JOINT DISCUSSIONS

JOINT DISCUSSION NO. 1

LARGE-SCALE VELOCITY FIELDS ON THE SUN

(Commissions 10 and 12)

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(Co-chairmen)

CONTENTS

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GLOBAL OSCILLATIONS OF THE SUN

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1. INTRODUCTION

The topic of this Joint Discussion has received enormously increased interest in the last couple of years, owing to its potential for the investigation of the structure of the interior of the sun, including related topics like the structure of the convection zone, solar metal abundance, and the still unsettled neutrino problem.

The first stimuli came from the startling observations of Hill et al. (1976) in Arizona, Severny et al. (1976) on Crimea, and Brookes et al. (1976) in Birmingham, accompanied by a large volume of theoretical papers, the details of analysis of which soon went beyond the actual status of the observational facts.

We then witnessed, however, the success of considerable refinements of the techniques of observation, together with an obvious widespread temptation to push the interpretation of many of the new results to the limits of optimism. Yet, despite of the still increasing body of data suggesting the reality of the solar origin of the observed phenomena, much scepticism was prompted by the complicated statistics and the intricate numerical procedures involved in the data analysis, as well as by the great uncertainty about the significance and the amounts of "noise" contributed to the signal by electronics, changes of the conditions of the ray path within the telescope, terrestrial atmospheric inhomogeneities and solar quasi-stationary motions.

Therefore, the solar origin of some of the observed effects is still hotly debated, and we shall attempt to present and discuss the various pros and contras in due order in the course of this session. This review does not attempt completeness, rather it reflects the privat bias of an observer right amidst the struggle.

Logically, our discussion will center around the progress achieved and the difficulties encountered in the course of the last triennium.

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 75–87.

2. THEORETICAL BACKGROUND

The high degree of accuracy achieved today in the theory of stellar pulsations (without claiming completeness we mention here the work of Ulrich, 1970, Wolff, 1972, Christensen-Dalsgaard et al., 1974, Ando and Osaki, 1975, Iben and Mahaffy, 1976, Goldreich and Keeley, 1977 ab, Christensen-Dalsgaard et al., 1979, with particular emphasis on solar oscillations and pulsations) has provided us with an extensive catalogue of eigenfrequencies both of radial and nonradial eigenmodes in the range of frequencies from the familiar 5-min oscillations to periods considerably longer than one hour, as of high order nonradial g-modes. A convenient overview of the entire spectrum is given in Fig. 2.2 of Hill (1978). Important features of this spectrum of eigenfrequencies are: the almost complete separation of g- and p-modes with some overlap of periods between 0.25 mHz and 0.4 mHz, a crowding of g-modes towards this latter frequency and the paucity of eigenmodes in the range from above 0.4 mHz to about 0.7 mHz.

Given an unlimited amount of uninterrupted observing time, and data free from systematic effects other than of solar origin, we only need to compare this catalogue of predicted frequencies with whichever peaks the sun likes to produce in its powerspectrum, in order to select from a range of proposed solar models the one who's predicted spectrum matches most closely the observed one.

Which are the motives lying behind this conceptually straightforward but in reality utterly difficult exercise? All of the existing stellar and solar models are derived from observations which do not penetrate beyond the surface (photosphere) of the star, and which represent, therefore, a negligible fraction of the mass of the star. Chosing appropriate values for some of the basic "free" parameters of stellar models, the ratio of mixing length to pressure scale height ℓ/H, and the chemical composition, various models can be constructed, all of which reproduce correctly the fundamental observables, characterizing a given star: its mass, luminosity, radius, and age.

However, these models can in principle be distinguished with regard to their slightly different eigenfrequencies. Consequently, a comparison with sufficiently accurate observations should help to decide among there models.

It is important to note, that the fundamental modes and p-modes are concentrated towards the stellar surface, and therefore are particularly suited as probes of the convection zone, and especially of the shallow superadiabatic surface layer, whereas the g-modes have their greatest energy density in the deep interior, with about the same amount of oscillatory energy in every antinode, the distances of which increase linearely on a log $r/R_{\odot}$ scale.

