Peering Inside the Sun with Helioseismology

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with collaborators

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1. INTRODUCTION TO THE SUN

OUR star, the Sun, is a very dynamic, interesting, and important astronomical object. It is the star about which we know the most, and studying it allows us to understand the properties of other stars and how they have evolved over time. Furthermore, the Sun obviously plays an enormous role for us here on Earth.

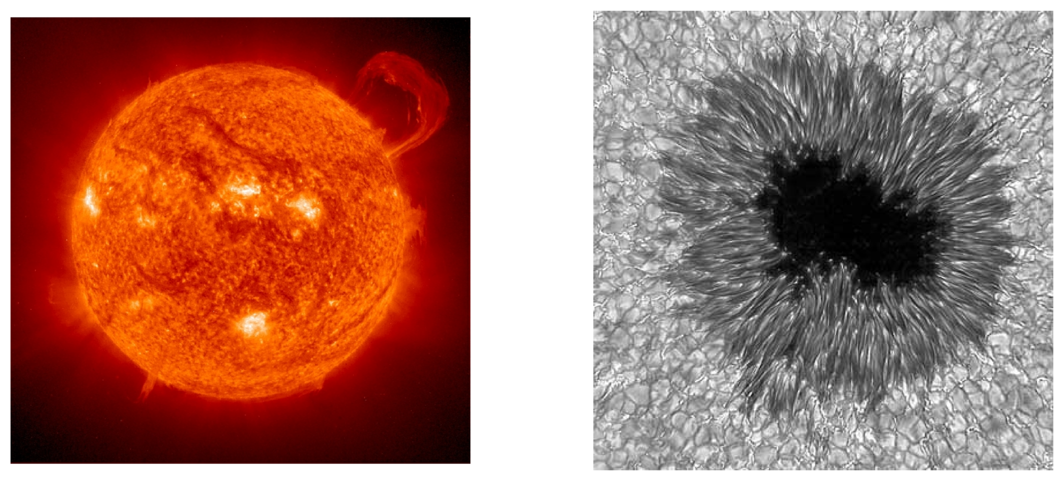

Figure 1: On the left, an image of the Sun in ultraviolet light taken from NASA's SOHO satellite. The "arm" in the upper right is a prominence. The hotter areas are white and the redder areas are cooler. On the right is a high-resolution image of a sunspot from a ground-based telescope in New Mexico. Sunspots are regions of very strong magnetic fields which are cooler and hence darker.

In Figure 1 you see an image of the dynamic atmosphere of the Sun above the surface in the *chromosphere.* The plasma in this region is about 60,000 K. The prominence near the corner extends over 100,000 miles into space. The cause of this phenomenon is most likely strong magnetic field-plasma interactions and energy release, which is also the cause of solar flares, coronal mass ejections, etc., which can and do affect things on Earth such as communications systems and our terrestrial atmosphere. Understanding the source and dynamics of the magnetic field (such as the sunspot seen in the right of Figure 1) is the greatest unsolved problem in solar physics.

Nonetheless, whatever one observes on and above the solar surface is ultimately driven and affected by what takes place beneath it. Helioseismology is the tool best suited for studying the solar interior.

2. THE SUN HAS WAVES

HOW does one begin to "look" inside the Sun? Fortunately, the method has existed for quite awhile, since it is analogous to how geophysicists study the Earth by exploiting earthquakes. The Sun is filled with acoustic waves, many more than the Earth has, and they are continuously excited near the surface and propagate deep inside. In other words, the Sun constantly has "sunquakes", and it rings like a bell. A typical "seismogram" of solar data is shown in Figure 2. Telescopes record the velocity of the surface motions and data processing then reveals signatures of the waves.

Helioseismology is the science of obtaining and interpreting solar seismic data to determine sub-surface properties. The main goal is to make images beneath the surface of properties such as flows, sound speed, temperature, rotation, and particularly, magnetic fields. Understanding these internal properties will give us a better overall picture of the Sun and allow us to connect the interior environment with what we actually see above the surface.

