Robert Leighton and the Dawn of Helioseismology

R. W. Noyes

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Abstract. We review the events leading up to and including the discovery in 1960 by Robert Leighton of the solar 5-minute oscillation, which may be characterized as the dawn of helioseismology.

This is a personal account, by one of his students, of the events surrounding the discovery of the solar 5-minute oscillation in the summer of 1960 by Robert Leighton. As his first solar graduate student, I had the good fortune to participate in these events, but there can be no doubt that the entire credit for the discovery must go to Bob Leighton.

I would like to begin with some relevant background. Leighton grew up in Los Angeles, attended Los Angeles City College, then transferred to Caltech in his junior year, where he then spent his entire working life, as undergraduate, then graduate student, post-doc and faculty member—always in physics. He took a hands-on approach to physics. For example, in a 1987 Oral History Interview, he described a problem that arose during his graduate work, which had to do with the specific heat of face-centered cubic crystals. He found it necessary to calculate a very complex integral, and the way he finally solved it was to make a 3-dimensional model in the shop and weigh it. He commented that this experience taught him he was not a theoretical physicist: “The way I solved the theoretical problem was to go into the shop and build something concrete.” He also said that to learn something new you do not just “buy something off the shelf and use it, but you do better to buy something and modify it so it works ten times better, or gin up something yourself that you have confidence will tell you something you might be interested in.”

After receiving his PhD in physics, Leighton joined Carl Anderson’s cosmic-ray cloud chamber group, and built a cloud chamber which he took to the top of Mt. Wilson to detect the arrival of cosmic rays and identify the particles by their charge and mass and decay modes. At Mt Wilson he met Olin Wilson who was observing with the 60-inch telescope, and because the telescope was undersubscribed Leighton got to use it for stargazing at the planets. He became intrigued with the challenge of obtaining high resolution images of the planets, and developed a photoelectric guider for that purpose, obtaining some of the finest images of Mars and Jupiter that had yet been obtained. In his Oral History he said that he didn’t learn much about planets; he was mainly interested in the technical aspects of getting high-resolution telescopic images. But he did note that this paid off later when he participated in the Mars Mariner program as probably the world’s expert on stabilizing images of planets.

1The incident described here, as well as others referred to throughout, are laid out in the California Institute of Technology Oral History Project, Interviews with Robert B. Leighton, 1986-7 (Aspaturian 1995)
At Mt. Wilson, Leighton was also well aware of the observations of the sun from the 60-foot solar tower telescope, where the observers would take daily survey images of the solar disk through the 12-inch lens. He was amazed that they routinely stopped the lens down to 4-inches, to achieve uniform, if mediocre, image quality. He became interested in obtaining the sharpest possible granulation images, in part to help resolve an ongoing controversy of the time, namely whether the granularity was a random pattern of bright and dark turbulent elements or whether there was a structure to the granulation pattern, with bright hot granules surrounded by narrow dark intergranular lanes, as suggested by historic but somewhat suspect photos made at the end of the previous century. He was also interested in the time evolution of granules: how they appear, move about and decay.

So in 1955 Leighton set out to make observations from the tower just after sunrise when the image quality could be extraordinary, if only for a few tens of minutes while the air remained perfectly still. For this project he built a special 35-mm film camera that could take many photos in quick succession. A key component was a shutter assembly he built for the purpose, incorporating three slotted disks driven by a set of gears so as to rotate about the same axis at different speeds; when the slots came into coincidence about once per second they would allow an exposure whose millisecond duration was determined by the width of the narrowest slot. Leighton began making series of observations just after sunrise when the atmosphere was still stable, and picked out the sharpest images. He immediately saw that the granularity was indeed asymmetric, consisting of bright centers of granules surrounded by narrow dark lanes (Leighton 1957).