Provided, this full range of frequencies is indeed observable, the structure (and the law of rotation - Section 6) can be analysed throughout the interior of the star. But, in order to achieve this, we need to identify the observed eigenmodes by their names, i.e. their radial and horizontal order numbers n and ℓ . I'm afraid to say that despite considerable efforts, we haven't made too much progress in this direction in the course of the last three years.

3. DISK OBSERVATIONS

Let me open this chapter with a brief account of the two observing techniques which have almost exclusively been applied in recent measurements of large scale velocity fields on the disk, and which are particularly suited to reduce the influence of unwanted signals.

a) Doppler shifts of solar lines can be monitored by collecting the radiation produced by resonant scattering of the solar light in the laboratory. Sodium, Potassium or Strontium vapor has been used, which is placed in a strong magnetic field in order to separate the red and violet wing of the solar line by alternating transmission of opposite circular polarisation. Of course, the signal received is strictly proportional to the intensity of the part of the solar line profile selected by the resonant line. (Roddier, 1965)

This method, providing an absolute wavelength reference and yielding an accuracy of better than 1 ms^{-1}, is best suited for full disk measurements and has been used extensively by the solar groups in Birmingham and in Nice.

b) The second method relies on an internal solar reference by splitting the solar image into an inner circular disk the signal of which is compared with the signal from the remaining outer ring. Thus, the method eliminates the effects of spin and orbital motions of the earth, spectrograph turbulence, instrument flexures, and electronic drifts, but not the position dependent effects caused by transparency gradients in the atmosphere or in the instrument. (The first method is subject to the same limitation).

The internal accuracy claimed is $\sim$0.5 ms^{-1} (10^{-5}Å!), but this method is also sensitive to guiding errors at the 2ms^{-1} per 1 arcsec level. Let us now turn to the observations. An example of a power spectrum of full disk velocity fluctuations covering the full range of periods from $\sim$5 min to more than 3 hours can be seen in Fig. 5 of Brookes et al. (1978). The most outstanding peak in this particular resonance experiment observation is found at periods of $\sim$2.2 hours. Other observing runs of the same authors show comparatively more power in the 30 to 50 min range.

Fig.7, of Kotov et al.(1979) shows a plot of several years' observations obtained with the second method both at Stanford and the Crimean station, subjected to a superposed epoch analysis, after fitting a least squares parabola to each days observation. At a period of 160.01 min a nearly sinusoidal signal with an amplitude of $\sim$1 ms^{-1} emerges, which exceeds the 3σ level and, therefore, appears to be statistically safe.

At the same level, with slightly lower amplitudes two other periods, at 148.361 min and 134.504 min can be detected. If the same analysis is applied to the same data after randomizing the sequential order of data points, the amplitude drops to less than 1.5 σ

More arguments are presented by the authors in favour of the solar origin of the 160 min signal. For example, a terrestrial O_2 line observed simultaneously with the solar FeI 5124 line does not exhibit pronounced periodicities, although about 1 ms^{-1} fluctuations are observed in this line as well.

Figs.1 and 2 of Scherrer et al.(1979) show in more detail the very close phase correlation holding between the Crimean and the Stanford observations over the past three years, leading to a precisely determined period of 160.010 min which slightly but significantly differs from an integer fraction of 1/9 of a day.

Fig.2 of Severny et al.(1978) illustrates a correlation observed between the infrared brightness of the disk and the velocity signal found by Koutchmy and Kotov, revealing fluctuations of the solar limb darkening function with a relative amplitude of 2.5×10^{-4}, being practically in phase with the velocity. It may be of interest, however, to note in this context that brightness fluctuations in excess of $6 \cdot 10^{-5}$ were never observed by Deubner (1977) in a 10 days dual channel photometry in the visible of the albedo of both Neptune and Uranus.

Is the information we have on the 160 min signal sufficient to identify the observed mode(s)? With regard to the quasi full disk mode of observation we are led to look for low ℓ eigenfunctions in our list of predicted frequencies. The $\ell = 2$, $n = 8, 9, 10$ g-modes of model 1 of Iben and Mahaffy (1976) seem to fit the observed periods best, whereas a $\ell = 1$ mode ($n = 5$ or 6) appears to be the best choice with regard to the 27d beat period of the 160 min signal reported by Severny et al.(1978), according to the formula

$$\nu_\ell = \nu_o \left(1 - \frac{1}{\ell(\ell+1)} \right) \qquad (1)$$

given by Wolff(1974a), where ν_o is the average rotation rate of the sun and ν_ℓ refers to the rotation rate of pulsations with non-radial mode number ℓ .

