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Why Study the Sun?

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Abstract. In this presentation we briefly describe the Sun through large number of illustrations and pictures of the Sun taken from early times to the present day space missions. The importance of the study of the Sun is emphasized as it is the nearest star which presents unparallelled views of surface details and numerous phenomena. Our Sun offers a unique celestial laboratory where a large variety of phenomena take place, ranging in temporal domain from a few milliseconds to several decades, in spatial domain from a few hundred kilometers to thousands of kilometers, and in the temperature domain from a few thousand degrees to several million degrees. Its mass motion ranges from thousandths to thousands of kilometers per second. Such an object provides us with a unique laboratory to study the state of matter in the Universe.

The existing solar ground-based and space missions have already revealed several mysteries of the outer environment of our Sun and much more is going to come in the near future from planned new sophisticated ground-based solar telescopes and Space missions.

The new technique of helioseismology has unravelled many secrets of the solar interior and has put the Standard Solar Model (SSM) on firm footing. The long-standing problem of solar neutrinos has been recently sorted out, and even the 'back side' view of the Sun can be seen using the technique of holographic helioseismology.

Key words. Sun—flares—prominences—coronal mass ejection—coronal holes—helioseismology.

1. Introduction

Let us bring our 4th magnitude, insignificant little star near enough to blaze into a minus 27th magnitude ball of fire – our Sun. This star is so near to us that we can see its minutest surface details. Because its warmth keeps this planet alive, it is the most important star for mankind. Every detail is worthy of observations and study.

In all ancient cultures, the Sun has occupied a central position. In many cultures and religions our Sun has been and is still being worshipped as the most powerful god and goddess. Large numbers of mythological stories have been woven around the Sun. The importance of the Sun had been well realized by the ancient man. It was used as a daily, seasonal, and annual clock. Huge monolithic structures like Stonehenge in England, Newgrange tunnel tomb in Ireland, Sun temples in Egypt, India and in many other countries were built to observe, time, and predict important solar events like the summer and winter solstices, equinoxes, etc.

With the beginning of the telescope era, the Sun was one object in the sky that attracted the attention of many great astronomers like Galileo, Herschel, etc. Even before the telescope era, the Sun was observed by the naked eye for many centuries by Chinese and early Greek astronomers. More than 125 sightings of dark spots – *blemishes* on the Sun have been reported. There is even a Chinese reference of observing a 'Black-blue vapour-cloud near an egg shaped dark spot' (Clark & Stephenson 1978). I think the observer had indeed seen a white light flare and perhaps this is the first reported flare, even before the famous Carrington flare of 1859.

With the advent of telescopes, the solar observations and studies progressed by leaps and bounds. The discovery of solar rotation, the 11-year sunspot cycle, the tilt of the Sun's axis by 7.5 degrees and many other discoveries followed. Very keen and persistent early solar observers like Father Secchi, Langley, Prof. Fernley and others, made extremely valuable solar observations. These observations showed remarkable details of solar features. For example in the left panel of Fig. 1 is shown a drawing of solar granulation and a sunspot pore made by Father Secchi in 1878, with an ordinary 13-inch refractor. Compare it with the modern picture taken with a state-of-the-art vacuum telescope equipped with image restoring systems as shown in the right panel of Fig. 1.

The right panel in Fig. 2 shows a drawing of a sunspot made by Father Secchi in 1878, displaying fine penumbral filaments and even the tiny sub arc second size umbral dots. How could he see such fine features and record them? In the left panel is shown a picture taken of a sunspot with the modern Dunn telescope at the NSO/Sac Peak Observatory, using adaptive optics.

With the introduction of physics and spectroscopy for the study of the Sun in the mid-nineteenth and early twentieth century, solar astronomy took another leap forward into the realm of solar astrophysics. Powerful new equipment, telescopes and spectrographs were located at suitable sites like Mount Wilson, Kodaikanal, Pic du

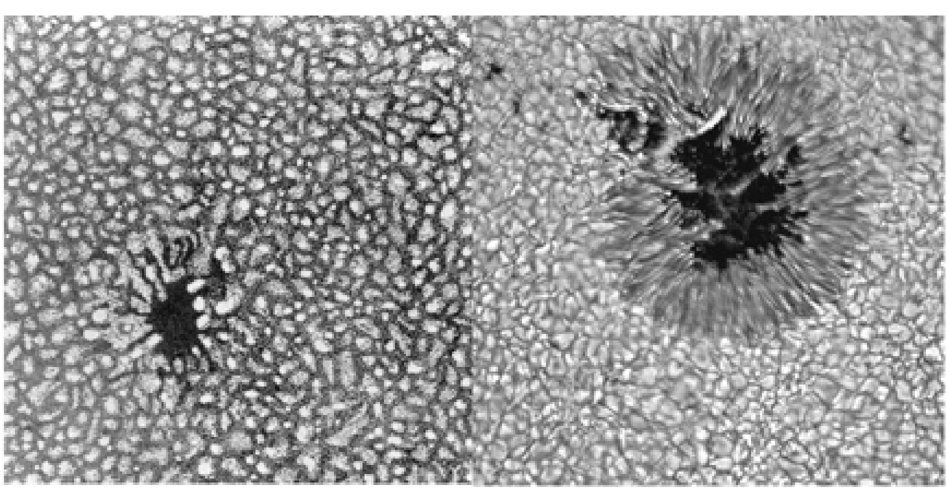

Figure 1. Left panel shows a drawing of solar granulations and a pore made visually by Father Secchi in 1878 with a 13-inch refracting telescope. Compare this with the high-resolution picture taken with modern day telescope shown in the right panel.

