Commentary by John Bahcall on

The Five-Minute Oscillations on the Solar Surface

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Helioseismology has two published birth certificates: the observational discovery (Leighton, Noyes, & Simon 1962, this volume) and the theoretical understanding (Ulrich 1970, this volume and independently, but slightly later, Leibacher & Stein 1971).

For readers who were not doing astronomy three decades ago, the contrast between then and now is hard to appreciate. Before the appearance of the epochal papers of Leighton et al. and of Ulrich, no one knew that the sun oscillates in characteristic eigenfrequencies that can be observed on the surface of the sun. No one imagined that these waves can be used to make precise measurements of the characteristics of the interior of the nearest star. Today many thousands of solar eigenfrequencies are measured routinely by international collaborations with extraordinary precision, typically better than 1 part in 10^4 or 10^5 (see references to BBSO, BISON, GONG, IRIS, LOWL, MDI, and Basu et al. 1996). These measurements are used to make accurate determinations of the interior sound speeds, the density profile, the interior rotational speeds, the depth of the convective zone, the helium abundance and the heavy-element to hydrogen ratio in the convective zone, and even the radius of the sun. Opacity calculations and equation of state calculations, the results of many years of research and massive computation by the most expert physicists and astrophysicists, are tested and improved by comparing theory and observation of solar eigenfrequencies.

How did this extraordinary revolution occur? I was fortunate enough to be at CalTech at the time the pioneering developments were occurring and to be a witness of what happened. Bob Leighton was a senior professor of physics, a cosmic ray and particle experimentalist who became interested in using his exceptional originality and technical ingenuity to make observations in astronomy. Roger Ulrich, at the time he began deriving the equations of helioseismology, was a young postdoctoral fellow working mainly with me (an associate professor of physics) on refining solar models for predicting neutrino fluxes. On his own initiative, Ulrich decided to try to explain the oscillatory surface phenomena that Leighton and his students had detected.

We never dreamed that solar neutrino experiments and helioseismology would one day complement each other.

At the time at which Ulrich's paper appeared, the prevailing view was that the five-minute oscillations were a surface phenomenon. In the decade since their discovery by Leighton and his collaborators, apparently no detailed consideration was given to the possibility that the observations represented the surface manifestation of waves propagating in the solar interior. In fact, Leighton and his colleagues conjectured that the oscillatory behavior which they observed was determined by "local properties of the solar atmosphere." Perhaps the sharpness of the solar photosphere, due to the large increase in opacity as hydrogen is ionized, was what focused the attention of astronomers on surface phenomena.

For many years, the problem of interpreting the observed oscillatory phenomena seemed out of reach. Leighton et al., in their monumental discovery paper, commented after discussing the physical origin of the measured average period (about 5 minutes): "Thus it appears that an accurate calculation of the observed period may be hopelessly difficult or even impossible."

Ulrich's epochal paper marked a turning point in the interpretation of the five-minute oscillations. He abandoned the simplifying assumption of an isothermal atmosphere and showed that the observed oscillations could be interpreted as the surface response to interior eigenmodes [1]. The apparent chaotic nature of the frequencies observed by Leighton and his colleagues was understood to be a result of the limited frequency resolution of their short time series and their combination of modes of very different spatial structures. Ulrich predicted that discrete eigenfrequencies would be discovered and derived the general behavior of the relation between frequency and spatial wave number. This is the key prediction that led to the field of helioseismology. The final paragraph of Ulrich's paper defines the "minimal conditions" that must be satisfied in order to observe the predicted discrete lines in the eigenfrequency-wave number plane, including spatial resolution, length of observation, region covered, and sensitivity in wavelength and velocity.

The paper by Ulrich is beautiful and I strongly urge you to spend a little time reading it. I find the paper inspirational in the way it shows that simple physics can lead to such profoundly important and precise results. The second section of Ulrich's paper is the most revolutionary. In only two pages, Ulrich summarizes the basic dispersion relation for the acoustic waves and concludes that "...the 5-minute oscillations are acoustic waves trapped below the solar photosphere and that power in the (k_h, ω)-diagram should be observed only along discrete lines." That is essence of the theory of helioseismology in one compact

[1]Leibacher and Stein, in their independent investigation, also abandoned the isothermal approximation and interpreted the observed oscillations as the surface response to interior oscillations. They did not discuss the horizontal structure of the modes, which leads to the prediction of discrete bands of eigenfrequencies.

sentence [2]

A quarter of a century later, after more than 10^5 modes have been measured accurately, these are still the basic ideas of helioseismology.

Only a few years after Ulrich's seminal paper, Deubner (1975) confirmed observationally Ulrich's basic picture of the solar surface roiling under the simultaneous motion of a large, discrete set of eigenmodes. Deubner's measurements initiated the precise science of helioseismology. If the papers of Leighton, Noyes, and Simon (1962) and of Ulrich (1970) and Leibacher and Stein (1971) constituted the birth of helioseismology, then Deubner's paper celebrated the bar mitzvah of the subject.

Quite remarkably, more than a quarter of a century after their pioneering papers were published, Leibacher (NSO) and Ulrich (UCLA) are both among the observational leaders in the field that their theoretical work helped to create. Leibacher is the project Director for the international Global Oscillation Network Group (GONG) and Ulrich is Principal Investigator for the 150-foot solar tower on Mount Wilson and a major contributor to the GOLF and MDI space experiments. Leibacher's collaborator, R. F. Stein (Michigan State), continues to interpret solar observations, primarily by simulating convection phenomena. Leighton (1919-1997) had distinguished careers in both physics and astronomy (solar, planetary, infrared, and millimeter). His two collaborators in the observational discovery of solar oscillatory phenomena, R. Noyes (Harvard) and G. Simon (NSO), are still active in helioseismology and related subjects. Noyes is one of the leaders in the nascent field of asteroseismology and Simon is an observer and modeler of solar surface phenomena.

The revolutionary research studies of Leibacher, Noyes, and Simon were part of their Phd thesis work, while Ulrich was a young postdoctoral fellow. Leighton was a senior physicist but a novice in solar astronomy. Did the pundits know too much to make a breakthrough?

For me personally, the most beautiful and ironic development of helioseismology has been the important role that the precise measurements of solar sound speeds have played in the discussion of the solar neutrino problem. The modern standard solar model predicts correctly the measured sound speeds to a root-mean-squared accuracy of 0.1% from $0.05R_\odot$ to $0.95R_\odot$ (e. g., Bahcall, Basu, & Pinsonneault 1998). This excellent agreement between the solar calculations and observations has been a key ingredient in convincing physicists

[2] Ulrich used a plane-parallel geometry, which was adequate for the modes with small horizontal wavelength that he discussed. Today, of course, the analysis is done in spherical harmonics to properly describe the solar geometry.

that solar neutrino experiments may be revealing physics not included in the standard electroweak theory.

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