Although these tentative identifications are not decisive with respect to the selection of one or the other of the proposed solar models, we may safely follow the authors' argument, that if we accept the hypothesis of the solar origin of the velocity signal, a mechanism for enhanced energy flux out of the solar core is available, which may explain the observed low neutrino flux.

Why is it, that among the many closely spaced frequencies in the g-mode spectrum just one, at 160.010 min, is excited? Gough (1976) argues that this frequency may correspond to a beat among two p-modes of similar nonradial structure, and that the high Q of the resonant g-mode requires a very close coincidence of the frequencies which may be expected to be fairly rare.

As pointed out before, other frequencies have been observed on the disk at shorter periods, e.g. by Brookes et al. (1976), but these peaks in the power spectra, although they can be clearly distinguished from noise, are not persistent. They cannot be identified. Attempts to measure long period temperature fluctuations on the solar disk by observing the variation of spectral line intensities had mostly negative results. In the range of periods between 30 min and 80 min Beckers and Ayres (1977) found no fluctuations of the CaIIK_1 intensity in excess of the noise level of 0.02%, integrated over the whole disk. Livingston et al. (1977) and Livingston (1979, private communication) reported similar negative results referring to their observations of the CI 5380 line (fluctuations < 0.3 K) and the MgI 5183 line. We shall refer to these observations again in the next section.

In conclusion of this section I wish to mention the work of Wolff (1974b, 1976) who finds indirect but rather abundant evidence for the presence of solar g-modes in the various solar cycle periodicities which can be derived from the variation of sunspot numbers. Wolff hypothesizes that g-modes with the same harmonic index ℓ but with different radial order number n couple through non-linear effects in the solar core to form coherent sets rotating according to formula (1). Sets with different harmonic index ℓ would rotate with slightly different rates, carrying rigidly rotating bands of increased energy output on opposite sides of the sun. The beating of these sets, preferable of those with low ℓ would periodically induce systematic flow patterns through alignment of the power bands which in turn are believed to concentrate magnetic energy, thus creating active longitudes, magnetic sector structures, coronal holes, in other words the well known major large scale manifestations of solar activity at the surface.

Out of 20 predicted beat frequencies among low order modes, Wolff (1976, Fig.1) finds 15 to match closely with lines of the solar variability spectrum, if he assumes an internal bulk rotation rate of 1/25.8 days sidereal (or 1/27.8 days synodic). A fast rotating solar core is evidently not supported by this work.

Wolff (1977) finds supporting evidence for his view of solar activity from an analogous investigation of white dwarf variability.

4. MEASUREMENTS AT THE LIMB

Most of the results discussed in this section were obtained from data acquired with an instrument, originally designed to measure the deflection of starlight by the sun (Oleson et al., 1974). At the Santa Catalina Laboratory for Experimental Relativity by Astrometry (SCLERA) the solar diameter measurements consist of accurately referenced scans of the solar limb on two diametrically opposite positions of the disk, employing a slit of length 100 arc sec tangent to the limb with scan amplitudes ranging from several arcsec to about half an arcmin. A special numerical technique (Finite Fourier Transform Definition = FFTD) defines the position of the limb by integration of the recorded signal with a weighting function, chosen to minimize the effects of seeing. For diameters of the seeing disk σ ranging from less than one arc sec to about 3 arcsec the position determined in such a way is nearly independent of σ (Hill et al., 1975).

The internal accuracy of each determination of the limb position is of the order of some milli arcsec. One minute averages of the resulting diameter measurements are taken, and after removal of low frequency trends power spectra of the diameter fluctuations are computed by Fourier transform.

Several such power spectra have been published, the most detailed description is given by Brown et al. (1978), Figs. 2 and 3. These spectra cover periods from about 70 sec to 3 hours. The fluctuation amplitudes measured are ~ 6 milli arcsec on the average with a steep rise to high amplitudes at very low frequencies and a rather flat spectrum at higher frequencies. The 5-min oscillations are hardly detectable. The peaks seen in the power spectra in the range from 7 to 70 min are regarded as significant power of solar origin by the SCLERA group (see e.g. Hill,1978 for an extensive survey).