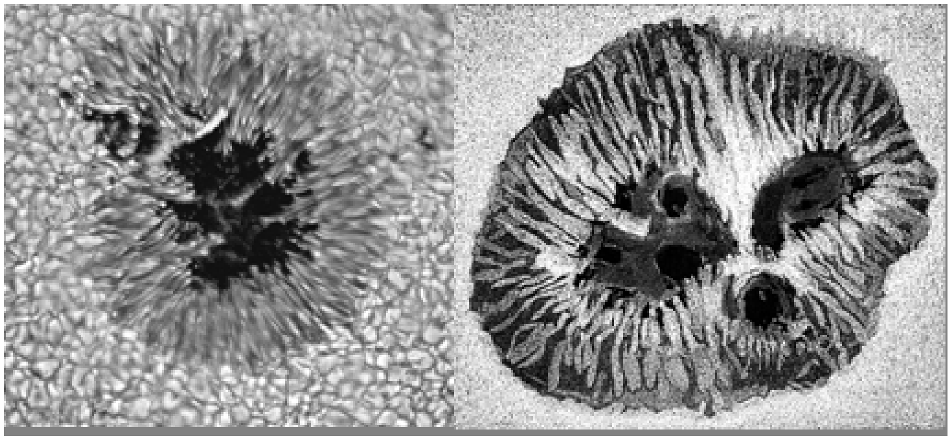

Figure 2. The left panel shows a picture taken of a sunspot with the modern Dunn telescope at the NSO/Sac Peak Observatory, using adaptive optics. In the right panel is shown a drawing of a sunspot made by Father Secchi in 1978, displaying fine penumbral filaments and even the tiny sub arc second size umbral dots.

Midi, etc., and making use of the new discoveries emerging in physics, helped to unravel several secrets of our Sun. Using spectroscopy, one important property of our Sun was revealed – that it is like an onion; you peel one layer after another and thereby see different depths, different features and even different phenomena. This is achieved by using different radiations originating in different layers of the solar atmosphere.

2. The outer layers

2.1 *Solar corona*

The outer most layers of the Sun, called the 'corona' could be seen only with the help of the Moon when it covers the disk of the Sun during a total solar eclipse (Fig. 3). The long streamers and plumes seen in these pictures are of extremely low density (10^8/particles per cc) plasma, but the temperature of these features is very high – of the order of a million degrees. The shape and size of the corona changes with time and exhibits solar cycle variations. Figure 3 also shows the variation of coronal structure during maximum and minimum period of the solar cycle. Note the roundish shape observed during the maximum period while during the minimum, the coronal streamers extend more in the east–west direction.

During totality, the naked-eye observers have seen the corona extend to even 15 to 20 solar radii. There is no photographic record available showing such extended corona. This is because the human eye has a very large dynamic range to perceive intensity variations. No photographic or CCD detectors can match it. So to enjoy the beauty of the total solar eclipse, our advice is to just close your eyes, say 20–25 minutes before the totality and get dark-adapted, and open your eyes only at the time of totality. Then you will really see the beauty of the corona. In Fig. 4 is shown a drawing made of the extended corona observed during the 1878 total solar eclipse.

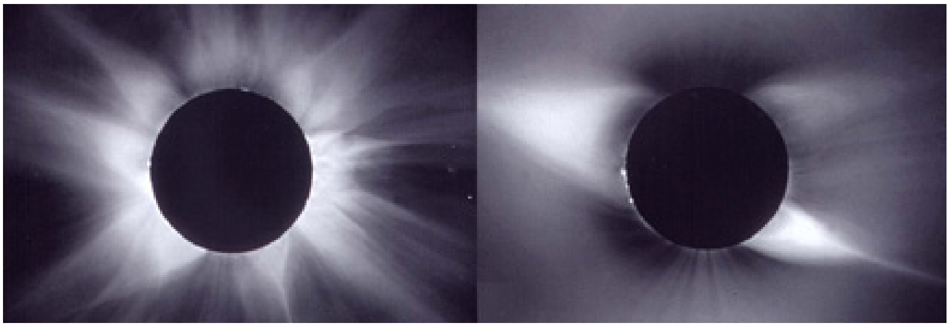

Figure 3. Left picture showing photograph taken on 16 Feburary 1980 during maximum and the right picture taken on 3 November 1994 during minimum activity period.

