25

IRIS and GONG

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25.1 Introduction

After the first success of helioseismology, it has been shown than new results could only be obtained from long set of continuous observations. Therefore different groups intented to set-up worldwide networks in order to observe the Sun 24 hours a day. This is the case of GONG and IRIS. Both are six-stations networks. Figure 1 shows the different sites of the two networks. They have one common site in Izaña.

IRIS has already 5 stations installed and running. The last site, in Australia, is under selection, and very probably will be in Culgoora, more accessible than the Western site selected by GONG team, in Learmonth. It will be set-up at the beginning of 1994. The operation, already started since 1990, will continue untill at least 2000. So far, the best piece of data obtained covers a period of three monthes, during Summer 1991, with a duty cycle of 60%, with only 3 instruments working. With 6 sites, a duty-cycle of at least 85% is expected.

The six instruments of the GONG network are constructed and under tests. The deployement is supposed to take place during the second half of 1994. The network will be fully operational in 1995. A duty-cycle higher than 90% is expected.

IRIS provides only full-disk velocity measurements, whereas GONG is designed to record images of the Sun, providing a spatial resolution. GONG will measure non-radial modes, from l=1 to l=200, when IRIS is only sensitive to radial and low degree non-radial modes (l=0 to 3). Fig. 2 shows

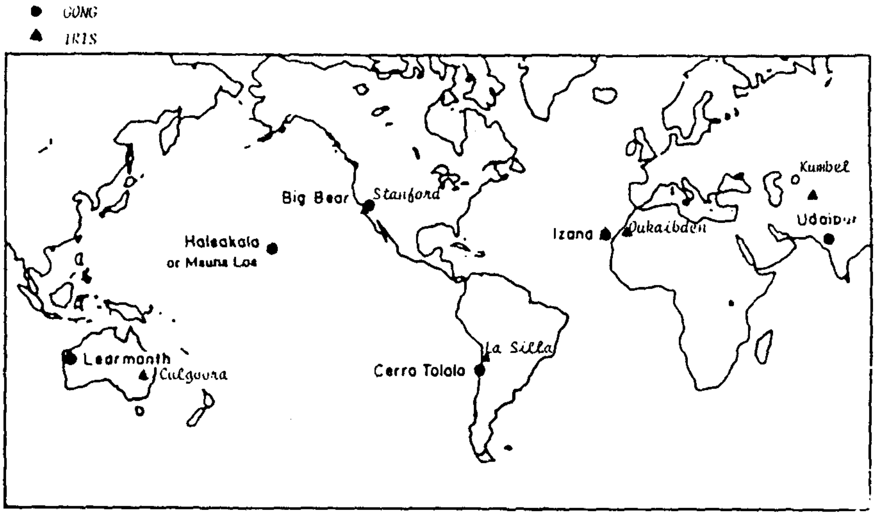

Fig. 25.1 The selected sites of the two networks IRIS and GONG.

the diagnostic diagram l-n, which can be obtained with GONG instrument. IRIS will detect the the modes at the extreme left of this figure. They are doing a complementary job, as all the modes are necessary to recover the physical parameters from an inversion technique. It is also important to note that only the low degree modes penetrate the deep interior of the Sun. The data obtained IRIS are then the best way to investigate the core of the Sun, where the nuclear reactions occure.

The recent results that we will present here come from a single set of data obtained with IRIS, during Summer 1991, with a resolution of $0.14 \mu Hz$. The duty-cycle is 57%. It is the best set of helioseismic data available so far.

Other results are expected very soon from IRIS data and from GONG when it will be operated. In particular, the density of probability of the peaks can be measured, as well as the noise level between the peaks. This will permit us to invesitgate the excitation mechanism and the interaction between the oscilations and the convection. Interaction with the chromosphere can be studied through the pseudo-modes (the energy above the atmospheric cut-off frequency).