He then tried to estimate the lifetime of the granularity, from the characteristic decay time of the correlation of the granularity pattern. His approach was to cross-correlate pairs of images taken at various time separations. But in 1955 it was not easy to do this, for one would have to use a microphotometer to digitize a set of photographic film images, then calculate the two-dimensional cross correlation function between them. A numerical calculation would have been a formidable task at the time, because computers were in rather primitive stages of development. So Leighton developed a piece of hardware, which he called an “Autocorrelation Machine”, to achieve the same result in an analog way. The Autocorrelation Machine was to play an important role in the analysis of solar velocity fields a few years later, so a brief description is in order: Leighton made film transparency enlargements of frames of interest to precisely the same scale, and placed a pair of such frames in a device he built that passed collimated light through the pair, then recorded the transmitted light with a photometer and chart recorder while the two transparencies were displaced relative to each other on a motor-driven stage. The chart record traced out the spatial autocorrelation function of the granularity pattern (if the two images were identical) or if the frames were taken at different times, the cross-correlation function between them. The area under the cross-correlation peak decreased as the time separation increased and the granularity pattern evolved. He found that the area decreased exponentially with a characteristic time of about 4 minutes, which could be considered an estimate of the “lifetime” of the granularity.

At about this time, Leighton became interested in magnetic fields in the sun. He was quite familiar, of course, with Horace Babcock’s magnetograph at the Mt. Wilson 150-foot tower, which used the Zeeman splitting of magnetically sensitive spectral lines to measure magnetic fields as weak as about 1 Gauss, sufficient to reveal the large-scale
solar magnetic field and its polarity reversal with the solar cycle. But the magnetograph was a scanning instrument with very coarse angular resolution. Leighton thought of a way to image magnetic fields on the sun with the few arcsec resolution obtainable with the Mt. Wilson spectroheliograph.

In his Oral History, Leighton gave credit for the idea to Fritz Zwicky in the Caltech Astronomy Department. Zwicky gave a talk in which he described photographing a galaxy in red and blue light, and then subtracting the images photographically to bring out color differences across the galaxy; this he did by placing a negative transparency of one image on top of a positive transparency of the other. He illustrated this technique with two photos he had made of a pile of tin cans, identical except that in one of them he had added one additional can to the pile. The individual photos were indistinguishable on superficial inspection, but in the photographic subtraction everything was grey except the one added can, which stood out like a sore thumb. This led Leighton to the idea of using the 60-foot tower spectroheliograph on Mt. Wilson to obtain two simultaneous images of the sun, in a narrow wavelength band on the wing of a magnetically-sensitive absorption line, but using polarizing optics to transmit only right-hand and left-hand circularly polarized light to the two images respectively. Then, wherever there was a significant line-of-sight magnetic field, the Zeeman shift would cause the dark spectral line core for one of the images to shifted toward the center of the slit and make the image a little darker, while for the other image the shift was away from the slit so that image became a little brighter. After photographic subtraction the differential magnetic signal would be doubled, while other and much larger variations in the image, due to effects identical to both images such as temperature, seeing variations, etc., would cancel out.

The 60-foot tower spectroheliograph had been built in the early 1900s and was essentially unchanged since then. It consists of a high-resolution vertical spectrograph, in which focused sunlight passes through an entrance slit, is dispersed by a grating, and produces a spectrum at an exit slit. The grating is oriented so that light in a chosen narrow spectral band passes through the exit slit and strikes a photographic plate. The instrument is mounted on bearings so that it can be driven uniformly so as to cause the entrance slit to scan across the solar image while the exit slit scans along a photographic plate, thereby laying down on the plate an image of the sun in the chosen spectral bandpass.

Leighton constructed a beamsplitting device that, when placed in careful alignment above the spectroheliograph entrance slit, produced two images on the entrance slit, identical except that a combination of a quarter-wave plate and polaroid filters placed above the entrance slit caused the two images to receive only right-hand and left-hand circularly polarized light respectively. Rotating the quarter-wave plate by $90^\circ$ would reverse the sense of the polarization, thus flipping the sign of the magnetic sensitivity of the two images. To make the magnetic observations, Leighton set the grating so as to place the violet wing of the spectral line Ca I $\lambda$ 6103 Å on the exit slit; this line was chosen because it is a simple Zeeman triplet with good magnetic sensitivity. In places on the sun with a significant line-of-sight magnetic field, one image became darker and the other brighter, as described above. Thus, in a photographic subtraction, or “Zeeman plate”, to a first approximation everything cancelled out except the magnetic signal, which was actually doubled.

