A SPECTROPHOTOMETER DEVOTED TO STELLAR SEISMOLOGY

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I wish to begin by saying a few words on an instrument which has been utilized thus far only to observe the sun, with a very small telescope of about 5cm diameter. This may appear to stand far away from the main topic of this meeting but in fact, the scientific program which is successfully being developed on the sun would be of major interest for stellar astronomy if it could be extended to at least a few bright stars. I will therefore describe also a possible extrapolation of an instrument to be used on the largest available telescopes for stellar observations.

HELIOSEISMOLOGY

It may look like a paradox, but until very recently, the solar interior was known only through the use of stellar evolution theory. Indeed, its proximity does not help in this case because the surface layers are opaque to all forms of electromagnetic radiation. The first two possibilities which have been developed by solar astronomers to obtain direct information related to the solar internal structure, namely the flux of neutrinos (Bahcall, 1981) and the oblateness of the polar solar circumference (Hill and Stebbins, 1975), have both provided confusing and controversial results. The validity of stellar evolution theory was immediately suspected, and this suspicion urged astronomers to find more precise observational information related to the sun's interior.

The seismology of the sun was born in 1975 (Deubner, 1975; Ando and Osaki, 1975) in this exciting context. Its basic principle is identical to the telluric seismology. If astronomers can observe and identify a few normal modes of oscillations of the solar sphere, they will provide a tool for investigating the solar interior by comparison of measured periods of oscillation with those calculated from theoretical models (Christensen-Dalsgaard and Gough, 1981; Fossat, 1981). Much more information can be obtained through the dynamical processes of excitation of damping of the observed oscillations, as well as through

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the rotational splitting of these oscillations which can give observational access to the rate of rotation of very deep layers.

Many different modes of oscillation of the sun have now been observed, with periods all around five minutes. The most informative on deep interior layers are those of lowest degree which have the largest geometrical structure. They are observationally accessible by measuring the Doppler shift integrated over the whole apparent solar disk, and such observations are similar in principle to those which can be made on any other star.

THE SOLAR SPECTROPHOTOMETER

Our research group has specialised in this type of observation since 1975. The instrumental requirements are a very high sensitivity (the largest observed Doppler oscillations are well below 1 m/s in amplitude) and a very high temporal resolution (to be able to resolve and identify different normal modes which are close together in the Fourier spectrum of solar oscillations). To satisfy the first requirement, we have developed an optical resonance spectrophotometer (Grec et al., 1976) which has a wide angular beam aperture acceptance (convenient for full disk solar observations) and an absence of any spectroscopic drift, the wavelength being defined by the atoms themselves.

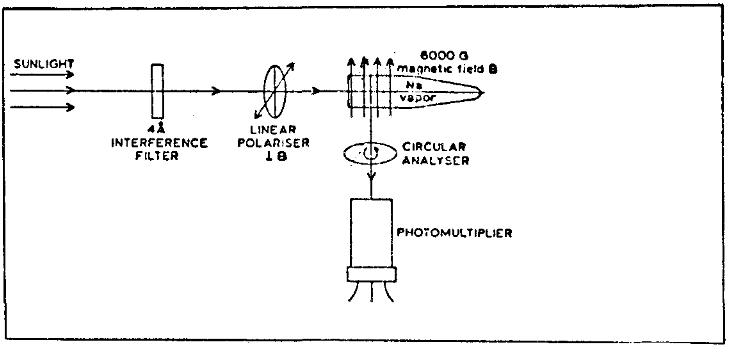

Figure 1: Schematic diagram of the solar sodium cell spectrophotometer.