As we have heard in the previous section, attempts by other research groups to detect brightness or velocity variations due to low order nonradial modes in full disk measurements were not successful. In fact, the amplitudes of the diameter fluctuations in the SCLERA measurements appear paradoxically large compared to the detection limits achieved in the other experiments.

Hill and his co-workers, after extensive studies of the wave equations in the solar atmosphere, attribute these "paradoxes" to an enhancement effect which favours the limb signal as compared to the other measured quantities. In essence, as a result of the wave motion, a redistribution of the measured intensity across the limb darkening function is observed rather than a real displacement of the limb (Hill et al. 1978).

Two particular results obtained from the SCLERA data are commonly regarded as most compelling evidence for the solar origin of the diameter fluctuation signal.

a) At 5 selected frequencies the absolute phase of the signal is determined for each of several (7) consecutive observing days, and after suitable adjustment by multiples of 2π , the phases are fitted by a straight line, leaving residuals less than approximately $\pi/3$. Hill and Caudell (1979) attribute a statistical probability of 3×10^{-12} to the possibility of obtaining such a fit simultaneously for 6 different frequencies.

b) If the observed signal was mostly caused by seeing, it is suggested that the amplitude of the signal as determined by the FFTD was independent of the scan amplitude. However, the ratio of signal amplitudes determined from simultaneous determinations with scan amplitudes of 6".8 and 27".2 differs from unity and varies considerably with frequency.

Complementary work was recently carried out by Brown (1979) by means of limb scans with the diode arrays of the Sacramento Peak Solar Tower. Brown investigates the solar p-modes in the 5-min range of periods. He finds some weak indications of the p-mode ridges in the k,ω diagram and, in support of the SCLERA results, points out that he observes concentration of power at low frequencies and low wavenumbers. At this point a cautionary note should be added which refers to personal experience with spectrographs of the Sac Peak type, suffering from considerable thermal instability. Observed power at low wave numbers as the one just mentioned, is frequently caused by air turbulence within the spectrograph and quietly disappears when the spectrograph is stable.

Brown also shows that the power he observes at higher frequencies is not in a thin shell, as expected from previous SCLERA work, but rather distributed over a wide range inward from the solar limb.

Estimates of the harmonic order index ℓ are possible with the aid of spatial filter functions derived for the SCLERA set-up (Hill, 1978, Fig. 4.2). The sensitivity of the apparatus is highest in the range of ℓ - values between 10 and 50, depending on the actual scan amplitude. However, a clearcut assessment of the spherical order number is not possible yet; and interference of many different modes within each resolution element of the higher frequency portion of the power spectrum is very likely. Identification is also tricky at frequencies below the cut-off frequency of g-modes, as a previous assignment of the fundamental radial mode to the observed 68 min period has proven. The model required to satisfy this identification had $X = 0.7$, $Z = 0.036$ and a neutrino output of $\sim$50 SNU.

5. OTHER SOURCES OF SIGNALS

In this section we shall discuss investigations concerned with a possible origin of the signals described in the two previous sections other than solar global modes of oscillation. Naturally the opinions in a hot debate like this are rather strong on either side and the reviewer asks for the indulgence of the audience (reader) if his own account of the affairs does appear to be not free from biases.

Solar Signals

Worden and Simon (1976) have studied the effects of supergranulation rotating past the field of view on the solar surface, on the velocity signal. In Fourier analyzing the data they find power at periods from about 2.5 to 4 hours, sufficiently strong and close to the 160 min velocity signal, to be worried about. However, the strong phase coherence reported by the Crimean group could never be explained by rotation of the rather irregular supergranular structure. In a similar vein, Worden and Keil (1979) have investigated what kind of effects rotation and evolution of structures observed on the disk in the FeI 5171 line, emitted at 450 km above $_{5000}$ = 1, could have at the limb on the diameter signal. It appears that rotation alone would manifest itself only at frequencies below 1 mHz, whereas evolutionary effects add considerable noise throughout the spectrum (Fig.2). Applying the FFTD technique, Worden and Keil arrive at signal amplitudes of 5 to 6 milli arcsec, quite comparable to the values quoted by Hill.

