The music of the spheres

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1. Introduction

The closest star known to us, the Sun, lies only a few *millionths* of the distance to the next closest star, Proxima Centauri. It is no wonder, then, that much of what we know about stars relies heavily on our knowledge of the Sun. Until recently, our only source of knowledge of the interior of the Sun was the many and varied phenomena visible on only the outermost 0.17% of the Sun. The remaining 99.83% was known largely through inference. The light that streams to us from the Sun is produced deep in its interior in regions that we can never see directly through a telescope. What we see on the surface of the Sun is but a pale manifestation of the powerful forces at work in the interior of our star. Over the past three decades astrophysicists have discovered ways to penetrate the opaque brilliance of the outer layers to explore what lies beneath.

This was made possible by the discovery of vibrations in the Sun, "Sunquakes", if you will. I could have chosen the title *Starquake!* for this paper, but somehow the title *Music of the spheres*[1] evoked less violent images. As far as Nature is concerned, though, it doesn't really matter, for the physics is the same.

[1] I am exercising considerable poetic licence in using this title. The doctrine of the harmony of the spheres originated with the Pythagorean Universe. This model postulated that the motions of heavenly bodies produced tones whose pitches depended on the velocities of those bodies. Our inability to hear this celestial music was ascribed to the fact that we hear it from birth and are thus insensitive to it.

Papers presented at the 3rd ASSA Symposium

Stars are just like people. The better you get to know them, the more complex they become. The Sun is no exception to this rule. The surface of the Sun is hardly static. It exhibits a bewildering variety of phenomena on different time-scales. These phenomena are but the surface manifestation of processes occurring deep in the solar interior. A simple projected image of the Sun reveals the existence of sunspots. The existence of sunspots was already known to the ancient Chinese who discovered them by looking at the Sun through heavy mist. Sunspots appear black only because they are cooler than their surroundings.

Typical sunspot temperatures are about 4000–4800 degrees Celsius, while the rest of the solar surface has an average temperature of around 6000° Celsius. Sunspots are cooler than their surroundings because the intense magnetic fields in them impede the upward flow of energy from below. The motion of sunspots shows that the Sun rotates once a month, and that the rotation is faster at the equator than at the poles.

A closer view of the solar surface reveals a rice-like pattern, known as "granulation," which changes minute by minute. The "grains" are in fact the tops of convection cells about 500–700 km across. These convection cells are organized in a subtle larger-scale pattern called "supergranulation" which has cells about 30 000 km wide.

As in the case of sunspots, the dark boundaries of the grains indicate regions of lower temperature. The bright grain centres are regions where hot gases rise up from below, and the dark grain boundaries are where cooler gases sink.

The surface of the Sun is also permeated by rather complex magnetic fields. These magnetic fields produce the fine filamentary structures that are visible during total solar eclipses. The magnetic field is also intimately linked to sunspot activity. Sunspots usually come in pairs. When we measure the magnetic polarity of individual sunspots in these pairs we find that they have opposite magnetic polarities. That is, if one sunspot is a magnetic north its partner is invariably a magnetic south. The reason for this is that sunspot pairs are produced when the magnetic field lines break through the solar surface. One member of a given pair marks where the field lines break through the surface, and the other spot marks where the field reenters the solar surface. Occasionally, violent eruptions of the field occur. These *solar flares* eject charged particles which interact with the Earth's ionosphere to produce bright aurorae and cause radio storms. Individual sunspots persist for several days to several months before disappearing. The total number of sunspots is not constant, but fluctuates cyclically with an 11-year period called the *solar cycle*, in step with a gradual variation in the Sun's magnetic field. A detailed account of the solar cycle is beyond the scope of this paper, but I mention it as another example of how the Sun's magnetic field is intimately linked to sunspot activity.

In contrast to its exterior, the interior of the Sun is known largely by inference. Briefly, energy is generated in the core by thermonuclear fusion, for it is only there that one finds the extreme pressures and temperatures required for two positively charged protons to overcome their mutual repulsion and fuse into a helium nucleus (hence the term thermonuclear fusion).