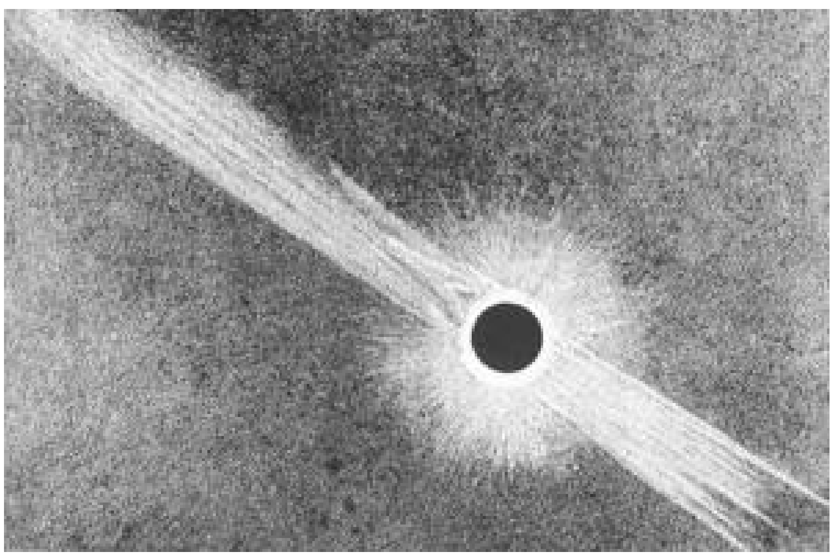

Figure 4. Drawing of the total eclipse made during 27 July 1878, note the extended corona to more than 12–13 solar radii.

2.2 *Chromosphere*

Using certain radiations, which originate in a particular layer of the solar atmosphere, one can see or detect features and physical conditions of that layer. For example, if you use an instrument to see through the monochromatic light of hydrogen H-alpha or ionized calcium or the radiation from any other strong line formed in the temperature range of about 10,000–12,000 K, you can study the chromosphere. Beyond the chromosphere, the temperature rises very steeply to million degrees in the corona, where most of the atoms get ionized. Radiations originating in the corona or in the transition region (a thin layer between the chromosphere and the corona), are due to highly ionized atoms of iron, calcium, neon, silica, etc., and emit in EUV and X-rays, displaying fine structures in this region of the solar atmosphere. In Fig. 5 is shown full disk pictures taken in the chromosphere in the light of HeI 10,830 Å, EUV at

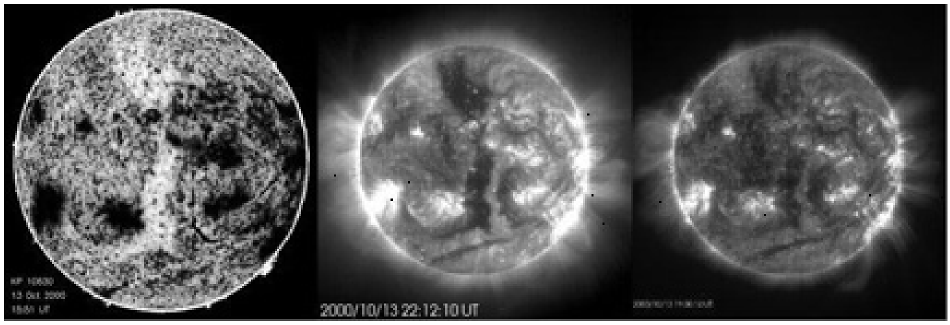

Figure 5. Full disk pictures taken on the same day in HeI 10830 Å, EUV and Soft X-ray radiations. Note the variation of the disk features in the 3 wavelengths.

195 Å and soft X-ray radiations. Compare the solar structures seen in these 3 wavelengths. In the first image, the large white patch marks the coronal hole region and the dark close structures are where HeI shows absorption. In the X-ray and EUV pictures the bright emission areas indicate close magnetic active regions, with strong magnetic fields.

2.3 *Solar prominences*

Solar prominences and mass ejections have been observed from early times during solar eclipses. Lately their significance has been realized in view of the Sun–Earth connection. Prominences seen against the disk are called as *filaments*. Extensive study of filaments is being carried out at the non-profit corporation; Helio Research by Sara Martin and her colleagues and using a 10-inch Martin telescope designed for filament observations. In Fig. 6 is shown a huge prominence observed at Big Bear Solar Observatory. Prominences are also observed in EUV radiations and microwave radio spectrum. To really enjoy the dynamical phenomena of solar prominences, one should see the prominence movies now available from several observatories. What supports the prominences, which are at a relatively lower temperature of about 10,000 K, but stay imbedded in the hot corona of million degrees? Why do they remain in the corona for days to weeks and suddenly erupt?

2.4 *Coronal mass ejection*

Frequently huge volume of plasma of low density are ejected away from the Sun, these are known as Coronal Mass Ejections or CMEs. The first indications of CME came from the Skylab Space mission in the early seventies. A CME seen in action is among the most beautiful dynamic solar phenomenon to observe. Daily movies of CMEs are now taken by LASCO instrument on board the SOHO spacecraft. There are three coronagraphs which can observe CMEs even up to 30 solar radii from the Sun. In Fig. 7 is shown a picture of a huge CME taken from LASCO. How these CMEs are formed and triggered are major problems to solve. Because CMEs are known to generate geomagnetic storms on the Earth, their properties are especially significant to record and study.

