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PROPERTIES OF SOLAR GRAVITY MODE SIGNALS IN TOTAL IRRADIANCE OBSERVATIONS

Ronald J. Kroll, Jian Chen* and Henry A. Hill

Department of Physics
University of Arizona
Tucson, Arizona 85721

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*Chen Jian is a graduate student of Beijing Astronomical Observatory, Beijing, People's Republic of China. currently studying at the University of Arizona.

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ABSTRACT

Further evidence has been found that a significant fraction of the gravity mode power density in the total irradiance observations appears in sidebands of classified eigenfrequencies. These sidebands whose amplitudes vary from year to year are interpreted as harmonics of the rotational frequencies of the nonuniform solar surface. These findings are for non axisymmetric modes and corroborate the findings of Kroll, Hill and Chen (Ref. 1) for axisymmetric modes. It is demonstrated that the generation of the sidebands lifts the usual restriction on the parity of the eigenfunctions for modes detectable in total irradiance observations.

1. INTRODUCTION

It has been reported by Kroll, Hill and Chen (Ref. 1) that for the $\ell = 2,3,4$ and 5, $m = 0$ classified gravity modes of Hill and Gu (Ref. 2), a significant fraction of the gravity mode power density in the total irradiance observations appears in sidebands of the eigenfrequencies where ℓ and m refer to the degree and angular order of the eigenfunction, respectively. The total irradiance observations were obtained with the Active Cavity Radiometer Irradiance Monitor [ACRIM] (Ref. 3) on the solar Maximum Mission. They also conclude that these sidebands are produced by the rotation of a nonuniform solar surface. Other examples of the manifestations of a rotating nonuniform surface are well documented (Refs. 4-8). Such findings as those reported by Kroll, Hill and Chen (Ref. 1) may impact in a rather dramatic way on how total irradiance observations are used in a solar seismology program. The presence of these surface-rotation associated sidebands adds considerable complexity to the power spectra and significantly reduces the signal-to-noise ratio from what is normally expected for the symmetry allowed gravity modes signals (ℓ+m even). Although the additional complexity in the power spectra reduces the effectiveness of total irradiance observations in the study of even (ℓ+m) gravity modes, the generation of the sidebands lifts the usual restriction of the parity of the eigenfunction (ℓ+m must be even) that can be detected in whole disk type observations. As a result, it should be possible to study gravity modes with even and odd values of (ℓ+m) in solar total irradiance. It may also be possible with a refined analysis to test the sign of the assigned values of m and obtain information on the values of ℓ.

The lifting of the usual restriction on the eigenfunction parity for the detectable modes in total irradiance observations has already been demonstrated (Ref. 1) in the case of $\ell = 3$ and 5, m=0 gravity modes classified by Hill and Gu (Ref. 2). We further examine the total irradiance observations in the following sections for additional evidence of deviations of the observed eigenfunction from that expected for an axisymmetric system for the gravity modes classified by Hill and Gu (Ref. 2) with $|m| \geq 1$.

In general, the rotating nonuniform surface of the Sun will lead to gravity mode power density at sidebands of the eigenfrequencies $\nu_{n\ell m}$ of the normal modes where n specifies the radial order of the eigenfunction. We assume that the nonuniform rotating surface effects on the observed radiation intensity I' can be described to a good approximation by

$$I' = A\, Y_{\ell}^{m}(\theta,\phi)\; f(\theta,\phi-\Omega t)\; e^{i2\pi\nu_{n\ell m}t} \quad , \qquad (1)$$

where A is a complex amplitude, Ω is the angular rotational speed of the surface which is a function of θ; θ and ϕ are heliocentric spherical coordinates, and t is the time variable. For a uniform surface, $f \equiv 1$. It is implicitly assumed that f changes slowly over the period of months, at least that part of f relevant to these observations.

The frequency locations of the sidebands of the $\nu_{n\ell m}$ where gravity mode associated power density is predicted are determined by the θ and ϕ dependence of f and the θ dependence of Y_{ℓ}^{m} and Ω. The maximum value of Ω is 428nHz observed at the equator and the minimum value is 295nHz observed at the poles of the Sun (Ref. 9).

2. TOTAL IRRADIANCE OBSERVATIONS

Observations of solar total irradiance made during 1980 and 1984 with ACRIM are used for this analysis. Obvious spikes in the data are removed and the data effectively high-pass filtered with a cutoff frequency of $\approx 4\mu$Hz. The time series were also low-pass filtered (triangular filter) with the first zero at 1mHz.

