Solar structure

A bridge in a gap in solar oscillations

from Douglas Gough

THE science of helioseismology had its origins only eight years ago in the successful resolution by Deubner[1] of the spatial and temporal structure of the Sun's five-minute oscillations. By measuring Doppler shifts in solar spectra, Deubner was able to deduce the velocity structure of the Sun's visible surface. Depicted as functions of longitude and time the shifts displayed ridge-like features just as if waves were trapped in the outer, convecting layers of the Sun. The effect had already been investigated theoretically by Ulrich[2]. Since then, many modes of oscillation have been observed and interpreted, not without controversy, and those reported by Duvall and Harvey[3] in this issue of *Nature* (p.24) represent a significant extension to the collection.

The diagnostic value of Deubner's observations was appreciated immediately, and it was soon realized that the convection zones of contemporary theoretical solar models were too shallow. To correct them required an increase in the helium content. That in turn meant that the neutrino flux should be higher than previously calculated thus aggravating a conflict with observation which has now plagued astrophysicists for more than a decade.

The five-minute oscillations are an example of a class of oscillations called p modes. They were so named because pressure provides the predominant restoring force. Basically they are standing acoustic waves, modified by gravity. In addition there can be g modes, whose restoring force is buoyancy. These are internal gravity waves that can propagate only in convectively stable regions. They can exist in the solar atmosphere, or in the deep radiative interior of the Sun. Most interior gravity waves are difficult to observe, because the convection zone presents a severe potential barrier that almost isolates them from the Sun's surface.

Besides p and g modes there are also the so-called f modes. These can be regarded as the analogue of surface ocean waves, and have the remarkable property that if their wavelengths are much less than the radius of the Sun (or the depth of the ocean), their frequencies are independent of the density stratification of the Sun (or the ocean); their identification requires a knowledge of only the solar mass and radius.

Roughly speaking, discrete eigen frequencies of solar oscillation can be labelled by two independent integers: the order of the mode, $2n$, which measures the number of nodes along a radial line; and the degree l, which is the degree of the spherical harmonic that factors from the eigenfunction. They correspond to the principal quantum number and the angular momentum quantum number in the theory of the hydrogen atom. The degree l can be regarded as a measure of the horizontal component of the oscillation wave number, and n characterizes the vertical component.

For any value of l, the modes can be ordered according to frequency. The frequencies of all g modes lie below the f-mode frequency ν_f at the same l, and decrease as n increases. The p-mode frequencies lie above ν_f, and increase with n.

Deubner's observations were designed to isolate nearly plane waves. Thus they were restricted to modes with $l \gg 1$, whose horizontal wavelengths are much less than the radius of the photosphere. Such modes are detectable for only comparatively low values of n. Hence the wave number vector, and also the velocity of propagation, are almost horizontal. Because temperature increases with depth, such waves suffer severe refraction and are thus confined within a shallow wave guide just beneath the photosphere. Its depth is $(2n+3)R/l$, where R is the radius of the Sun. The oscillation frequencies measure the mean sound speed in the wave guide, and thus provide a useful diagnostic of the Sun's structure. It was from this diagnostic that the high interior helium abundance Y, about 25 per cent by mass, was deduced. Notice, however, that because l is large ($\gtrsim$ 100), only the very outer layers of the Sun are sampled. Extrapolation to conditions in the solar interior depends on indirect deductions from the theory of stellar evolution, which at best can be regarded as somewhat uncertain.

A more direct indication of conditions in the solar interior has been obtained from measurements of either intensity fluctuations of Doppler shifts in light integrated over substantial portions of the solar image. There is strong cancellation from modes with $l \gg 1$, and only low-degree modes can be detected. As with the high-degree modes, most of the power is in oscillations with periods near five minutes, and since the fundamental acoustic pulsation period is about one hour, it follows that the total wave number must be quite large. Since l is small, n/l must be 'large' (typically $0 \leq l \leqslant 5$ and $15 \leqslant n \leqslant 30$). These modes are very interesting, because they propagate nearly vertically and so succeed in penetrating to the very core of the Sun.

Low-degree modes were first identified by Isaak and his colleagues[4] from Birmingham, and later were unambiguously resolved in the observations of Grec *et al.*[5]. A least-squares fit of the theoretical eigenfrequencies of a sequence of solar models to these new data[6] was found also to favour $Y \simeq 0.25$. However the fit is far from perfect. Consequently, by emphasizing certain aspects of only the low-degree data, it has been possible to maintain the view that, notwithstanding the high-degree modes, a solar model with $Y \lesssim 0.17$ will eventually turn out to be closer to the truth[7,8]. This possibility has interesting cosmological consequences because the solar helium abundance imposes an important constraint on big-bang theories of primordial nucleosynthesis. The difference between a model with ($Y \lesssim 0.17$ and one with $Y \simeq 0.25$ lies in the value of n that is assigned to a particular mode. That cannot be inferred from observations of only the low-degree five-minute modes, since the origin of n is not observed.

In this issue of *Nature* (see p. 24), an important paper[3] appears to remove the ambiguity. By projecting longitudinally averaged Doppler measurements onto zonal harmonics, Duvall and Harvey have been able to connect the sequences of low-degree modes with those having $l \gg 1$. Since when $l \gg 1$ the f mode is unambiguously identified, subject only to the hypothesis that all the modes are excited (for which there is considerable justification), one can count ridges in the power spectrum at high l to identify n. Duvall and Harvey's connection with the low-degree modes then provides n for these modes too. The result corresponds to the prediction of the theoretical solar model with the higher helium content.

The matter must not be regarded as being totally settled, however. We must heed the discrepancy that still exists between theory and observation, not forgetting the problem with the neutrino flux. To resolve the structure of the Sun's interior will probably require knowing the frequencies of p modes with low n and l, and of some internal g modes too. Duvall and Harvey present observational evidence for the existence of those g modes. That gives us hope that more accurate diagnosis will some day be possible. ☐

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