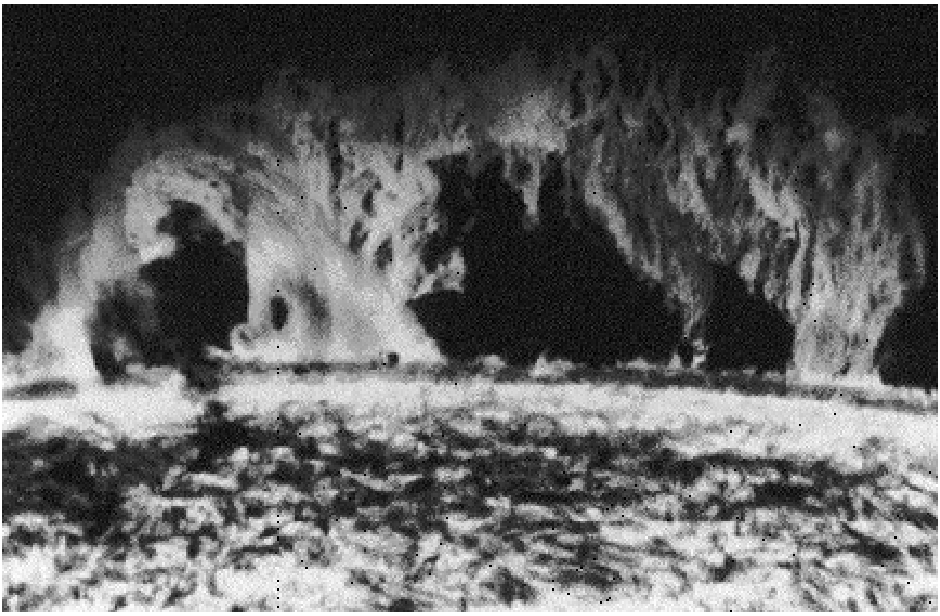

Figure 6. Picture of a huge solar prominence observed at Big Bear Solar Observatory.

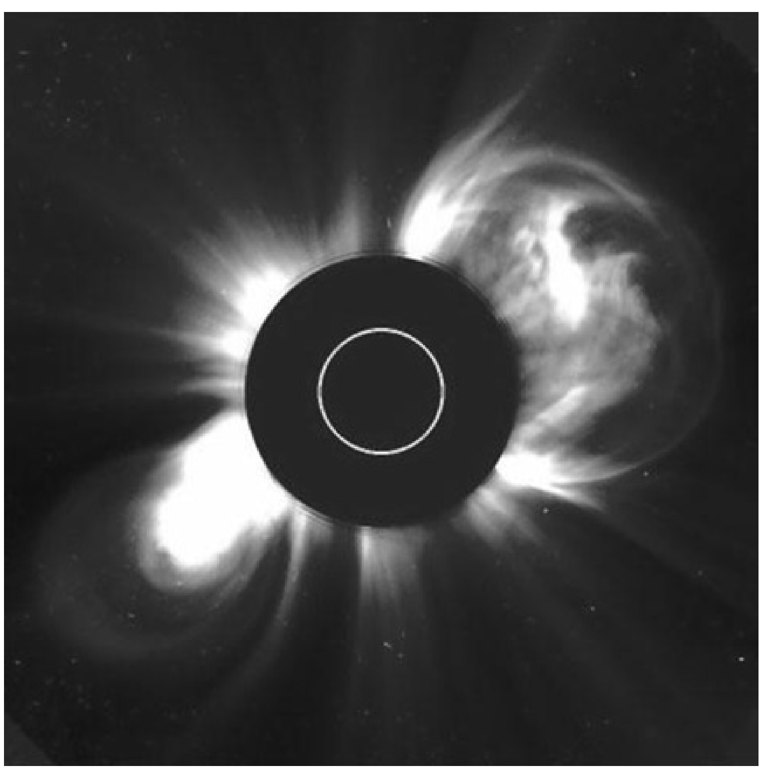

Figure 7. A huge coronal mass ejection observed from LASCO instrument on SOHO spacecraft.

2.5 *Coronal holes*

The foremost discovery that was revealed by rockets, Orbiting Solar Observatory (OSO) and Skylab spacecrafts in the early seventies was that of large, dark regions observed on X-ray pictures of the Sun, now known as *coronal holes*. Why the X-ray emission is depleted over certain regions on the Sun was a subject of great theoretical investigation. It was further found that these coronal holes correspond to regions where high-speed solar wind emanates from the Sun, and that there is a positional correspondence with the photospheric magnetic field. These regions show unipolar magnetic field, that is the field lines are 'open' over the coronal holes. However, over magnetic active regions the field lines join fields of opposite polarities and these regions appear as intense bright areas in X-rays and EUV. In Fig. 8 is shown a huge coronal hole observed during successive 5 rotations. Notice the rigid rotation of this coronal hole. Why does the coronal hole rotate so rigidly, displaying no diffential rotation and appearing almost glued to the photosphere?

3. Photosphere

3.1 *Granulation*

The whole solar disk appears mottled or granular when seen even under moderate seeing conditions, why? Scientists now believe that it is due to the manifestation of convection from below the photosphere. Although granular structure was observed and beautiful drawings were made by early solar astronomers, its real significance was realized by Schwarzchild and Richardson only in the early fifties. Since then extremely high spatial resolution observations of granulations have been obtained through modern telescopes, such as the Swedish Solar Vacuum Telescope (SSVT),