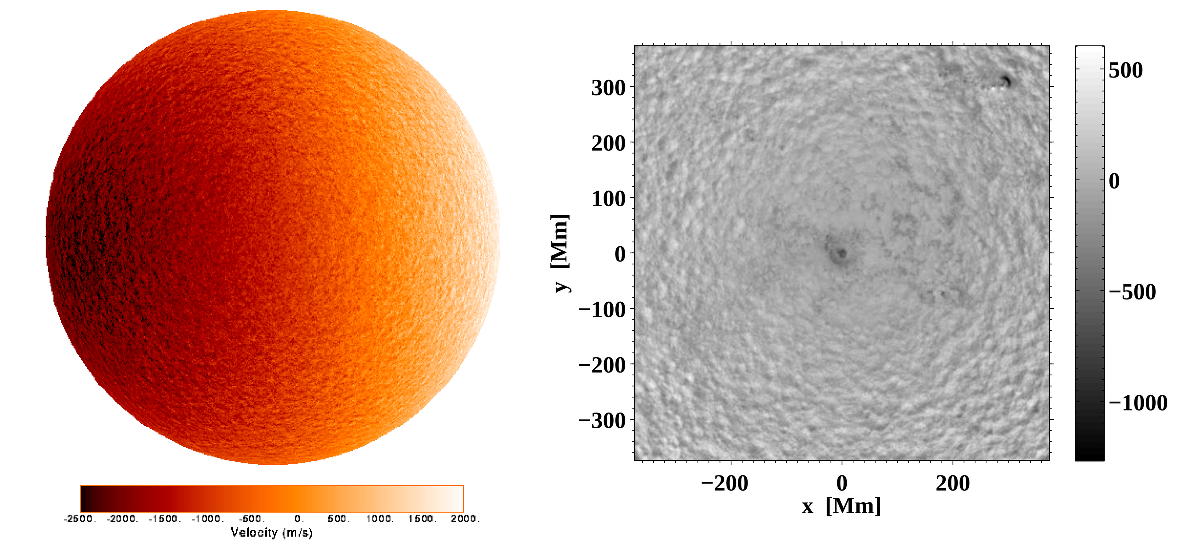

Figure 2: On the left is a Dopplergram from SOHO of the Sun which measures the line-of-sight velocity of tiny patches of surface motions (basically up or down). Notice that the main component of this raw image is the Sun's rotation of about 2 km/s. Darker colors represents motion towards the Earth and lighter colors away. If one zooms in and removes the effects of rotation, the Doppler map on the right is obtained.

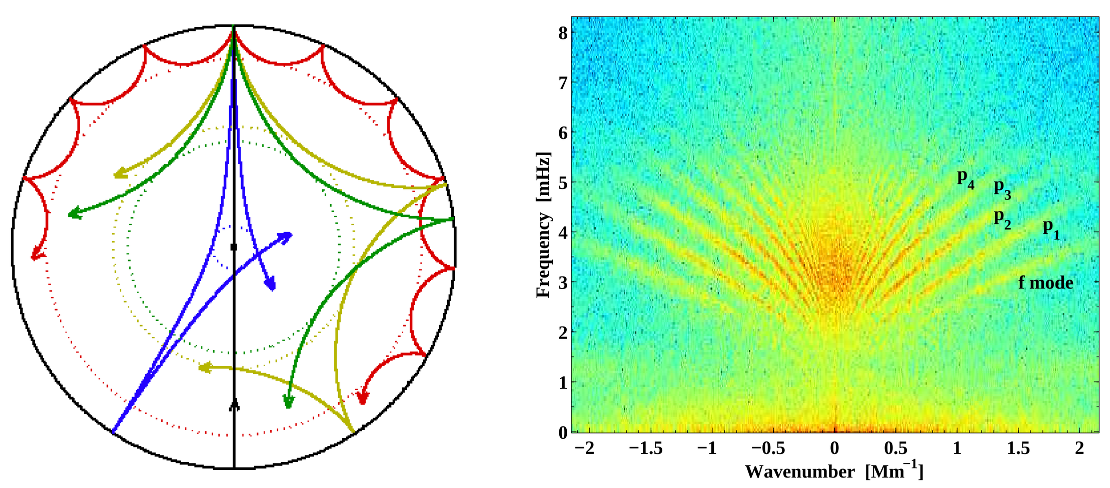

Figure 3: On the left is an illustration of how acoustic waves propagate throughout the solar interior. The waves are excited at the surface from turbulent convection and the different ray paths depend on the frequency and wavenumber. The figure on the right is a power spectrum of the acoustic oscillations over a six-hour time span which shows the discrete modes (eigenfrequencies).

3. METHODS

THE way that helioseismology is able to "map" the solar interior is a three-step process. The first step is obtaining and analyzing data to determine the frequencies of solar oscillations and how long it takes the waves to travel from one point on the surface to any other point. The second step is to model the interaction of the waves with any inhomogeneities in the waves' path, such as flow and temperature perturbations or magnetic field. The products of this step are sensitivity functions, or kernels, as in Figure 4. The final step is to use the data and the kernels and solve an *inverse problem* to recover the solar perturbation throughout the interior.