The Terrestrial Atmosphere

Grec and Fossat (1977) have in their measurements of full disk velocity fluctuations obtained with the resonance experiment never been able to find any significant power at low frequencies, above the noise level. Blaming the terrestrial atmosphere for contributing the major part of this noise they investigated air mass fluctuations as well as transparency changes of the atmosphere at various stations (Capri, La Silla, Kitt Peak) as a function of frequency and angular separation. They find a large coherence for separation angles smaller than 1°, for frequencies from 5 min to 90 min.

Scaling of these observed fluctuations according to a simple model leads to noise amplitudes well comparable with the measured low ω power in disk and limb observations. Also, according to Fossat and Grec (1978) the transparency gradient of the undisturbed atmosphere due to different zenith distances is alone capable of shifting the weighted average velocity of the full disk by amounts, sufficient to explain (after subtracting the customary parabolic fit from the drift curve) harmonics of 1/8, 1/9 and 1/10 of a day in the power spectrum with amplitudes exceeding 0.5 ms^{-1}. Of course this hypothesis does not explain the observed gradual phase shift from year to year by about 30 min per year. Taking account of the quite commonly observed asymmetry of the extinction curves with respect to the local meridian, we should however be aware of the effects, that a slowly increasing - worldwide - pollution (haziness) of the air might have on the determination of such phases. At the time being we are more worried by reports from Stanford (Fossat, during this discussion) which state that the data windows alone (i.e. all measured data being replaced by a constant number) are sufficient to yield the previously reported phases. (Editors note: Shortly after this discussion, P.H. Scherrer argued that this was true for 1976, but not for the later years). Is the assumption made by the SCLERA group about the independence of the ratio of the atmospheric noise signals on frequency really justified? Observing on a good day the seeing patterns of the terrestrial atmosphere transfiguring and drifting across the granulation pattern on the disk, one feels rather doubtful, whether in this process the wavenumber spectrum is independent of frequency.

Finally we should keep in mind possible effects of transparency changes and air turbulence within the instrument, as pointed out before.

Numerical "Signals"

Statistical tests of the phase coherence analogous to the phase fitting procedure quoted in Sec.4 were independently carried out both by Grec and Fossat (1979) and by Worden and Keil (1979) with random numbers. The results were similar: the artificial r.m.s. residual errors are of the order of 0.73 radians, to be compared with 0.77 radians read from Fig. 1 of Hill d Caudell's (1979) paper. In the light of this comparison, the phase fitting diagram looks much less convincing (even though slightly lower r.m.s. values were quoted by H. Hill during this discussion).

Summarizing this section together with the two previous ones it seems fair to note that:

a) there is power observed in Fourier spectra of fluctuations of the solar diameter and of velocities averaged over the entire disk. The power is distributed over a wide range of the solar spectrum of low order normal modes. The observations provide some evidence of non-randomness of the signals suggesting a solar origin.

b) Various solar and non-solar sources of noise exist, which must inevitably contribute to the observed signals over the same wide range of frequencies and with amplitudes roughly comparable to the observed amplitudes. Very long series of observations are necessary to separate the wheat from this chaff, and to improve the data sufficiently for unambiguous mode identifications.

6. THE COHERENCE OF p-MODES ON THE DISK

Figs. 1 and 2 of the paper by Deubner et al. (1979), obtained from measurements of the 5-min oscillations at the Sac Peak Solar Tower, illustrate the by now familiar structure of the solar p-modes in the k,ω diagram. What have we learnt from it?

A small but significant discrepancy between the predicted position of the p-modes according to $\ell/H = 2$ models and the observed position of the ridges suggests a modification of the solar envelope models in the sense of much larger mixing length ratios, lowering the base of the convection zone and increasing the metal abundance. This also amounts to aggravating the neutrino problem. Other changes of the model don't seem to affect the eigenfrequencies much (Gough, 1979, private communication).