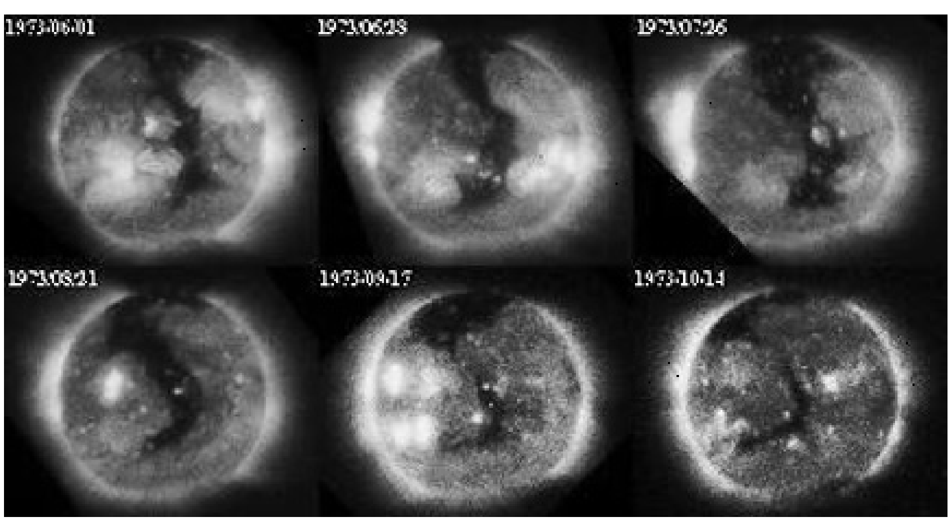

Figure 8. Showing North–South oriented coronal hole on X-ray pictures taken from Skylab, beginning from 1 May 1973 at an interval of 27 days, displaying almost persistent co-rotating coronal hole for 5 rotations.

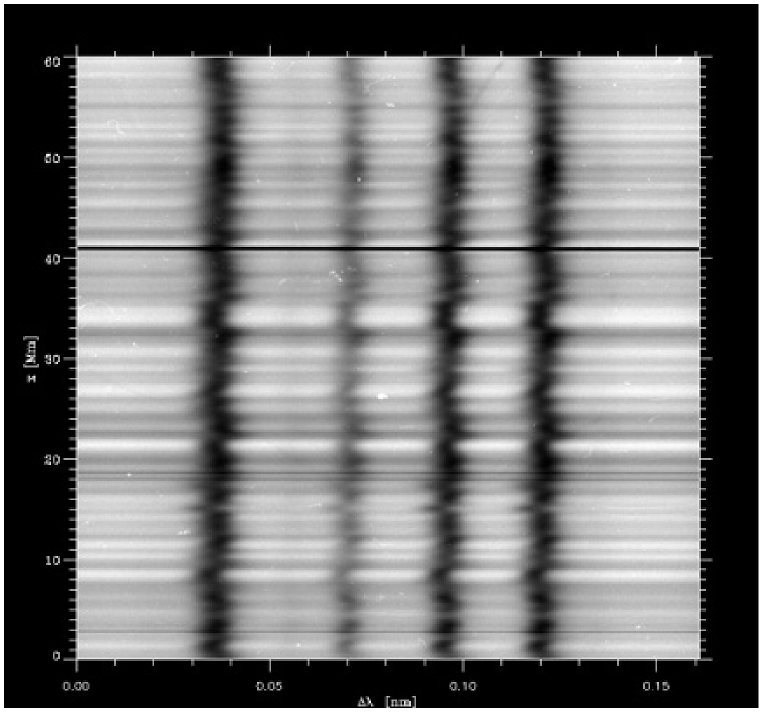

Figure 9. Showing a high resolution spectrum of solar granulation, bright and dark streaks are due to granule brightness variation and zigzag pattern in the absorption lines is due to the vertical granular motion. It will be noticed that the line shifts in darker regions generally appear towards longer wavelength side (right side) implying downward motion.

Dutch Open Telescope (DOT), the German Vacuum Telescope, the Dunn Vacuum telescope at Sacramento Peak in USA and other telescopes. In the left panel of Fig. 1 is shown a high resolution picture taken with the Sac peak telescope. Compare this with Father Secchi's drawing of granulations made in 1878 shown in the right panel of the same figure. How similar they are! The solar granulation also displays vertical motion, which is seen as wiggly lines in the spectrum, due to the Doppler shift of spectral lines as shown in Fig. 9 taken through the German vacuum telescope.

3.2 *Sunspots*

What more do we see on the solar surface? When one looks in the integrated light, what one generally finds are dark spots of varying size and shapes, lasting from a few hours to several weeks and months. In Fig. 10 is shown a full disk photoheliogram with a large number of spots distributed over the solar disk. Sometimes the Sun is devoid of such dark spots. What are these spots? As they appear dark, they should be relatively cooler regions of the solar atmosphere. They are infact about 2000 K degrees less than the surrounding photosphere. The questions, are 'how could they stay for weeks and months surrounded by high temperature region and why are they dark?'. It is observed that they are also the seat of strong magnetic field of the order of 2000 to 4000 gauss. Magnetic field in spots was first discovered by George Hale