This fusion process releases a lot of energy which then diffuses out through the central radiative zone by atomic emission and absorption. The radiative zone is surrounded by a convective envelope in which the energy is transported by circulation processes where hotter material rises and cooler material sinks. This is the same process as occurs in a pot of boiling water. The granules mentioned above are the tops of giant convection cells.

By everyday standards it takes a *very* long time for energy to get out of the Sun. The energy produced in a fusion reaction in the centre of the Sun takes about a million years to work its way out to the surface (700 000 km) and then only 8 minutes to travel the remaining 150 million km to the Earth! Having had such a tortuous journey out of the Sun the photons we measure have lost all information about the conditions in the energy-producing regions.

Fortunately, there is one form of radiation that escapes unscathed directly from the centre of the Sun. This radiation comprises elusive subatomic particles called neutrinos.

2. Seeing inside the Sun - I: Neutrinos

Neutrinos are subatomic particles released as one of the products of the fusion reactions in the centre of the Sun. They have spin, zero charge, probably a very tiny mass, and very high energy.

They are so weakly interacting that most would easily pass through a light year of solid lead. An unimaginably large number ($\sim 10^{14}$) of solar neutrinos passes through your body every second. The existence of neutrinos was predicted by the German physicist Wolfgang Pauli in 1930 to explain (among other things) "missing" angular momentum in some subatomic particle interactions.

In 1964 Raymond Davis began to record solar neutrinos. His "telescope" consists of a large underground tank containing 100 000 gallons of cleaning fluid (tetrachloroethylene, C_2Cl_4) in an abandoned gold mine in South Dakota. The experiment is conducted underground to shield the instrument from undesirable cosmic rays that produce spurious results.

The heavier stable isotope of chlorine is able to capture neutrinos by the reaction $Cl^{37} + \nu \rightarrow A^{37} + e^-$ The argon isotope is a radioactive gas with a half-life of about 35 days.

Only about $^1/_3$ of the expected solar neutrinos have been detected by neutrino experiments like Davis'. This discrepancy, dubbed "the solar neutrino problem" by astrophysicists, suggests that either we don't really understand how the Sun shines, or that something is wrong with our understanding of neutrino physics, or both. We will return to this discrepancy later.

Neutrinos are also produced in other stars, but you can imagine how much harder those are to detect. Nevertheless, we have already detected neutrinos from one other star. About 169 000 years ago a star exploded in the Large Magellanic Cloud. The light of that explosion only reached us in 1987 and we called that star "Supernova 1987a".

Enormous numbers of neutrinos were generated in that explosion and about 10 of them were recorded by a neutrino detector called Kamiokande in Japan (actually, that detector was looking for the signature of proton decay, but that is another story). Since Japan is in the northern hemisphere and the supernova was visible in the southern skies this means that the neutrinos had to penetrate the Earth to get to that detector!

3. Interlude - Waves, the Doppler effect and Fraunhofer absorption lines

Before continuing with our story, I will pause to define some of the terminology that we will use in our discussion of the music of the spheres. Readers familiar with the concepts of waves, the Doppler effect and spectral absorption lines may wish to skip to Section 4.

3.1 Waves

When you drop a stone into water the familiar expanding circular ripple you get is a wave. A wave is thus a travelling disturbance in some medium[2]. If the disturbance is periodic, a wave train is created. Figure 1 shows a photograph taken looking down on a wave train on the surface of water. The parallel lines are called wave fronts.

Below the photograph is a schematic side view of the wave train, illustrating its main features. The difference in height between the unperturbed surface and the crests (or troughs) is called the *amplitude* of the wave. The distance between two consecutive crests is the *wavelength* of the wave and the time required for two consecutive crests to pass a given point is known as the *period* of the wave. In sound waves, increasing wavelength corresponds to decreasing pitch. In light waves, long wavelengths correspond to red light, short wavelengths to blue light. Radio waves are just light waves of very long wavelength. X-rays, on the other hand, are light waves of very short wavelength.

