LINE PROFILES AND ROTATIONAL SPLITTING OF INDIVIDUAL P-MODES

V.G. GAVRYUSEV
CAISMI CNR, Largo E.Fermi 5, 50125, Florence, Italy

AND

E.A. GAVRYUSEVA
Osservatorio Astronomico di Capodimonte, via Moiariello 16, I-80131, Naples, Italy
Institute for Nuclear Research RAN, Moscow, Russia

1. Data and their Evaluation

We used GONG time series for $\ell = 0, 1, 2, 3$ from June 10, 1995 to January 7, 1997, 578 days in total. The duty cycle varies significantly during this period of time but on average it is sufficiently high, and the remaining gaps are irregular. Because of this we do not see daily side lobes in the spectra obtained.

The time series for $\ell = 0$ (**ts0**) is nearly the reduction of the complex GONG image to the "Sun as a star" measurement. Radial, dipole and quadrupole solar *p*-modes are visible in this time series. The $\ell = 1$ doublets have the highest power among the other *p*-modes, in the spectrum of this time series. Then the $\ell = 0$ modes and the triplets of $\ell = 2$ modes follow. The $\ell = 3$ multiplets are poorly visible in **ts0**.

The series for $\ell = 1$ (**ts1**), $\ell = 2$ (**ts2**) and $\ell = 3$ (**ts3**) are regular GONG time series obtained by the complex procedure of spatial filtering of the complete image. This filtering procedure is not ideal for several reasons, and the resulting time series are contaminated by the spatial leakage of the surrounding *p*-modes of other ℓ. It leads to serious difficulties in the interpretation of the power spectra obtained in many cases.

As it is known, the power of the solar *p*-modes varies with time. As a result, the power spectra of long time series, obtained by standard Fourier transform, have erratic structures at the location of the *p*-mode profiles and multiplets. We have applied the FPA technique, described by Gavryusev & Gavryuseva (1996), to reveal the mode line profiles and their parameters. This simple modification of standard Fourier transform permits to eliminate the main contribution of the natural window function into the resulting power spectra and provides an adequate approximation to the **current** line shapes. The existence of strong variations of the *p*-mode power on time scales of the order from several days to several weeks and months limits the accuracy of the line profile parameters obtained from a time series of a given duration. Each time span

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of a given duration provides only some approximation to the limit line profile. Due to statistical fluctuations the deviation of the current line shape parameters from the limit parameters can vary drastically depending on the inner statistics of the given time span. Evidently, the strong variation of the mode power on a certain time scale means that the statistics can be significant only when the time span is **much longer** than this time scale.

2. $\ell = 0$ Mean Line Profiles

From the analysis of the **ts0** series we have obtained the line profiles for radial modes of radial order from 11 to 26. While it was claimed that due to spatial leakage other time series can contain the surrounding modes, satisfying the condition $|\Delta\ell + \Delta m| = even$, we have not found the presence of the radial modes in **ts1**, **ts2** and **ts3**, except perhaps for some traces. We investigated the frequency spread for time spans of different duration (Gavryusev & Gavryuseva, 1997). For the 600-day time span we have deduced an uncertainty of the frequency of the order of $30 - 40\ nHz$. We determined all parameters of the modes, i.e., frequency, peak power density and half-line width, but in this short note we present only the frequencies (Table 1).

The statistics of the big pulses, which give the strongest impact on the mode line profile, seems already sufficiently high for 600 days. All current line shapes for the modes with radial order less than 23 seem sufficiently good approximations to the expected symmetrical Lorentzians. In some cases there is a small asymmetry between left and right half-line widths, which could still be caused by statistical fluctuations or even by possible trends of the mean frequencies in time. We cannot yet distinguish one reason from another. But there is certainly no visible asymmetry between the left and the right line wings, as it is seen for high ℓ.

3. $\ell = 1$ and $\ell = 2$ Mean Line Profiles

The dipole solar oscillations ($\ell = 1$) are visible in all GONG time series we have analyzed. In the spectra of **ts0** they are visible as a doublet. In the spectra of **ts1** series for $m = -1, 0, +1$ there should be visible only one component in each series. But it is not exactly like this. While the $m = 0$ series contains always only a single corresponding component, the two other series manifest usually the doublets. Additional components of different azimuthal order m are suppressed, but visible. Hence the parameters of the $m = \pm 1$ components are still affected by one another. For $\ell = 1$ there is an even more serious problem which strongly complicates the possibility of evaluating the multiplet parameters for many radial orders. Due to the spatial leakage of the modes with ℓ probably as high as 10, the precise determination of all parameters in many multiplets is impossible. We used the information, obtained from all (16) time series analyzed, supposing that the effect of leakage is different for different time series and discarding all ambiguous situations. Finally it was possible to evaluate the line parameters for practically all m-components of the dipole modes of radial orders $n = 11 - 23$. Their frequencies and the corresponding splittings are presented in Table 1.