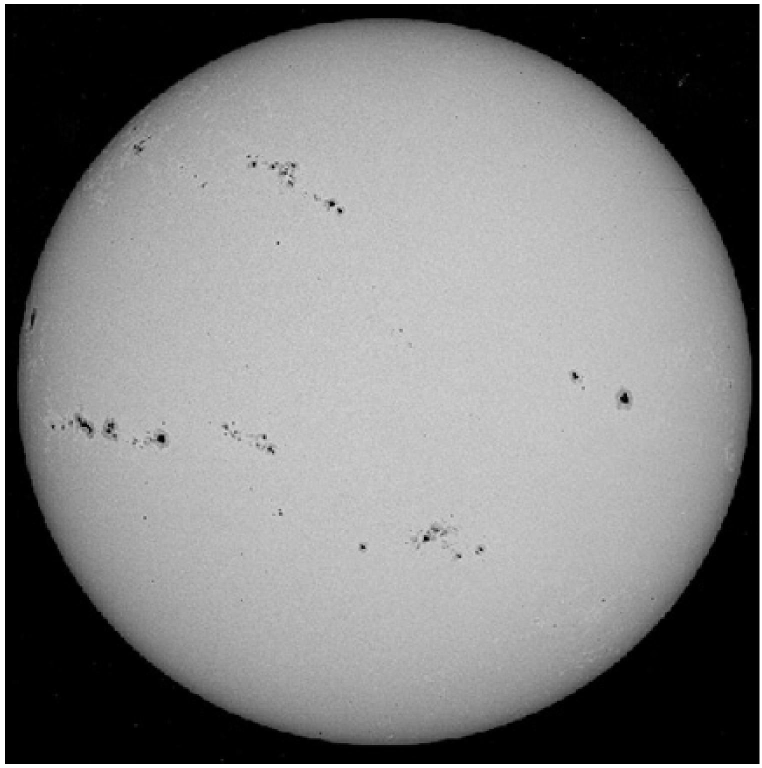

Figure 10. Full disk picture taken in white light, showing large number of sunspots.

at Mount Wilson Observatory in 1907; actually it was the first cosmic magnetic field that was discovered. Some scientists believe that spots are dark because they inhibit the emergence of convective energy due to the magnetic field. This raises the question, 'what happens to the missing energy from the spots?'.

Some large spots near or on the limb, occasionally display a slight depression that is known as the Wilson Effect. However, it is not yet confirmed whether this is really a phyical depression of the solar surface over spots or it is due to a density change. In Fig. 2 is shown a high-resolution picture of a sunspot taken with the Dunn telescope at Sac Peak Observatory. In the same figure is shown Father Secchi's drawing of a sunspot. Compare the two pictures. How similar they are – one taken with the most modern vacuum telescope and the other drawn by a very skilled observer using an ordinary 13-inch refractor. Sunspots also display intricate structure, both in the penumbrae and unmbrae and mass motion. In Fig. 11 is shown a picture of a spot group, taken with the Dunn telescope, displaying beautifully light bridges in the umbra and penumbral filament structures of the order of 0.1 arcsec.

Spot groups appear in different shapes and sizes, in Fig. 12 is shown a peculiar spiral spot group. Such spots develop strong shear and possible evidence of twisting of magnetic field lines. High-resolution movies of sunspots made by DOT and SSVT are now available at DOT and SSVT's websites on Internet. Some of these movies display penumbral filament motion – inwards towards the umbra. However the Evershed effect is known to display an outward motion. Why are these two oppositely directed motions

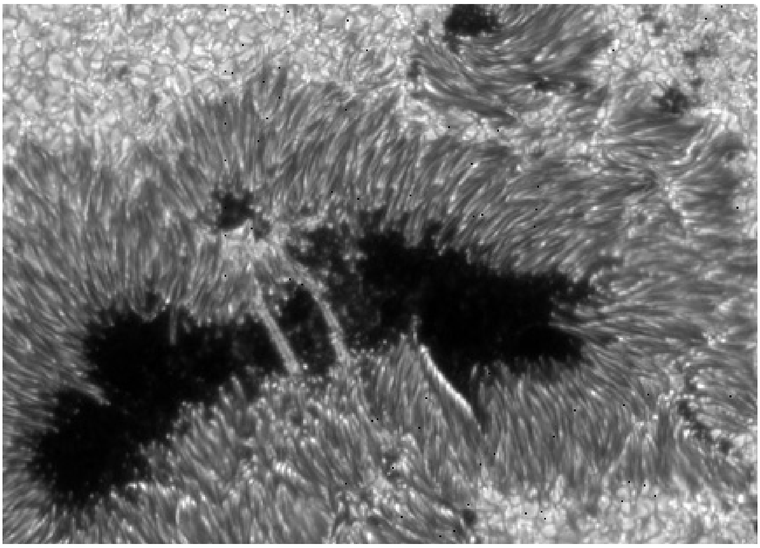

Figure 11. High resolution picture taken from Dunn telescope at Sac Peak of a sunspot group showing light bridges in sunspot umbra.

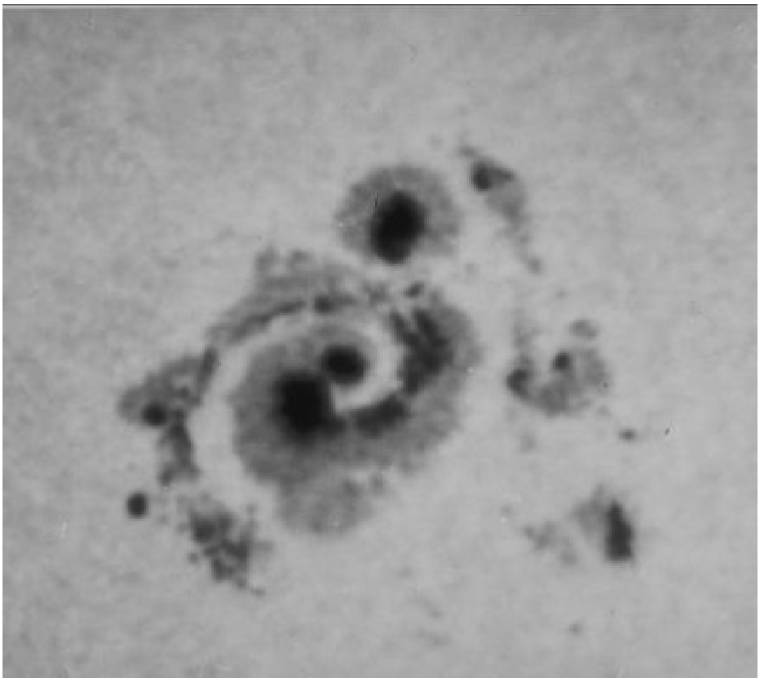

Figure 12. A very peculiar spiral shape sunspot group observed in white light.