This instrument, shown schematically in Figure 1, has been able to satisfy also the second requirement by being used at the geographic South Pole, where the sun stands high in the sky for a long time and data samples much longer than 12 hours can be collected (Grec et al, 1980). Figure 2 shows an acoustic spectrum of the sun obtained from the South Pole data. 75 different modes of oscillation, of amplitudes in the range 4-40cm/s have been unambiguously identified. The comparison of this result with theory has brought back the standard solar model as

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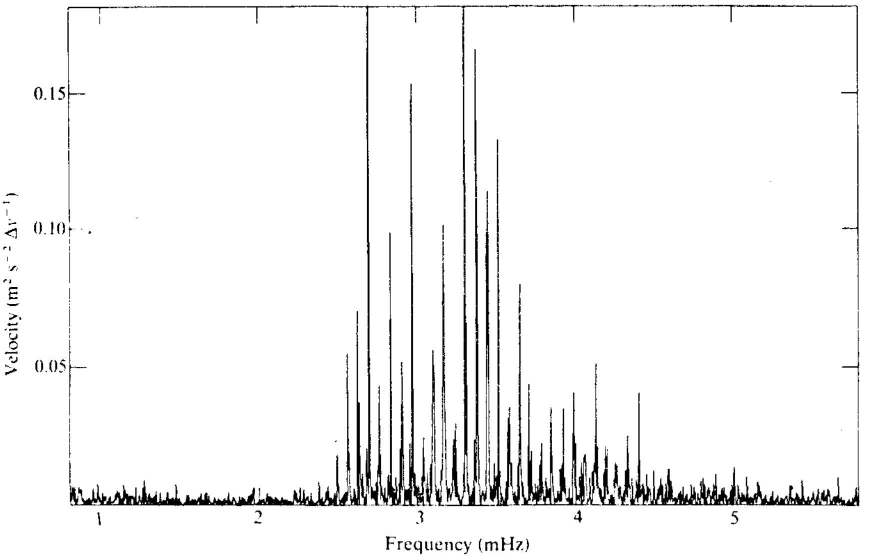

Figure 2: Acoustic power spectrum of the sun, calculated from 120 hours of continuous data recorded at the Geographic South Pole; 75 different normal modes of oscillation have been identified in this power spectrum

being close to the best fit (Christensen-Dalsgaard and Gough, 1981) and consequently the neutrino problem remains to be solved.

APPLICATION TO STELLAR MEASUREMENTS

It should be noted that the present status of observational results, as well as assumptions in stellar evolution theory, does not allow one to be sure that the best fit is unique in the comparison between observed and calculated pulsating modes. Obviously further progress is required. The acoustic spectral range of solar oscillations accessible to observations will be widened by more Antarctic observations and later by observations from space. At present, the next major progress to be expected is a similar observation on a different star. Many stars of spectral types not too different from that of the sun are probably pulsating, like the sun, over a wide range of small amplitude harmonics (Unno et al., 1979). If such observations can be successfully made on even a very small number of stars other than the sun, it would provide new and complementary information of great benefit for the theory of stellar evolution, and consequently for all astrophysics.

What would be the observational requirement to get the minimal information if we assumed the sun to be removed far enough away to be viewed as a typical star? Having noticed that the acoustic spectrum

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shown in Figure 2 contains sharp peaks which are almost equidistant, it can be deduced that a superposed frequency analysis of this spectrum with adequate frequency separation, would allow the integrated information to be obtained out of a surrounding noise level of the order of 1m s^{-1} per frequency bin. It may well be that some stars of different spectral types like Procyon are oscillating with somewhat larger amplitudes (Christensen-Dalsgaard 1981), but we think that we should define the required sensitivity by comparison with the solar case, the only one for which real results have already been obtained. Consequently the success of this program requires reducing the limit of 1m s^{-1} sensitivity for periods of a few minutes and longer (the periods of oscillation will increase with an increased size of the star, and most bright stars are bright because they are giant stars).

PROPOSED STELLAR INSTRUMENTATION

Several attempts at such observations have been made already, using standard spectroscopic equipment (Smith, 1981) or highly stabilized Perot-Fabry interferometers (Traub et al., 1978). Another possibility has been presented at this meeting by Jacques Beckers (1982). Up to the present time, the noise level has not been reduced below 5 to 10m s^{-1} and so far, only optical resonance spectroscopy has been proved to be able to reach 1m s^{-1} and better. However, our present spectrophotometer was designed for solar observations and it has a photon efficiency much too low for any stellar investigation. In 1978, we built a modified version designed to collect the light scattered by sodium atoms in a much wider solid angle and optimized for the light transmission of all other components. This modified spectrophotometer was tested with the Palomar 5 metre telescope on Arcturus and it proved to be able to give results as good as Pepsios (Traub et al., 1978) but not better. The optical design is intrinsically limited by a photon efficiency which is still too low.