3.2 The Doppler effect

This is the name given to the familiar experience of the pitch of an oncoming siren being higher than that of the same siren as it recedes into the distance. A qualitative understanding of why this is so may be gained from a simple geometrical argument. Imagine a stationary source S of a wave disturbance on the surface of a pond. The disturbance can be anything periodic - a stream of water drops, for example. This produces the familiar pattern of concentric circular ripples on the surface as shown in the leftmost diagram of Figure 2.

[2]Light waves are an exception to this. They can propagate through a vacuum - as indeed they must, or we would not be able to see the stars.

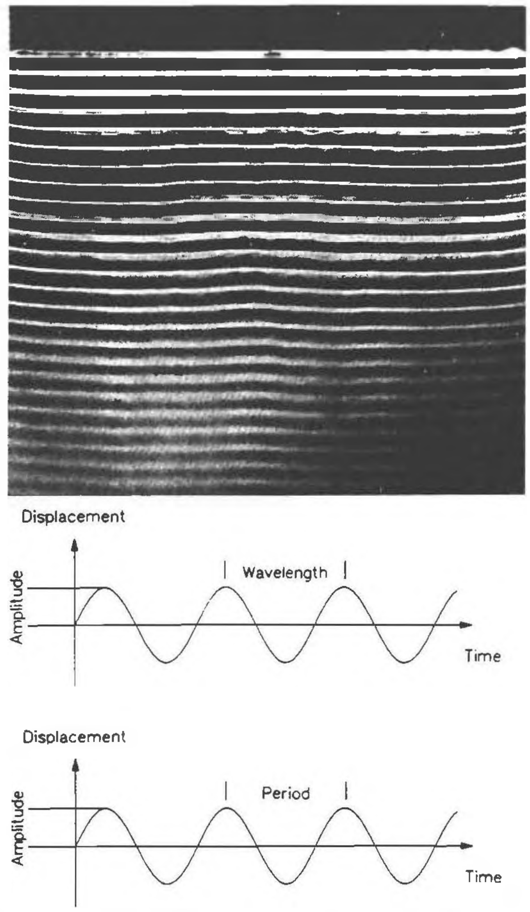

Figure 1. (Top) Waves in a ripple tank. (Bottom) Schematic definition of wave terminology.

If, however, the source of the waves moves with a velocity v_s, then the wave fronts will be squashed up ahead of the source and stretched out behind it, as shown in the second diagram of Figure 2. This stretching or squashing of the wavelength is called a *Doppler shift*.

It is important to appreciate that the Doppler effect arises whenever there is *relative* motion of the wave source with respect to the observer. The degree of Doppler shifting increases as the relative speed between the observer and wave source increases. In the case of sound waves, approaching objects are heard at a higher pitch, receding objects at a lower pitch. In the case of light waves, approaching objects appear bluer than they are, receding objects appear redder than they are. Although we are familiar with