In the **ts2** series only the corresponding m components are visible. The contamination by spatial leakage of other modes is also less severe for $\ell = 2$ modes. All that makes the results obtained for the $\ell = 2$ multiplet parameters more satisfactory. We evaluated the line parameters for all m-components of the quadrupole modes of

TABLE 1. The $\ell = 0$ and $\ell = 1$ modes frequencies, μHz. The splitting is sideral; σ is the standard deviation. The last line gives the average splitting.

ℓ	0		1			
n / m		-1	0	+1	splitting	σ
10			1612.734			
11	1686.523	1748.888	1749.350	1749.677	0.493	0.025
12	1822.124	1884.632	1885.019	1885.468	0.459	0.040
13	1957.451	2020.373	2020.771	2021.092	0.392	0.073
14	2093.506	2156.361	2156.767	2156.991	0.338	0.096
15	2228.693	2291.644	2291.960	2292.253	0.334	0.109
16	2362.806	2425.235	2425.629	2425.834	0.340	0.099
17	2496.181	2558.616	2559.055	2559.527	0.489	0.073
18	2629.674	2692.660	2693.329	2693.757	0.567	0.114
19	2764.060	2827.633	2828.261	2828.518	0.473	0.035
20	2898.967	2962.930	2963.290	2963.564	0.339	0.056
21	3033.675	3097.890	3098.286	3098.818	0.494	0.095
22	3168.596	3232.570	3233.040	3233.653	0.581	0.082
23	3303.488	3367.925	3368.343	3369.014	0.574	0.162
24	3438.752					
25	3574.738					
26	3710.313					
					0.458	0.137

$n = 10 - 25$. The m-component frequencies and the splittings are shown in Table 2. For each individual mode, including the components of the rotational multiplets, we have determined the parameters directly from the mode profile revealed by the FPA method. The presence of neighboring modes disturbs the profile. The joint fitting of neighboring modes have been done to reconstruct the characteristics of the oscillations. It is very important to stress that components of different azimuthal order m as a rule have different amplitudes. For example, only the $n = 13$ and $n = 22$ modes amongst the dipole oscillations presented in the Table 1 have about the same amplitude. The line width is also different. Such asymmetry could be due to the temporal variation of the mode power. But our study (Gavryusev & Gavryuseva, 1997) clearly shows that the power of modes of different azimuthal order is stably different during approximately 800 days. Such asymmetry must be taken into account when spectra are fitted with Lorentzians.

4. Rotational splitting

The averages of the splittings for all radial orders of dipole and quadrupole multiplets are shown in the bottom lines in Tables 1 ($\ell = 1$) and 2 ($\ell = 2$).

The individual values of the splitting obtained from GONG for different radial

TABLE 2. The $\ell = 2$ modes frequencies, μHz. The splitting is sideral; σ is the standard deviation. The last line gives the average splitting.

ℓ			2				
n / m	-2	-1	0	+1	+2	splitting	σ
10	1673.730	1674.170	1674.510	1674.900	1675.305	0.424	0.030
11	1809.433	1809.840	1810.188	1810.660	1811.171	0.464	0.065
12	1944.956	1945.423	1945.681	1946.164	1946.654	0.454	0.066
13	2081.132	2081.740	2082.202	2082.512	2082.985	0.493	0.084
14	2216.743	2217.323	2217.680	2218.020	2218.459	0.459	0.082
15	2351.323	2351.898	2352.217	2352.790	2353.190	0.497	0.099
16	2484.993	2485.455	2485.907	2486.193	2486.700	0.457	0.074
17	2618.803	2619.275	2619.625	2619.980	2620.544	0.465	0.086
18	2753.330	2753.990	2754.603	2754.647	2755.152	0.486	0.162
19	2888.848	2889.076	2889.490	2889.792	2890.153	0.356	0.057
20	3023.834	3024.515	3024.790	3025.145	3025.448	0.433	0.115
21	3158.867	3159.561	3159.813	3160.360	3160.861	0.528	0.089
22	3294.436	3294.860	3295.155	3295.460	3296.062	0.436	0.094
23	3429.794	3430.220	3430.520	3430.854	3431.547	0.468	0.173
24	3565.664	3566.624	3566.574	3566.949	3567.371	0.457	0.273
25	3702.423	3702.767	3702.912	3703.740	3704.295	0.498	0.163
						0.461	0.038

order n have large error bars, corresponding to the high errors still obtained for the frequencies of the components in the multiplets. The distances between the components vary significantly from one another and from the mean splitting value. For $\ell = 1$ this happens much more frequently than for $\ell = 2$. It seems that this effect is mainly due to the contamination by the spatial leakage of the other modes.

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