existing in the sunspot penumbra? As mentioned earlier sunspots also have magnetic fields, very strong magnetic fields of the order of even 4000 gauss have been detected in spots.

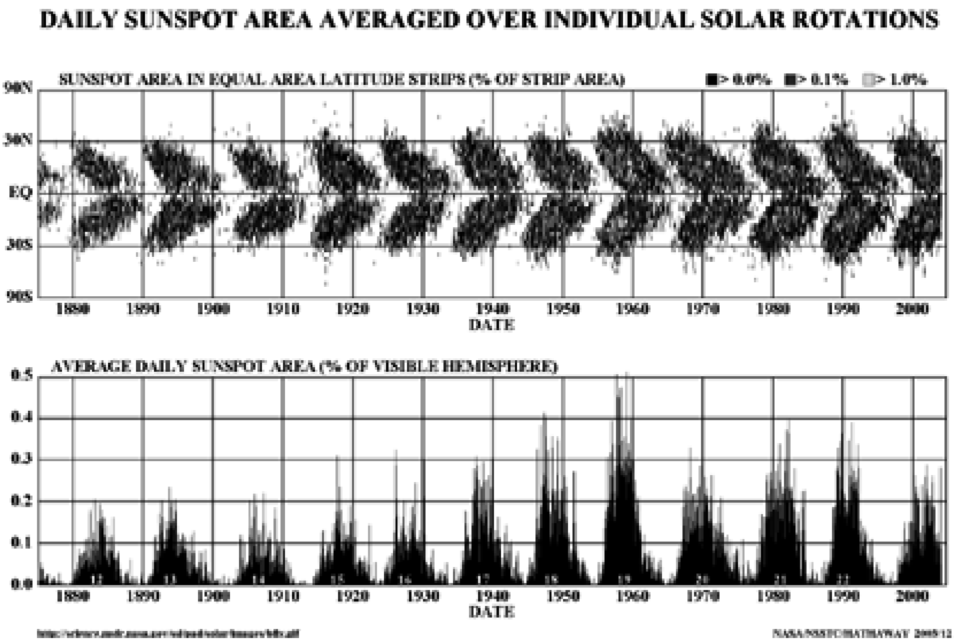

Figure 13. Upper panel shows the 'Butterfly diagram' indicating the latitude drift of sunspots during the 11-cycle from 1875 to 2003. Lower panel shows the average daily sunspot numbers during this period.

3.3 *Solar cycle*

The number of sunspots varies with time, this is known as the *sunspot solar cycle*. Every 11 years our Sun goes through a period with a maximum and minimum number of spots. In Fig. 13 is shown a plot of sunspot position on the disk and number of spots with time. New spots appear at high latitudes and slowly form closer and closer to the solar equator as the cycle progresses. This diagram is known as the 'butterfly diagram'. Surprisingly during the period from 1640 to 1715 AD, the Sun displayed no solar activity, it was completely devoid of sunspots! This period is known as 'Maunder Minimum'. Why did the Sun stop producing sunspots during this period? This aspect needs to be investigated, as no explanation has come forward for this minimum. How the sunspots appear and disappear on the solar surface needs a thorough explanation. There are some theories to explain generation and disappearance of sunspots, but none of them are able to explain all the observed phenomena.

3.4 *General magnetic field*

Besides the strong magnetic field discovered in sunspots, the father and son team, Horce and Harold Babcocks found that magnetic fields exist all over the Sun, this is now known as the *general magnetic field*. In Fig. 14 is shown a magnetogram of longitudinal – a line of sight component of the magnetic field along with white light picture of that day. The dark areas mark the positive polarity, while the white regions mark the negative polarity. The general magnetic field also shows variation with the solar activity cycle. During high activity periods, the disk is cluttered with large number of

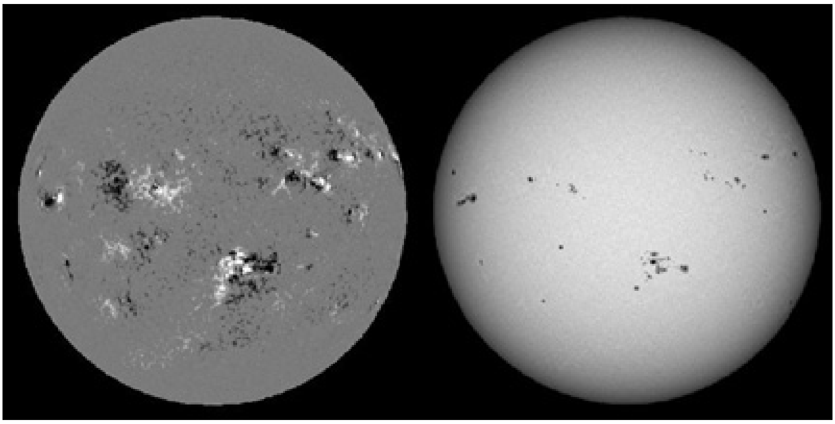

Figure 14. Pictures of full disk white light and magnetogram made during the period of high activity.