The time series for each year are then divided approximately in half resulting in two 135.40 d time series from 1980 and 118.14 d and 116.85 d time series from 1984. Four power spectra are then computed from the Fast Fourier Transform of each of the data sets.

3. POWER SPECTRUM ANALYSIS PROGRAM AND RESULTS

The properties of the total irradiance power spectra are studied by examining the mean power density and mean square deviations of the power density in the 1980 and 1984 power spectra separately. The two years are treated separately because a higher noise level is observed in 1980 relative to 1984. The mean power density and the mean square deviations of the power density are independent quantities and both are examined for properties of the gravity mode signals. Differences between the mean power density at frequencies where gravity mode associated sideband power density is predicted and the mean power density at frequencies where only background power density is expected are calculated. Similar differences are calculated for the mean square deviations of the power density.

The frequencies at which the power spectra were examined are given by $|\Delta\nu|$ = 0.35, 0.42, 0.64, 0.71, 0.78, 0.85, 0.98, 1.05, 1.12, 1.19, 1.26, 1.39, 1.46, 1.53, 1.60 and 1.67 μHz where $\Delta\nu = \nu - \nu_{n\ell m}$. These frequencies sample the 1st, 2nd, 3rd and 4th harmonic sidebands of Ω centered on the $\nu_{n\ell m}$ at the frequency spacing of 0.07μHz. The sample spacing of 0.07μHz approximates the frequency resolution of the power spectra which is $\approx$ 0.086μHz. The $|\Delta\nu_{bg}|$ = 0.27, 0.50, 0.57 and 0.92μHz were used for obtaining observed values of mean background power density and mean square deviations of the background power density. The $\Delta\nu_{bg}$ fall outside of the frequency bands belonging to the predicted gravity mode associated sidebands. This analysis is restricted to the ℓ = 1, 2, 3, 4 and 5, $|m| \geq 1$ modes with $75 \leq \nu_{n\ell m} \leq 135\mu$Hz that have been classified by Hill and Gu (Ref. 2). For the ℓ = 1, 2, 3, 4 and 5, $|m|$=1 modes, there are 8, 11, 11, 10 and 11 classified modes, respectively and for the $\ell = 2, 3, 4$ and 5 $|m|=2$ modes, there are 9, 11, 8 and 5, respectively. These numbers for modes classified per ℓ and $|m|$ value are also typical for the classified modes with $|m| \geq 3$.

The mean power density difference for a given $|\Delta\nu|$, year and value of ℓ is denoted by $\Delta\bar{P}_{\Delta\nu}$ where $\Delta\bar{P}_{\Delta\nu}$ is defined for a given mode as

$$\Delta\bar{P}_{\Delta\nu} = \overline{P(\Delta\nu)} - \bar{P}_{bg} \quad , \qquad (2)$$

$\bar{P}$ is the average of the power density over the radial order n, the two power spectra for a specified year and $\Delta\nu = \pm|\Delta\nu|$; $\bar{P}_{bg}$ is the average of the power density over the two power spectra for the specified year and over the set of $\Delta\nu = \pm|\Delta\nu_{bg}|$. The difference of the mean square deviations of power density denoted by $\Delta\,\overline{(P-\bar{P})^2}_{\Delta\nu}$ is defined in a similar manner as

$$\Delta\,\overline{(P-\bar{P})^2}_{\Delta\nu} = \overline{\left[P(\Delta\nu) - \bar{P}(\Delta\nu)\right]^2} - \overline{(P-\bar{P})^2}_{bg} \quad , \qquad (3)$$

where $\overline{\left[P(\Delta\nu) - \bar{P}(\Delta\nu)\right]^2}$ is the average of the square deviation of power density over the radial order n, the two power spectra for the specified year and $\Delta\nu = \pm|\Delta\nu|$ and $\overline{(P-\bar{P})^2}_{bg}$ is the average of the square deviation of the power density over the two power spectra for the specified year and over the set of $\Delta\nu = \pm|\Delta\nu_{bg}|$.

