shifts of these separations, obtained from their regression equations, are also less than 1 σ. In the descending phase of solar activity, variations of these separations seem to be disorderly. Between 2001 and 2002, the separations < σ₀₂ > and < d₁₃ > increase suddenly. They decrease firstly and then increase obviously between ~ 2001 and 2007. However, the magnitudes of their shifts are roughly 1 σ or more. The separation < d₀₁ > has an obvious and systematic decrease between ~ 2004 and 2007. The magnitude of the variation is about 1.5 σ. The separation < d₀₂ > decreases slightly between ~ 2001 and 2007, but the magnitude is less than 1 σ. The results of linear fits: slope, residual sum of squares χ², and correlation coefficient R of regression equations, are summarized in Table 1.

In order to further understand the variations of separations with the solar activity, Figure 4 shows separations plotted against F10 in the ascending phase of solar activity. Figure

² www.ngdc.noaa.gov/stp/SOLAR/getdata.html
4 shows that the separations almost not vary with activity. The results of linear least-squares fits between the separations and F10 are summarized in the left panel of Table 2. The magnitudes of variations of these separations are only about 0.04 µHz, which is less than 1 σ. Moreover, Figure 5 shows that the changes of the large separations with the F10 in the descending phase of the solar activity. The shifts of the large separations are also less than 1 σ. Figure 5 also shows the variations of small separations with the F10 during ∼ 2004 - 2007. In this period of time, the changes of these separations with the F10 are obvious and systematic. However, the magnitudes of variations of these separations are around 1 σ or more. The results of linear fits between the separations and F10 are shown in the right panel of Table 2.

In Figure 6, we show the temporal variations of separation ratios \( \langle d_{02}/3\Delta_0 \rangle \), \( \langle d_{13}/5\Delta_1 \rangle \), \( \langle d_{01}/\Delta_0 \rangle \) and \( \langle \sigma_{02}/\Delta_0 \rangle \). The results of linear fits between the ratios and time are presented in Table 1. The changes of the ratios with time are similar to those of the corresponding small separations. In the ascending phase of solar activity, shifts of the ratios are less than 1 σ. In the descending phase of activity, from ∼ 2004 to 2007, the changes of the ratios with time are systematic. However, the magnitudes of the changes are still roughly 1 σ or more. Since the fractional changes of the large separations are much less than those of small separations during the activity, the contribution to the changes in the ratios from the variations of the large separations is much less than that from the small separations. The effects of the
Fig. 5. Mean separations observed between \( \sim \) 2004 and 2007 are plotted as a function of 10.7 cm radio flux. But the large separations are observed between \( \sim \) 2001 and 2007. The error bars indicate 1 \( \sigma \) errors. The lines represent the best linear fits between the plotted quantities.

Fig. 6. Temporal variations of separation ratios. The error bars indicate 1 \( \sigma \) errors. The lines show the linear fits between the plotted quantities.
changes in the large separations on the changes in the ratios are almost negligible. The changes in the ratios with time are mainly determined by the changes in the small separations.

The magnitudes of temporal variations for some individual separations are very large but should not be significant. In the ascending phase of the solar activity, the magnitudes of variations of separations, obtained from regression equations, are about 0.04 $\mu$Hz, which is less than 1 $\sigma$. During $\sim$ 2004 - 2007, the changes in separations are systematic. However, the magnitudes of the changes are roughly 1 $\sigma$ or more. Using BiSON data, Chaplin et al. (2005) show that variations of the separation ratios between low and high activity is at a marginal level of significance. Moreover, using simple averages, from the gradient of mean frequency shift of the MDI given by Jiménez-Reyes et al. (2004) in their Table 1, one can get a shift gradient in the centroids would be 1.61 and 2.02 nHz/SFU for $l = 0$ and 2 respectively. For a 120 SFU increase in solar activity, the change in separation $<d_{02}>$ would then be about 0.05 $\mu$Hz, which is consistent with our result.

3. Discussion and conclusion

The characteristic frequency $\nu_0$, i.e. the large separation, is an integral property of the entire star. Because the solar sound speed is a decreasing function of the solar radius, the contribution to $\nu_0$ from the outer layers of the Sun is larger than that from the solar inner regions (Gough & Novotny 1990). Thus the large separation should be more sensitive to the changes in the outer layers than those in the inner regions and could be affected by the near surface activity. Moreover small separations are more sensitive to the conditions in stellar interior than those in outer layers. Thus the large separations should be more sensitive to the activity than the small separations. However, in fact, the magnitudes of variations of the large separations are about 0.07 $\mu$Hz during the activity, which is less than 1 $\sigma$. The magnitude of variations of $<d_{02}>$ is also less than 1 $\sigma$ over the activity cycle. However, other small separations show a systematic shift during $\sim$ 2004 - 2007, and the magnitudes of their variations are roughly 1 $\sigma$ or more.

Small separations $<d_{l+2}>$, $<\sigma_{02}>$ and $<d_{01}>$ show a sudden change between 2001 and 2002. The fractional changes shown in Figure 2 of ratios in two GMFs (one in 1996 and one in 2001) are consistent with the prediction of Chaplin et al. (2005). However, if we use the data of 2002 instead of the data of 2001, the results would be different. The small separations show different behaviors in the ascending and descending phases of the cycle. In the ascending phase, variations of the small separations are less than 1 $\sigma$. In the descending phase, the small separations show a systematic shift during 2004 - 2007. And the magnitudes of the changes in $<d_{13}>$, $<\sigma_{02}>$ and $<d_{01}>$ are roughly 1 $\sigma$ or more. It is not clear whether the variations are caused by the systematic errors in measurements.

The large separations increase slightly with increasing of the solar activity. But the magnitudes of temporal variations of the mean large separations of the low-degree p-modes are
only about 0.07 μHz over the activity cycle, which is less than 1 σ. Small separations \(< d_{ll+2} >\), \(< \sigma_{02} >\) and \(< d_{01} >\) show different behaviors in the ascending and descending phases of the cycle. In the ascending phase, variations of the small separations are less than 1 σ. However, the small separations show a systematic shift during 2004 - 2007. The magnitudes of the changes in \(< d_{01} >\), \(< \sigma_{02} >\) and \(< d_{13} >\) in this period of time are about 1 σ or more. The variations of the ratios of the small to large separations with time are similar to the changes of the small separations. Changes in the large separations have a negligible impact on the variations in the ratios. The variations of the separations may be a consequence of the influence from the surface activity or systematic errors in measurements or some processes taking place in the solar interior. For further work, the data over cycle 22/23 would be required.

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