Leighton actually went a step further. After obtaining a pair of magnetic spectroheliograms in this way, he would immediately switch the quarter-wave plate by $90^\circ$ and
record a second pair of spectroheliograms. So the second Zeeman plate also showed the same magnetic features, but now of the opposite sign. Then, he would photographically cancel these two already-cancelled plates to make a doubly-cancelled, or “Zeeman Sum” plate, in which the magnetic signals were doubled again, while any remaining non-magnetic signals would be further reduced.

The darkroom technique required for cancelling, and double-cancelling, the photographic plates was actually quite complicated. The contact prints of the original glass plates had to be carefully developed to unity contrast ratio or “gamma”, so that when placed emulsion-to-emulsion on the original all features would cancel out, leaving a uniform gray. Then, when placed (and carefully cemented in registration) on the opposite member of the pair, all features would cancel for the magnetic signal, which would be doubled. As a further complication, making a double cancellation required an intermediate step of projection-printing each of the singly-cancelled plates onto a new plate so as to produce a copy with its emulsion on the surface rather than sandwiched between two layers of glass. Finally, a contact print of one of these projection copies was made and glued in registration on the other one. Leighton carried out these reductions in his home darkroom, since the facilities at the Mt. Wilson 60-foot tower telescope were inadequate.

Figure 1 shows the result (Leighton 1959). For the first time one could see that the magnetic field away from sunspots has an intricate small-scale structure that closely matches the pattern of Ca \textsuperscript{2} H and K line emission, which was long known to reflect localized heating in so-called plages in the chromosphere. While commonplace knowledge now, in 1959 this was an important new discovery: photospheric magnetic fields with strengths of several tens of gauss or more are a key agent leading to the heating of the overlying solar chromosphere.

On a personal note, here is where I came into the picture. I helped Leighton to finish up his paper on magnetic fields in plages, and he then suggested I take a machine shop course. Not only was this in keeping with his “hands-on” philosophy, but also he was looking for help in building a large version of the rotating-sector camera system that he had built for his 1955 granulation study. We designed the camera system to make high-speed photographs of the full 7-inch solar image from the 60-foot tower, alternating in each of red, green, and blue colors every few seconds, all the while moving back and forth on rails to compensate for telescope focal length differences between the three colors. The purpose was to explore the temperature structure and time variation of granulation, and of limb faculae. I worked on building and operating this camera during the spring and summer of 1959, during which we obtained a number of series of high-quality images of the full-disk photosphere.

In the meantime, Leighton was thinking about an obvious variant of his differential approach to imaging magnetic fields. Namely, one could use a similar approach to map solar velocity fields rather than magnetic fields, by obtaining simultaneous spectroheliograms differing only in their sensitivity to velocity rather than to magnetic fields. As before, Hale’s spectroheliograph with a beamsplitter could be used to acquire pairs of nearly identical images, and one could place a pair of glass blocks under the exit slit, tilted in opposite directions to tune one image to the red wing and the other to the violet wing of a spectral line. Then images of upward moving features made on the red wing of a spectral line would become brighter, while those recorded on the violet wing would become darker. Photographic cancellation of pairs of such images should retain only line-of-sight velocity fields, on a spatial scale as small as a few arcseconds.
An obvious target was the solar granulation, whose typical lifetime Leighton had already explored by direct photography. Perhaps we could measure the details of how granulation velocities change as the granulation brightness pattern itself evolves.

At the same time, a real drawback was the small field of view of Hale’s spectroheliograph. Its entrance slit was only about 3 inches long, and when divided in half to record simultaneous images through the beam splitter, the fractional coverage of the 7-inch solar image from the telescope would be painfully small. So with support from Ira Bowen, the director of Mt. Wilson and Palomar Observatories, Leighton rebuilt the head of the spectroheliograph so as to accommodate entrance and exit slits that were a full 7 inches long. He also constructed a larger beam splitter that spanned the new slit length with two 3.5-inch images. Also, the exit slit assembly was re-built to incorporate the tilt-able glass blocks needed to shift the bandpass to the red and violet wings of a spectral line for the two images.