Under the null hypothesis that no gravity mode signals are present and/or the gravity mode classifications are incorrect on the whole, the various possible sums of $\Delta\bar{P}_{\Delta\nu}/\sigma_1$ and $\Delta\overline{\left(P-\bar{P}\right)^2_{\Delta\nu}}/\sigma_2$ should all be zero, where σ_1 and σ_2 are the respective standard deviations of the $\Delta\bar{P}_{\Delta\nu}$ and $\Delta\left(P-\bar{P}\right)^2_{\Delta\nu}$ used in a given sum. To test the null hypothesis for each value of $|m|$, we first look for each $|m|$ value at the combined sums of $\Sigma\ (\Delta\bar{P}_{\Delta\nu}/\sigma_1)$ and $\Sigma\ [\overline{\Delta(P-\bar{P})^2_{\Delta\nu}}/\sigma_2]$ for 1980 and 1984, the 32 $\Delta\nu$ corresponding to the first four harmonics of Ω and for $\ell = 2, 3, 4$ and 5. The results are

$$\Sigma\frac{\Delta\bar{P}_{\Delta\nu}}{\sigma_1} + \Sigma\frac{\overline{\Delta(P-\bar{P})^2_{\Delta\nu}}}{\sigma_2} = \left\{\begin{array}{rl} 18.509 \pm 6.32; & |m| = 1 \\ 4.402 \pm 5.66; & |m| = 2 \\ -10.938 \pm 4.90; & |m| = 3 \\ 9.806 \pm 4.00; & |m| = 4 \\ -4.954 \pm 2.83; & |m| = 5 \end{array}\right. . \qquad (4)$$

The distribution of $\Sigma\ \frac{\Delta\bar{P}}{\sigma_1} + \Sigma\ \frac{\overline{\Delta(P-\bar{P})^2}}{\sigma_2}$ in Equation (4) is consistent with that which would be predicted if the mode classifications are correct and if there are gravity mode associated sideband signals in the power spectra of total irradiance observations. Based on the observed amplitudes of the g-mode signals obtained with the 1979 differential radius observations (Ref. 10) and the m dependence of the spatial filter function appropriate to these latter observations (Refs. 11,12), it is predicted that the gravity mode power density in the total irradiance observations should be approximately proportional to $1/(1+0.5m^2)$. Using the actual values published for the spatial filter function, the $|m|=1$ value in Equation (4), and taking into account the number of classified modes used for each value of $|m|$, we would predict that these corresponding signals for $|m|=2$, 3, 4 and 5 would be 8.3 ± 2.9, 4.5 ± 1.6, 1.6 ± 0.6 and 0.8 ± 0.3. Similar values would result if the predictions were based on the m=0 results obtained by Kroll, Hill and Chen (Ref. 1) for

$$P_{\Delta\nu}/\sigma_1) \text{ and } \Sigma\ [\overline{\Delta(P-\bar{P})^2}_{\Delta\nu}/\sigma_2].$$

It is apparent from the predicted distribution of gravity mode associated signals and the standard deviations quoted in Equation (4) that it is only meaningful to test at this time for $|m| = 1$ gravity mode related signals. For this reason the analysis in the following sections will be confined to consideration of the $|m|=1$ classified modes except when performing tests with the set of unclassified modes.

The probability p for obtaining the result for $|m|=1$ in Equation (4) assuming that the null hypothesis is correct and assuming a normal distribution for the sum is

$$p = 1.7 \times 10^{-3} \quad . \qquad (5)$$

This finding indicates that it is unlikely that the null hypothesis is correct for the $|m|=1$ modes. More specifically, for the hypothesis that gravity mode associated sidebands are not present, this finding indicates that it is equally unlikely that this hypothesis is correct.

The preceeding test was repeated for the modes which were not classified in the work of Hill and Gu (Ref. 2) with $\ell = 1, 2, 3, 4$ and 5, $|m| \geq 0$ and with $75 \leq \nu_{n\ell m} \leq 135\mu Hz$. The results are

$$\Sigma \frac{\Delta\bar{P}_{\Delta\nu}}{\sigma_1} + \Sigma \frac{\overline{\Delta(P-\bar{P})^2_{\Delta\nu}}}{\sigma_2} = \begin{cases} 3.50 \pm 4.47; & |m| = 0 \\ -3.42 \pm 5.66; & |m| = 1 \\ 8.50 \pm 5.66; & |m| = 2 \\ 4.19 \pm 4.90; & |m| = 3 \\ -3.80 \pm 4.47; & |m| = 4,5 \end{cases} . \qquad (6)$$

These results are consistent with the predicted null hypothesis that no gravity mode associated signals are present. In particular, the results in Equation (6) are consistent with zero for the $|m|=0$ and $|m|=1$ unclassified modes.