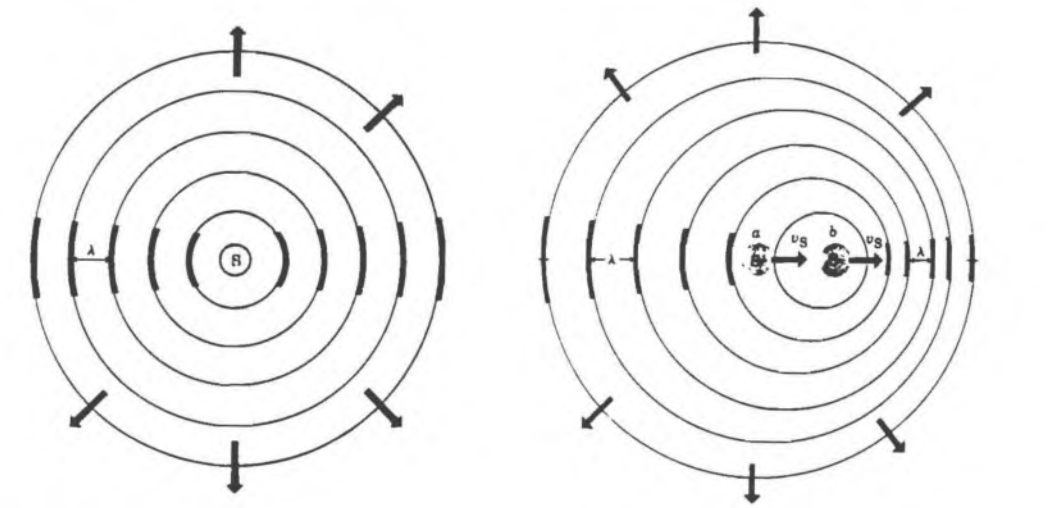

Figure 2. The Doppler effect

Doppler shifting of sound waves, we have no familiar daily experience of Doppler shifted light waves because light travels a million times faster than sound in our atmosphere. If your car could reach speeds of 360 million km/h then all oncoming red traffic lights would appear green to you. (Of course, a traffic officer standing at the side of the road would see you running a red light. Einstein's theory of relativity arises from considerations such as these, but that is another story.)

3.3 Fraunhofer absorption lines

In the early 1800's the German physicist Josef Fraunhofer discovered the presence of dark lines in the spectrum of sunlight. As light streams out from the Sun it passes through the cooler gases of the outer solar atmosphere. These gases absorb certain very specific wavelengths of light which are governed by the elements comprising the gas. Thus, the element hydrogen absorbs only a certain set of wavelengths, helium a different set, and so on. Because these wavelengths are missing from the sunlight reaching the Earth, a spectrum of the Sun contains dark lines in the place of the wavelengths (colours) that have been absorbed.

If there is relative motion between the gas in which the Fraunhofer lines are formed and the observer the Fraunhofer lines will be Doppler shifted (along with the rest of the spectrum, of course). Thus the Fraunhofer lines can be used to identify the elements comprising the gas *and* they can tell us how fast the

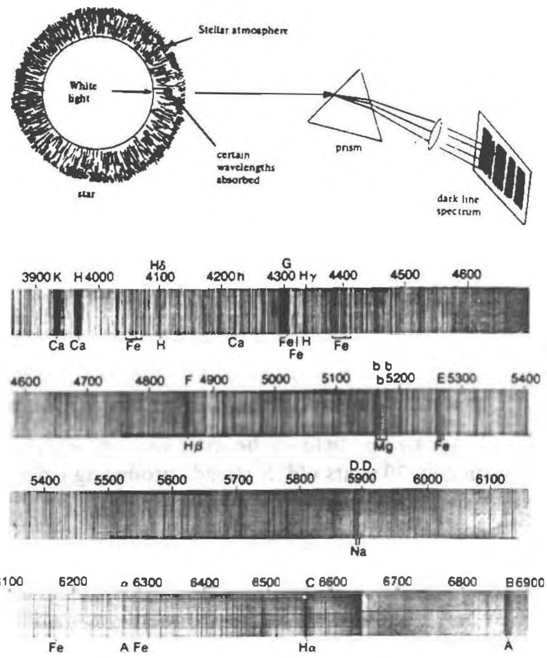

Figure 3. (Top) The origin of Fraunhofer lines in the solar spectrum. (Bottom) Part of a solar spectrum showing Fraunhofer lines.

gas is moving towards or away from us. Figure 3 shows schematically the origin of Fraunhofer lines as well as part of the spectrum of the Sun. The wavelengths of certain prominent lines are indicated in ångströms (10^{-10} m). The elements responsible for some of the lines are also indicated.