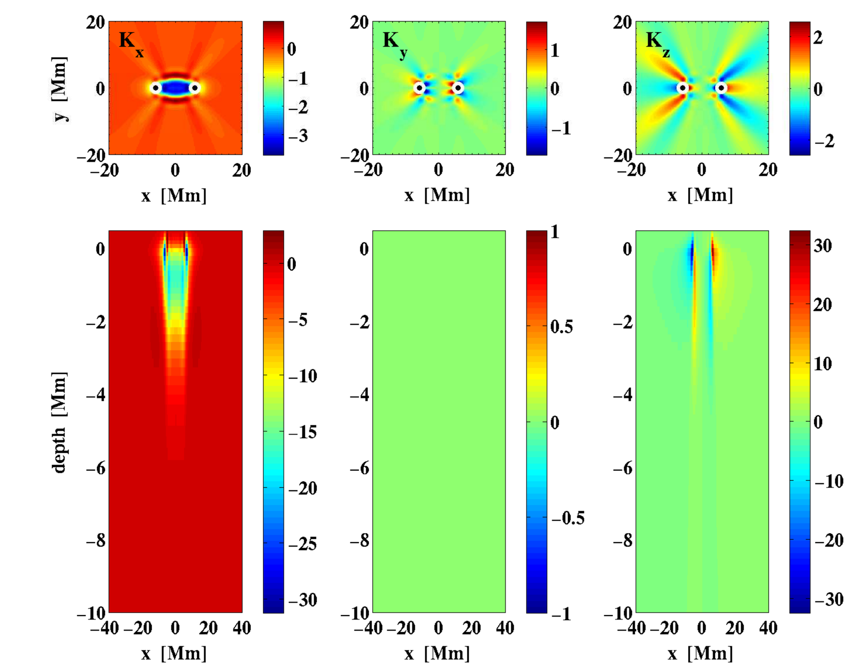

Figure 4: Sensitivity kernels for spatially-varying flows. These three-dimensional functions quantify shifts in the travel times of waves due to their interactions with plasma flows between two points. Positive values denote a slowing down of the waves and negative values denote a speeding up of the waves.

4. WHAT WE HAVE LEARNED SO FAR

FROM various techniques of helioseismology we have been able to determine very precisely the Sun's differential rotation with latitude - the Sun does not rotate as a solid body like the Earth. The sound speed profile has also been measured nearly to the inner core. Since solar sound waves propagate for a very long time, we have also been able to make images of the far side of the Sun. This is useful because it could be used to predict violent disturbances like flares that might erupt once they appear Earth side.

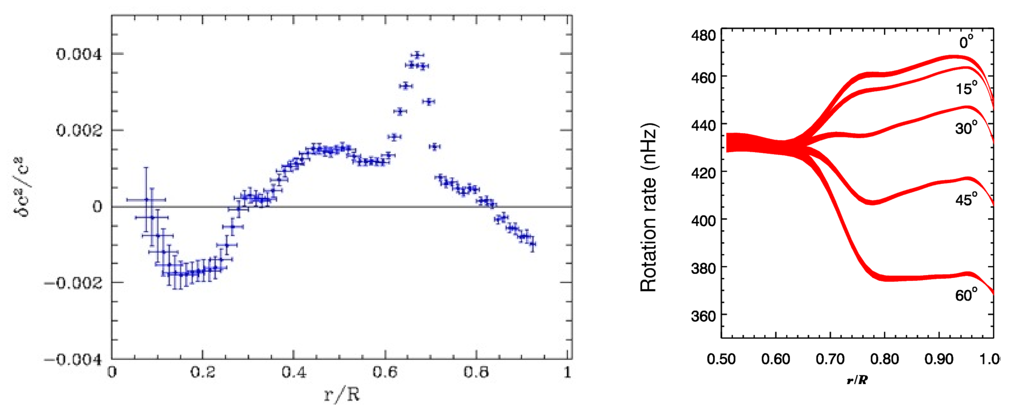

Figure 5: On the left is a plot of the inferred sound-speed profile of the Sun. It shows the **difference** between what is found with helioseismology and what is computed from a standard solar model. The bump is a signature of the transition between the convection and radiation zones. The right figure shows the differential rotation of the Sun and how it varies with depth and latitude.