The substantial re-build of the spectroheliograph and associated optics was carried out over the winter and spring of 1960, and we began scientific observations with the new system in late May and early June of 1960. We made both Doppler and Zeeman observations of many lines, including the Ca $\lambda$ 6103 Å line, and stronger and weaker lines such as Na $\lambda$ 5896 Å and Fe $\lambda$ 6102 Å and others.

The raw observations in the red and violet wings of spectral lines like Ca $\lambda$ 6103 Å immediately showed an interesting asymmetry (Figure 2). Namely, the “contrast” of the features seen in the red wing of the line was substantially larger than those seen in the violet wing. This effect, which is obvious in all moderately strong photospheric lines,
is due to a correlation between brightness and velocity, in the sense that brighter (hence hotter) areas are rising (hence blue-shifted), while darker (cooler) areas are falling (hence red-shifted). In red-wing images, rising elements appear brighter on two counts: they are hotter, and the dark line core is doppler-shifted towards the violet and hence away from the slit; likewise falling elements are darker both because they are cooler and because the line core is shifted redward, toward the slit. Conversely, for images exposed on the violet wing the effects due to temperature and velocity oppose each other, leading to much less contrast between rising and falling elements. This bodily transport of hot material upward and cooler material downward implies a net upward flux of mechanical energy, which we were later able to estimate as of order 2 watt/cm$^2$ (Leighton et al. 1962).

The next step was to photographically cancel a pair of simultaneous red-wing and violet-wing images of the sort in Figure 2 to create a “Doppler plate” showing only the velocity fields. Figure 3 shows as an example Doppler plates in the wings of the Ca $\lambda$ 6103 Å and Na $\lambda$ 5896 Å absorption lines; the latter, being considerably stronger, is formed somewhat higher in the solar atmosphere. Both images show a velocity pattern reminiscent of the solar granulation but significantly larger in spatial scale. From measurements with the autocorrelation machine, the spatial scale was found to be of order 2700 km at the formation height of Ca $\lambda$ 6103 Å, increasing with height; and the amplitude of the velocity variations of order 0.4 km/s, also increasing with height (Leighton et al. 1962).

An obvious next step, by analogy with the magnetic field study, would be to create a “Doppler Sum” plate by exposing two Doppler image pairs in quick succession and reversing the tilt of the glass line-shifting blocks in between, so that the velocity signals would add in the second cancellation. However, there is a very important difference
between Doppler Sum and Zeeman Sum plates. Namely, the lifetime of the magnetic features seen in a Zeeman Sum plate is long compared to the total scan duration of a few minutes, so the magnetic features seen on such a plate are essentially identical to those seen on a singly-cancelled Zeeman plate but doubled in amplitude. However, the coherence time of the granulation pattern is only a few minutes, which is comparable to the scan time to take a pair of Doppler plates. If the velocity field associated with the granulation has a similar coherence time, then a Doppler sum plate would be complicated by the time changes of the velocity field during the observation.

In his Oral History Leighton said that after worrying about this a bit he realized that rather than being a problem this was an opportunity: One could expose two Doppler plates in succession in which nothing was changed in the equipment; that is, the tilted glass blocks would not be reversed between the exposures. Then the only differences between the two plates would be those due to time changes in the velocity field during the observation. We called a double cancellation of two such plates a “Doppler Difference” plate, where the pattern at any point on the plate reflects the difference in the line-of-sight velocity pattern over the time interval $\Delta t$ that elapsed between the two scans over that point on the image. $\Delta t$ would be nearly zero at the end of the plate where the first scan ended and the second one began a few seconds later. At the other end of the plate, where the first scan started and the second one ended, $\Delta t$ would be several minutes, the exact value depending on the scanning speed of the spectroheliograph. The Doppler Difference image should be nearly featureless at the end where $\Delta t \sim 0$, and
the rms variation, or “contrast”, of the pattern should increase steadily toward the other end of the plate, approaching a value reflecting the difference between velocity fields that are completely uncorrelated. Conversely, a Doppler Sum plate should show a very large contrast signal at the end where $\Delta t \sim 0$ and the amplitude of the velocity signal was essentially doubled, gradually decreasing with distance along the plate as the difference pattern approached what one would see by summing together two uncorrelated velocity field patterns.