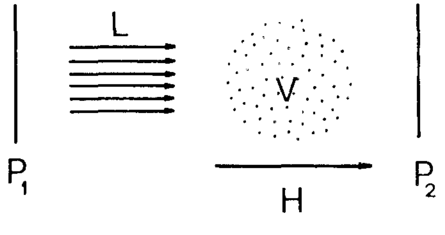

Figure 3: Schematic diagram of the planned stellar sodium cell spectrophotometer (from Cacciani, 1975)

We are now turning to an alternative method which uses optical resonance and which has been developed in Italy in the last ten years by Cacciani's group (Agnelli et al., 1975). It consists of utilising beam transmitted through sodium vapour between two crossed linear polarizers (Figure 3). In the presence of a longitudinal magnetic field, the differential absorption of the two circularly polarized Zeeman components, as well as the rotation of the plane of polarization due to the imaginary part of the refractive index (Macaluso-Corbino effect) result in a non-zero transmission between the crossed polarizers. By a suitable choice of magnetic field and sodium vapour pressure, this device acts as a filter having a transmission curve like that shown on Figure 4.

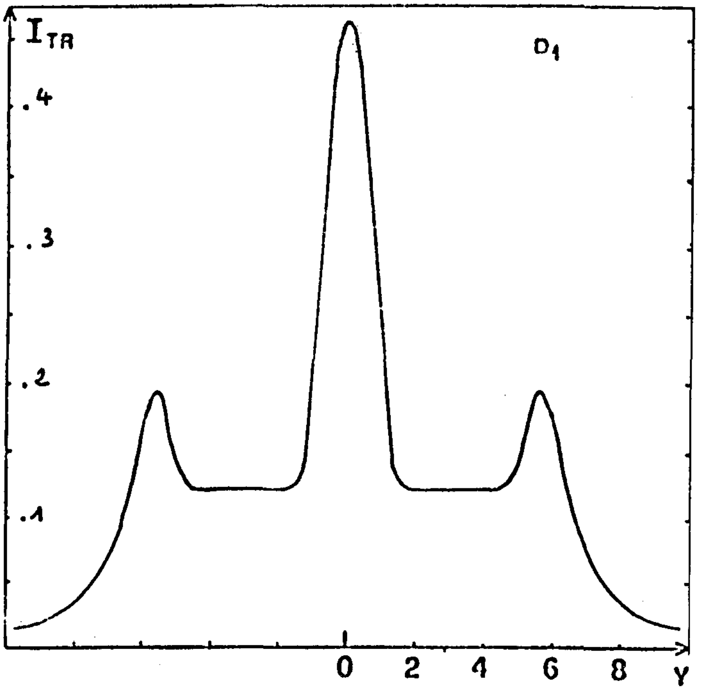

Figure 4: Example of transmission which can be obtained with the sodium filter of Figure 3.

By replacing the entrance polarizer by a Wollaston prism, both directions of polarization can be used and the transmission of Figure 4 can be multiplied by 2 and then gets close to 100%.

The first obvious advantage of this use of optical resonance is that it gives a narrow-band filter able to provide an image (which is not possible with our solar spectrophotometer). It was developed in this direction by Cacciani to get monochromatic images of the solar chromosphere. The second point we wish now to take advantage of is the use of all of the geometrical entrance beam, with a high transmission. It seems then possible to get a photon efficiency at least as good as that obtainable with any other spectroscopic technique, while still taking advantage of the high spectral stability of the optical resonance.

Our plan is to have such an instrument ready in the coming year, and, when used with the largest telescopes such as that which we have above our heads during this meeting, we think that we will be able to reach the 1m s^{-1} sensitivity on the brightest stars.

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