4. Seeing inside the Sun - II: oscillations

Ironically, several years before Davis started his neutrino experiments, a team of Californian physicists at CalTech made a discovery that opened a new window to the interior of the Sun and may yet lead to the solution of the solar neutrino problem. In 1960 Robert Leighton, Robert Noyes and George Simon, were studying the turbulent motions of gases on the solar surface by tracking Doppler shifts in the solar absorption lines. Although they expected to find chaotic patterns, Leighton and his colleagues found that typically half of the surface of the Sun is covered by patches that oscillate intermittently with periods near 5 minutes. For about ten years it was thought that these oscillations were a local phenomenon, triggered perhaps by eruptions in the convection zone, until Roger Ulrich, and independently John Leibacher and Robert Stein, realized that the oscillations are a surface manifestation of trapped sound waves bouncing around inside the Sun. The cause of the oscillations is still a matter of debate, but they are probably produced by the very turbulence that Leighton and his colleagues wanted to study.

The trapped sound waves inside the Sun are analogous to trapped waves inside the Earth after an earthquake. Much of what is known about the interior of the Earth comes from studies of how earthquake waves propagate through the interior of the Earth (a study known as *geoseismology*). Inside the Earth, pressure waves from an earthquake change direction when they pass the interface between two internal layers. The detection of oscillations in the Sun has given rise to the field of *helioseismology* which, though only 30 years old, is already producing a rich yield of exciting results.

Let us now examine more closely what happens to sound waves inside the Sun. The Sun is a gaseous sphere that lacks the sharp discontinuities present in the Earth's interior. Nevertheless, there are significant gradients of pressure, density and composition. The surface of the Sun itself defines a fairly sharp reflecting boundary. A sound wave approaching the surface from below (Figure 4, top) is reflected back downwards into the solar interior.

The speed of sound in a gas depends on the temperature and the average mass of the particles comprising that gas. Since the temperature increases with depth, so does the sound speed. This means that the deeper parts of the descending wave front move faster than the shallower parts and the wave is gradually

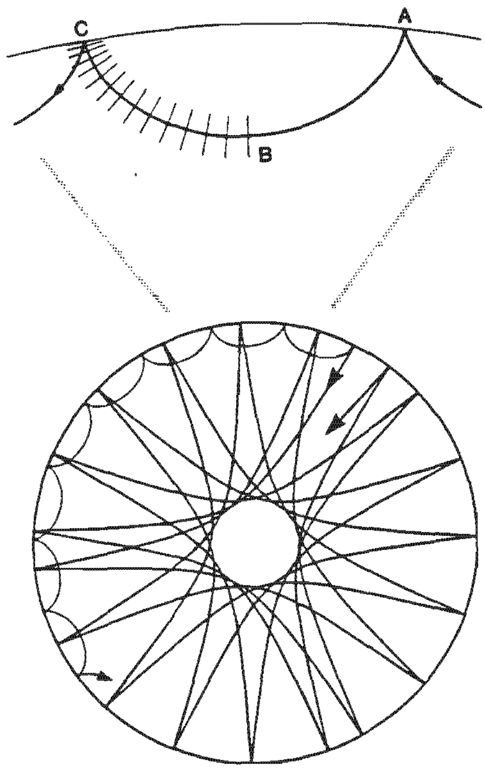

Figure 4. Reflection at the surface and refraction in the interior define an acoustic cavity.

refracted (bent) back upwards. The now ascending wave eventually encounters the solar surface, where it is once again reflected back downwards and the whole process is repeated. The trapped acoustic waves circumnavigate the interior of the Sun (Fig. 4, bottom) and interfere constructively with themselves to produce a resonance, or standing wave, which produces the surface oscillations that we see. The horizontal wavelength and period of the surface oscillation vary with the period of the resonating wave and its depth of penetration.

The waves just described are said to be trapped in an acoustic cavity. Every acoustic cavity has a fundamental resonant period which is roughly the time taken for the corresponding wave to propagate from the top to the bottom of the cavity and back. The turn-around depth for a given sound wave marks the point where the horizontal phase speed of the wave equals