By the end of May 1960 we had taken a number of raw plates from which to create Doppler plates as well as Doppler Difference and Sum plates. As noted above, in order to carry out the intricate photographic reduction process, Leighton carried out this work in his home darkroom in Altadena. Over one weekend in early June, after a certain number of raw plates were accumulated, he took them to his home in Altadena to process them further there.

I remember very clearly that when we next met on the mountain, Leighton said to me, “Bob, I’ve found your Thesis Project!” He went on to say that the solar velocities seemed to show an oscillatory behavior with a period of about 5 minutes, so that if, for example, at any point on the sun the material is moving upward at a given instant, it will be moving downward about 2.5 minutes later, and 5 minutes later it will moving upward again. My immediate reaction was one of incredulity, and I remember blurting out something like “No! that can’t be!” I don’t know whether Leighton was shocked or amused at this response, but it must have made an impression, for 27 years later in his Oral History he recalled the incident, including my reaction, essentially as recounted here.

To convince me, Leighton showed me some of the Doppler difference plates he had produced, which he had brought up the mountain for that purpose. The left-hand image in Figure 4 is an example, using data obtained somewhat later in the line Ba II $\lambda$ 4554 Å. The plot accompanying that image shows the height of autocorrelation curves we recorded with the Autocorrelation Machine, by masking out vertical strips between the tick marks at the bottom of the image and then displacing them vertically. The autocorrelation heights yield a quantitative measurement of what is apparent in the image: the spatial variation is negligible near zero time difference $\Delta t$, rises to a maximum around 150 second time difference, then decreases again to a minimum near $\Delta t \sim 300$ s.

In Leighton’s 1987 Oral History he talked further about his discovery. We had obtained the data to create Doppler Difference plates in various spectral lines, and at various scanning speeds depending on the brightness of the different spectral lines as produced by the spectroheliograph. Leighton found that in spite of the different scan speeds all showed the contrast increasing and then decreasing to a minimum at a plate location corresponding to a 5-minute time difference. In his Oral History he described his feeling when he saw this: “It was one of the few times I’d actually seen something and realized, Aha! Now I know something about the Sun that nobody else knows.”

I think it is fair to consider Leighton’s “Aha” moment to mark the dawn of helioseismology.

Shortly after the initial discovery from the Doppler Difference plates, Leighton reduced some of the Doppler Sum plates, in which we had reversed the tilt of the glass blocks between the pair of exposures. The right panel of Figure 4 shows the result, namely that at the end of the plate where the time difference is nearly zero the amplitude of the Doppler pattern is now doubled, but at the location on the plate corresponding
to a time difference of about 150 seconds the amplitude reaches a minimum, and then rises again to another maximum at a plate location corresponding to time difference $\Delta t \sim 300$ s. The depth of the minimum near $\Delta t \sim 150$ s indicates that the oscillatory motions comprise nearly all of the velocity field in the upper solar photosphere at the level of formation of the Ba ii line wing.

Figure 5 is another Doppler Sum plate, this one covering not only the center of the solar disk, but also the limb region. The minimum of contrast after a time delay of about 150 seconds is again evident, but also clearly visible is a much larger-scale pattern partway toward the limb. This pattern does not oscillate on a 5-minute timescale, and clearly consists of essentially horizontal flows, since it is not seen at all at disk center. Furthermore, it occurs essentially uniformly all over the sun, as is is clearly seen by making a Doppler Sum image of the entire solar disk (using an auxiliary optical system that produced a full-disk image small enough to fit on the divided entrance slit, albeit with reduced resolution); see Figure 6. In this figure the 300 s oscillatory velocity field was largely suppressed by scanning the second Doppler image in the same direction as the first, after a time delay of 150 seconds (Leighton 1963).