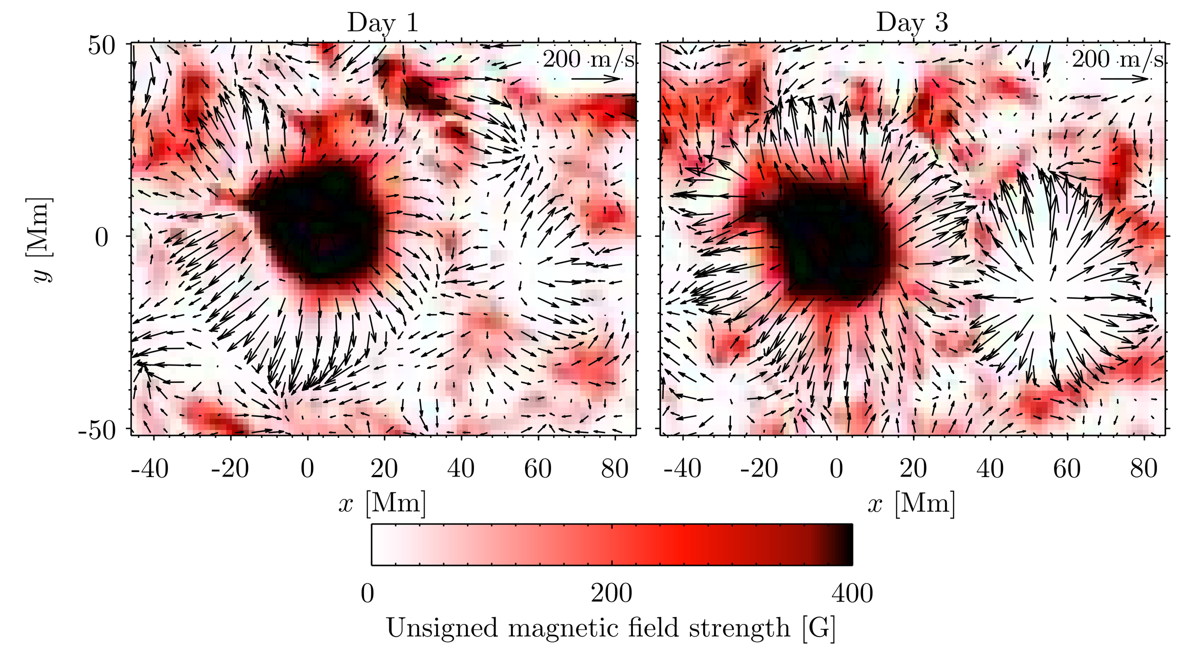

Figure 6: Near-surface plasma flows around a sunspot over a three-day period. The arrows denote the horizontal velocity field and the color scale is the magnetic field. Notice the large *supergranule* appear next to the sunspot on the third day. Maps like this allow us to study the interactions of flows and magnetic field.

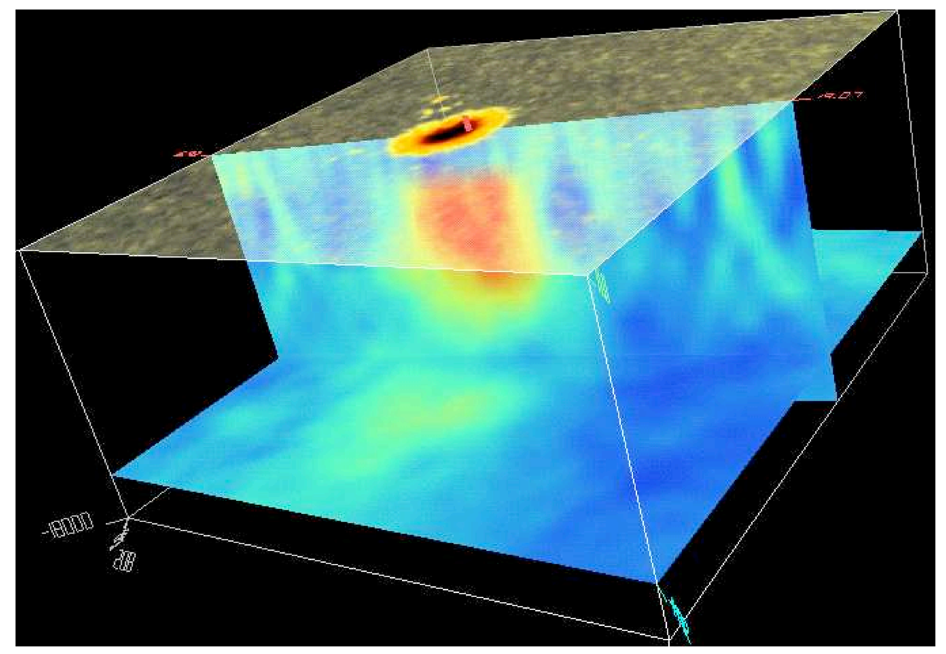

Figure 7: A three-dimensional visualization of a sunspot and the temperature profile beneath it. The image of the sunspot is observational data and the color scale representing the temperature is inferred from a helioseismic inversion. (Courtesy of Stanford/SOI).

Future helioseismic studies will try to probe the deepest layers. The ultimate goal is to make images such as in Figures 6 and 7 throughout the entire solar interior for all features and over several solar cycles (~ 30 years). Only then will we be able to obtain a complete picture of the important physics in the Sun and other stars.

References

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