From the observed width of the p-mode ridges we can infer the Q-value of the oscillations, after taking the "instrumental" broadening effects into account: finite data window, finite slit length, perspective foreshortening at angles $\theta \neq 0$, and the obliqueness of the oscillatory motions. From our own data we obtain

$$\begin{array}{ll} Q \simeq 70 & \text{for } k > 0.4\ \mathrm{Mm}^{-1} \\ 90 < Q < 130 & k > 0.3\ \mathrm{Mm}^{-1} \\ Q \simeq \infty & k < 0.3\ \mathrm{Mm}^{-1} \end{array}$$

The k,ω diagram shown by Harvey in this discussion confirms the trend of increasing the sharpness of the ridges with increasing the duration of the observation.

Of course, we are most interested in observations of p-modes with very low ω (or k), because these penetrate to greater depths in the convection zone. Since the scan amplitude, which determines the wavenumber resolution is limited by the spherical geometry of the sun, permitting only scans not much longer than $L = 2\pi R_o/6$, single modes cannot be resolved in k, and at low k values ($< 0.2\ \mathrm{Mm}^{-1}$), where the gradient of the ridges is rather steep, the ridges begin to merge. Taking advantage of the steepness of the ridges, Rhodes (1979) has shown in a recent paper that an uninterrupted observing time of $\gtrsim 52$ hours would be sufficient to achieve full resolution of signle modes in ω, as necessary for comparison with model calculations, and for accurate estimates of internal rotation rates (cf. Deubner et al., 1979).

Is there a sufficient amount of power at low k values? In Fig. 6.3 of his paper, Hill (1978) has compiled a diagram showing the observed amplitudes of the 5-min oscillations as a function of the aperture size A. For a white power spectrum the spectral power would be expected to fall off as $P \propto A^{-1}$. However, at very large A values "abnormal" power seems to exceed the linear extension of the simple power law. This could be explained by relatively higher amplitudes (power per unit area) of the oscillations at long wavelengths.

Collapsing the observed k,ω diagram of the p-modes on the k-axis yields a power spectrum $P_2(k)$ which can approximately be described as

$$P_2(k) \propto P_o e^{-k/k_o} \quad \text{with } k_o = 0.32\ \mathrm{Mm}^{-1} \tag{2}$$

The power per unit area is obtained from (2) by multiplication with $2\pi\ k$

$$P(k) \propto P'_o \cdot 2\pi\ k \cdot e^{-k/k_o} \tag{3}$$

This function has a maximum at fairly low k values ($k = k_o$), corroborating the previous conclusion.

With the spatial window transform as a weighting function and taking the spherical geometry into account the spatial filterfunction can be obtained from (3). Taking the full solar disk as aperture, eigenmodes with $\ell = 0$ or 1 are expected to dominate the observed power spectrum, whereas for higher ℓ the sensitivity drops off approximately as ℓ^{-3} (Hill,1978).

Recent full disk velocity measurements by Claverie et al. (1979) with the resonance experiment very clearly show the signature of low p-modes:

(a) From day to day, and from year to year consistent power spectra have been obtained with fairly equidistant lines at fixed positions in the 5-min range.

(b) The distribution of power in this range (the envelope of the peaks) is consistent with the one observed at the low k end of spatially resolved k,ω diagrams, its centroid being shifted significantly to frequencies lower than 2π /300s.

The importance of this observational breakthrough with respect to investigations of the structure of the interior of the sun can hardly be overestimated, even in comparison with the results discussed in Sec.3 and 4. Preliminary inferences are already given by Claverie et al. in their paper (1979): The average frequency interval of successive lines of same order ℓ in the observed spectra is $\Delta\nu = 135.6$ μHz. Provided that the observed lines are $\ell = 0$ or 1 lines it is implied by an extrapolation of model predictions, that the metal abundance is $Z \leqslant 0.004$ and the solar neutrino flux is $N \leqslant 2.3$ SNU.

At this point, it appears unfortunate, that this result is at variance with the conclusions drawn before from the observations of p-modes at high k-values. It will be of considerable interest to see, what we can learn in the future from this discrepancy in further, refined studies of the quaint old five minute oscillations, and with respect to Sec.3 and 4 of our discussion, from large scale long period observations scheduled for the coming observing season at the South Pole Station by Fossat and his colleagues.

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