But the most important observational result to come are the tables of frequencies, available for each year. These values will provide not only extremely precise sound-speed profile, which could be used as a test of the models, but also the variations with time of the frequencies. The long-term variations will be a excellent indication of the nature of the solar-cycle. And

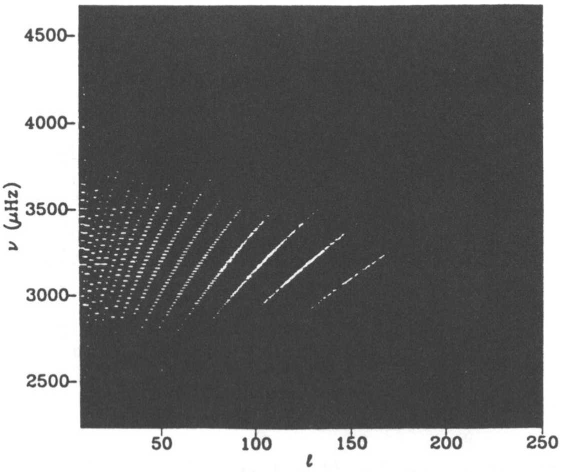

Fig. 25.2 A typical $l - \nu$ diagram of the solar p-modes as seen by the GONG experiment. Each peak correspond to an individual mode with a specific l and n value, where l is the spherical harmonic degree and n is the radial order. IRIS is only sensitive to low degree modes, i.e. the first vertical column on the left of the picture.

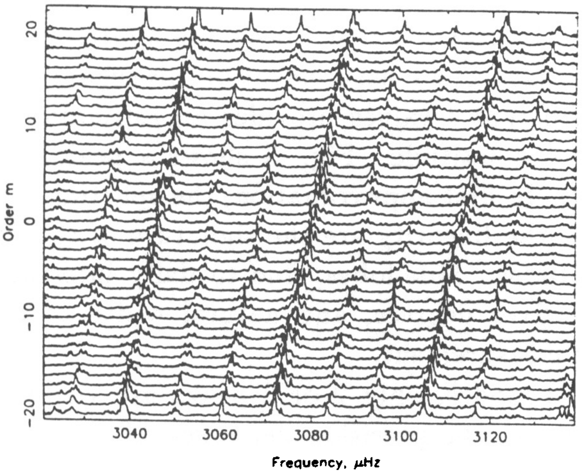

Fig. 3. Typical power spectra of solar oscillation data from Big Bear Solar Observatory; each horizontal trace is a section of a power spectrum for different m with $l = 20$. The peaks in the $m = 0$ spectrum at $\nu = 3047$, 3080 and 3114 μHz are from modes with $(n,l) = (15,19)$, (15,20) and (15,21), respectively. Peaks spaced ± 11.6 μHz around these features are temporal sidelobes arising from the day/night observing window. The shift in the frequency of the peaks as a function of m illustrates the rotational frequency splitting.

Fig. 25.3 Due to the solar rotation, each individual white point is composed of $2l + 1$ modes, with slightly different frequencies depending on the tesseral order m, as visible in the rightern picture.

short-term variations might give us predictions of solar activity at the scale of the week.

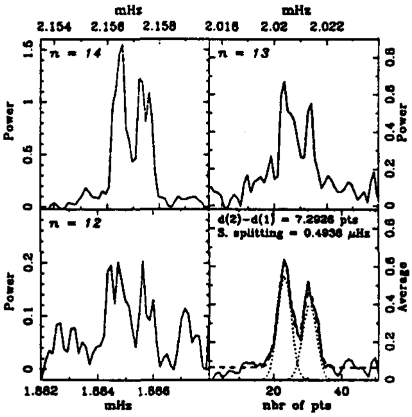

Fig. 25.4 The three modes ($l = 1, n = 12, 13, 14$) are individually shown, with their weighted average on which the sum of two gaussian curves has been fit.

25.2 A precise measurement of low degree rotational splitting

The internal rotation of the Sun causes the splitting of the peaks of a p-mode in $2l + 1$ peaks. The measurement of this separation between different m values, for different l values provides an estimation of the rotation at different depth and latitude. Fig. 3 shows a peak $l = 20$, separated in fourty one peaks. In first approximation, the splitting is proportional to m. Discrepancies to the linearity are the signature of the differantial rotation at different latitudes. Side-lobes, due to daily interruptions, interference between consecutives degrees, and natural width of the peaks limit the precision of the measurement.

For low degree modes, only 2 or 3 peaks are visible and generally unresolved. Therefore, the precision decreases as the depth increases. The core rotation was unknown so far. In particular, it has been impossible to discard any of the two theories, the fast rotating core or the rigid rotator.

The line width of the modes decreases with frequency, but only reach small enough values at low frequencies, about 2 mHz, where the amplitude are very low.

The very low noise level reached with IRIS measurements permited the detection of this low order modes and shows 3 resolved $l = 1$ modes around 2 mHz, which are the $n = 12$ to 14 modes. These modes are displayed on Fig. 4.