We now return to the $|m|=1$ modes for a series of diagnostic tests because of the statistical significance of the $|m|=1$ results given in Equations (3) and (6). First for the $|m|=1$ modes, the combined sums of $\Sigma\ (\Delta\bar{P}_{\Delta\nu}/\sigma_1)$ and $\Sigma \left[\overline{\Delta(P-\bar{P})^2_{\Delta\nu}}/\sigma_2\right]$ over $\ell = 1, 2, 3, 4$ and 5 and the 32 $\Delta\nu$ are examined for 1980 and 1984 separately. Under the null hypothesis that no gravity mode signals are present and/or the gravity mode classifications are incorrect on the whole, the sums for 1980 and 1984 should both be zero. The results are:

$$\Sigma \frac{\Delta\bar{P}_{\Delta\nu}}{\sigma_1} + \Sigma \frac{\overline{\Delta(P-\bar{P})^2_{\Delta\nu}}}{\sigma_2} = \begin{cases} 9.76 \pm 4.47; & 1980 \\ 8.74 \pm 4.47; & 1984 \end{cases} . \quad (7)$$

The probability p for obtaining these results assuming that the null hypothesis is correct and assuming a normal distribution for the respective sums is

$$p = \begin{cases} 0.015 & ; \quad 1980 \\ 0.025 & ; \quad 1984 \end{cases} . \quad (8)$$

These findings indicate that it is unlikely that the null hypothesis is correct for both 1980 and 1984.

It is interesting to note that the strength of the sidebands for the ℓ = 1, 3 and 5 classified modes is similar to that observed for the sidebands of the ℓ = 2 and 4 classified modes. For a relative measure of these strengths, the combined sums of $\Sigma \left(\Delta\bar{P}_{\Delta\nu}/\sigma_1\right)$ and $\Sigma \left[\overline{\Delta(P-\bar{P})^2_{\Delta\nu}}/\sigma_2\right]$ are calculated separately for the even ℓ = 2 and 4 modes and the odd ℓ = 1, 3 and 5 modes. In this case, the sums are extended over 1980 and 1984, the 32 values of $\Delta\nu$ and the respective even and odd values of ℓ. The results are:

$$\Sigma \frac{\Delta\tilde{P}_{\Delta\nu}}{\sigma_1} + \Sigma \frac{\overline{(P-\bar{P})^2_{\Delta\nu}}}{\sigma_2} = \begin{cases} 10.64 \pm 4.00; & \ell = 2,\ 4 \\ 7.86 \pm 4.90; & \ell = 1,\ 3,\ 5 \end{cases} . \qquad (9)$$

The comparable strengths indicated by these findings for what is usually considered the symmetry allowed even (ℓ+m) signals and the symmetry forbidden odd (ℓ+m) signals is consistent with the sidebands being generated by a rotating nonuniform surface. A similar violation was reported by Kroll, Hill and Chen (Ref. 1) for the m=0 modes.

The strength of the sidebands in 1984 relative to 1980 are also different by a factor of 0.50 ± 0.31 as measured by $\Sigma \left(\Delta\bar{P}_{\Delta\nu}\right)$ and $\Sigma \left[\Delta\overline{(P-\bar{P})^2_{\Delta\nu}}\right]$. This result is in good agreement with the corresponding factor of 0.54 ± 0.33 obtained by Kroll, Hill and Chen (Ref. 1) for m=0 modes. The mean background power density for 1980 and 1984 differ by a factor of 0.50±0.05. This observed correlation between strength of sidebands and power background density is also consistent with the sideband power density being generated by a rotating nonuniform surface whose characteristics vary from one year to another. It was further found that the total gravity mode associated power density in the sidebands is an order of magnitude larger than the gravity mode power density located at the $\nu_{n\ell m}$. This finding may be important in understanding the difficulty experienced in detecting gravity mode signals in total irradiance observations (Refs. 13,14), a conclusion similar to that made by Kroll, Hill and Chen (Ref. 1) based on work with m=0 modes.

In summary, statistically significant evidence of $|m|=1$ gravity mode associated sideband power density has been found in both the 1980 and 1984 total irradiance power spectra. Thus, combined with the findings of Kroll, Hill and Chen (Ref. 1), we can now conclude that $|m|=0$ and $|m|=1$ gravity mode associated sideband power density is present in the total irradiance observations. Furthermore, the sideband structure is interpreted as the effects of rotation of a nonuniform surface and not the signature of rotational splitting, since the strength of the sidebands for 1980 and 1984 are different by a factor of ≈ 2, the sideband strength is proportional to the mean background power density, and the strength of the even (ℓ+m) and odd (ℓ+m) sidebands are comparable.

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