At about this time, fellow graduate student George Simon joined Leighton as a PhD student. The discovery of the regular pattern of horizontal flows made a superb thesis topic for George. He was to spend the next year and a half exploring the nature of the phenomenon, which he and Leighton were soon to name the solar “supergranulation”. Simon showed (Simon 1963; Simon & Leighton 1964) that the primarily horizontal flow field of the supergranulation clearly sweeps the magnetic fields to the boundaries of the supergranulation “cells”, and as a result creates the chromospheric
network of emission due to heating at those boundaries associated with the concentrated magnetic fields there.

Armed with the initial results on both the 5-minute oscillation and the supergranulation, in August of 1960 Leighton went off to an I.A.U. Symposium on aerodynamic phenomena in stellar atmospheres in Varenna, Italy, and there made the first announcement (Leighton 1960) of the detection of both the 5-minute oscillation and the supergranulation velocity field.

We continued to study the properties of both of these velocity fields over the next couple of years. As for the small-scale velocity field, we found that it appeared to have two components: an oscillatory component with a mean period of about 296 seconds, decreasing slightly with increasing altitude of line formation, and becoming more vertical with increasing altitude; and a non-oscillatory component which was smaller in scale and did not increase in amplitude with height. We, and others, interpreted the non-oscillatory component as being associated with the changing pattern of granular convection, and the oscillatory component as representing the resonant response of the overlying atmosphere to bright granules rising through the top of the convection zone. This interpretation turned out to be a blind alley: what we were really seeing as oscillat-
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Figure 6. Doppler Sum plate with the 5-min oscillation signal suppressed; this shows the outflowing horizontal velocities of the supergranulation. Dark areas are receding. Reproduced from Leighton (1963) by permission of the Copyright Clearance Center

ing local elements of the granulation-induced velocity field was really the interference pattern of a myriad of acoustic oscillation modes of the entire sun.

Thus, although I consider it to be an apt metaphor that Leighton’s discovery of the 5-minute solar oscillations in his home darkroom in the early summer of 1960 marked the “dawn” of helioseismology, it wasn’t the real “daybreak”. That would come only in later years when the work of a rapidly growing community of scientists, including many of the participants in this workshop, led to the understanding of their true nature, and as a consequence to amazing advances in our knowledge of the interiors of the sun and other stars.

A few words of epilogue: I finished my thesis (Noyes 1963) on the 5-minute oscillations in summer 1962, and a year later George Simon finished his (Simon 1963) on the Supergranulation. Neil Sheeley joined Leighton’s group in 1962, and wrote a thesis (Sheeley 1965) on the transport of magnetic fields on the sun through supergranular diffusion. Following that, in 1966 Alan Title wrote a thesis (Title 1966) on velocities in the Hα chromosphere using a videomagnetograph approach that built upon Leighton’s photographic cancellation methods. All of this grew out of the extraordinary summer of 1960 at the 60-foot tower. Leighton in his Oral History 27 years later expressed pleasure that his students had remained active in solar physics; as for himself, he said he “fell off the wagon”. But I remember him more than once saying to me that “Science is where you find it”, and he found many new and very productive research areas in subsequent
years – starting with infrared astronomy where he manufactured a novel infrared survey telescope with G. Neugebauer, moving on to play a leading role in JPL’s Mars Mariner program, and toward the end of his active career bolting together large structures with great precision to create diffraction-limited mm and sub-mm dishes for Owens Valley and Hawaii. In his Oral History he said that as a child he enjoyed building stuff with erector sets, and that later in his career he returned to the same thing, albeit on a larger scale. Unfortunately, toward the end of his life Leighton was stricken by a degenerative brain disease and so was not fully aware of the full flowering of helioseismology and asteroseismology as we see it today. How pleased he would be if he could be here this week and take part in the exciting discussions of all the tremendous science that has come and continues to come from that “aha” moment in his home darkroom in 1960.

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References

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