The mean splitting measured by different methods on the three doublets is $0.490 \pm 0.030 \mu Hz$. Fig. 5 shows the values of the splitting of $l = 1$ modes

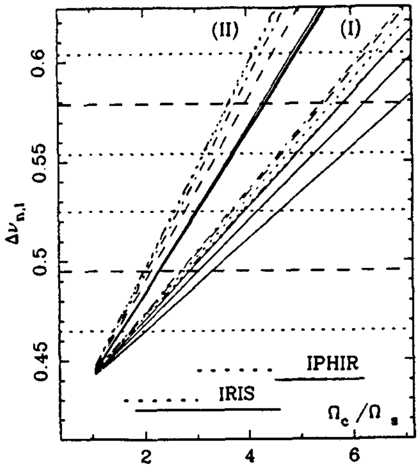

Fig. 25.5 Variation of the rotational splitting for $l = 1$ and $n = 12, 13, 14$ (full lines) relative to the ratio Ω_c/Ω_s for two different models The observed splitting given by IRIS and IPHIR are reported, taking into account the error bars. The derived domain of core rotation rate are indicated at the bottom of the figure.

for two different models, for different n values, as a function of the core rotation. It can be seen that the value found on IRIS data almost excludes the value encountered with IPHIR measurements.

The possible rotation lies between 1.5 and 4 surface rotation, depending on the model. This is for $l = 1$.

Other measurements has been made on $l = 2$ modes in the same frequency range. But, the signal to noise ratio is much lower and did not provide any convincing measurement. Presently, we are working on the modes between 2.5 and 3.5 mHz, where, following Libbrecht the half width is higher than $1 \mu Hz$, but almost constant. Therefore, it is possible to average up to 7 modes in order to improve the statistic. On the averaged modes, we measure the width by fitting three mean $l = 0$ modes on the mean $l = 2$ mode. The same has been done on $l = 3$ also. The results tend to validate the hypothesis of slow rotating core, with a frequency not higher than twice the surface rotation frequency.

25.3 On the acoustic cut-off frequency of the Sun

The solar p-modes are a standing wave of the whole Sun between an internal refracting point, depending upon the degree and an reflecting point at limit of the photosphere. The reflection occurs if the frequency is lower than the

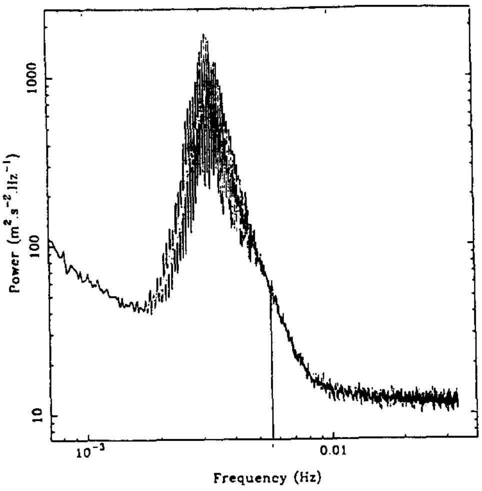

Fig. 25.6 Average spectrum of 309 individual days of observation taken with the IRIS stations of Kumbel, La Silla, Oukaïbden and Izaña.

atmospheric cut-off frequency, otherwise the wave propagates through the atmosphere and no mode can exist.

That is what can be seen on the right side of a typical solar spectrum, as displayed on Fig. 6. The amplitude of the modes decreases while the line width increases. However it can be seen that a substancial energy above the noise level remains whereas the contrast between modes has entirely vanished.

What happens here is that as the frequency increases the reflection coefficient decreases. Then a part of the energy contained in the mode is transmitted to the chromosphere, so the mode is damped and its natural width increases. When the reflection coefficient reaches zero, no standing wave remains and we have only an interference pattern between an ascending waves coming directly from the excitation zone, and another one which has been first refracted inside the Sun. The periodicity of the interference pattern is just the separation between modes of consecutive n values.

In the case of full-disk measurements, it happens that $l = 1$ modes and the sum of $l = 0$ and 2 modes have almost the same amplitude, and a frequency shift equal to the half of the periodicity. Therefore, when we have a null reflection, the two cosine interference patterns added provide a flat level. This explains why the contrast vanishes on the Fig. 6 and gives us the opportunity of measuring very precisely the atmospheric cut-off frequency.

Other independant methods have been apllied to the data. Phase differences between measeruments with the sodium and potassium lines, which are formed at different level in the photosphere, have been measured for different frequencies. An unique value has been found through the different methods, thus giving us a high level of confidence on the measured value, which is

$$\nu_{atm} = 5.55 \pm 0.1 mHz$$

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