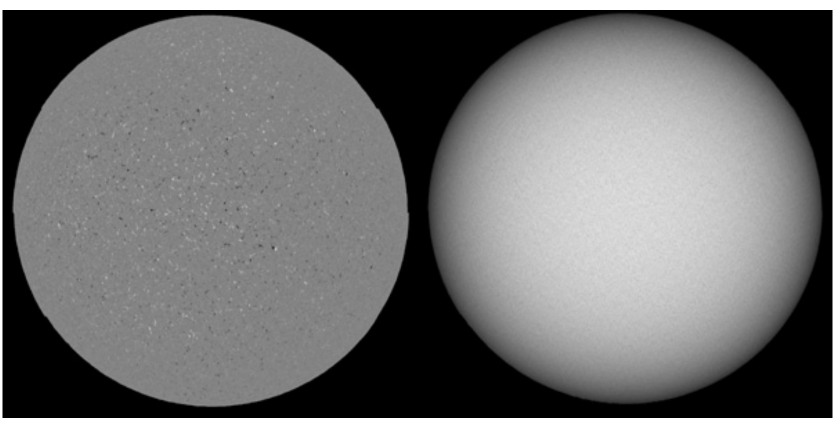

Figure 15. Pictures of full disk white light and magnetogram made during the period of low activity.

sunspot groups and intense magnetic regions, as shown in Fig. 14. During low activity periods, the solar disk appears completely blank without spots. Magnetic fields, as small bipolar mottled structure, as shown in Fig. 15. Maps of the general magnetic field are routinely made and are available on regular basis from number of solar observatories. The GONG (Gobal Oscillation Network Group) and MDI (Michelson Doppler Imager) instruments provide numerous daily full disk magnetograms. High spatial resolution magnetic field maps are now obtained with SSVT (Swedish Solar Vacuum Telescope) and other modern telescopes displaying magnetic features of less than 0.5 arcsec in sizes. The question of generation and dissipation of magnetic fields on the Sun is one of the puzzling problems for MHD theoreticians.

3.5 *Solar irradiance*

If the Sun were a variable star, of say only 0.1–0.2-magnitude variability, like many stars in the sky, could the human race have survived? The answer is NO. The solar radiation has been constant over billions of years, and this has helped to develop life on this planet. Lately, the interest to look into the 'constancy' of the *solar irradiance* has greatly increased along with greater interest in Sun–Earth relations. From space-based instruments, highly accurate data are now available which indicate that the solar irradiance, which previously was called as the *solar constant*, is indeed not at all that constant. Slight variation of about 0.1% during the 11-year solar cycle have been noticed. Does this variation affect our Earth's climate? This is a question to resolve.

4. Solar flares

Occasionally near magnetic active regions, suddenly intense emission of electromagnetic radiations are observed; this phenomenon is known as a *solar flare*. Solar flares are one of the most fascinating phenomena on the Sun. In visible radiations, the best view is in the chromosphere. Solar flares release enormous amounts of energy ranging from 10^{29} to 10^{32} ergs in a few minutes, in spectral frequencies from radio, visible, extreme ultra violet, X-rays and Gamma rays and even particles and cosmic rays. Flares affect our interplanetary space and a whole gamut of our Earth's environment. One such intense flare was observed at the Udaipur Solar Observatory on 28 October 2003, the H-alpha sequence of development of this double ribbon flare is shown in Fig. 16. Beautiful post flare loops are seen in visible H-alpha and EUV radiations. Extensive study of flare phenomena has been and is still continuing. Both theoretical and experiment minds are engaged in this business. In Fig. 17 is shown a peculiar flare observed by TRACE in EUV; notice the canopy structure of EUV emission.

5. Supergranulation

In the late fifties, a most stunning discovery was made by a physicist, Robert Leighton of Caltech, USA. He demonstrated that over the solar surface there are large 'velocity cells' of 30,000–40,000 km size, wherein material flows from the cell's centre outwards, towards the edge of the cell. These cells could be seen only when one makes a picture of the solar disk displaying Doppler shift of gases. Corresponding to these cells there was nothing seen on pictures taken in white light. However, these cells did correspond in position and structure with network seen in Ca II spectroheliograms. Since then these are called as *supergranulation*. In Fig. 18 is shown a full disk velocity picture displaying supergranulation; the bright and dark regions at the cell boundaries, indicate approaching and receding velocities.

6. EUV emission

Extreme Ultra Violet (EUV) observations made by a number of spacecrafts, namely Skylab, Yohkoh, EIT, TRACE, etc., have revolutionized the observational solar physics. Hundreds of new phenomena have been discovered and studied in great detail. The extremely fine structures of the order of few hundred km in size have been observed by the TRACE, EIT space crafts. These observations reveal that the so called uniform, homogenous solar atmosphere, assumed by theoreticians for simplicity is **not** at all homogeneous, but is permeated by fine structure of loops, controlled by magnetic field. Figure 19 shows a typical example of fine coronal loop structure of less than 0.2 arcsec width. TRACE movies of such loops show the development and dynamics of loops.

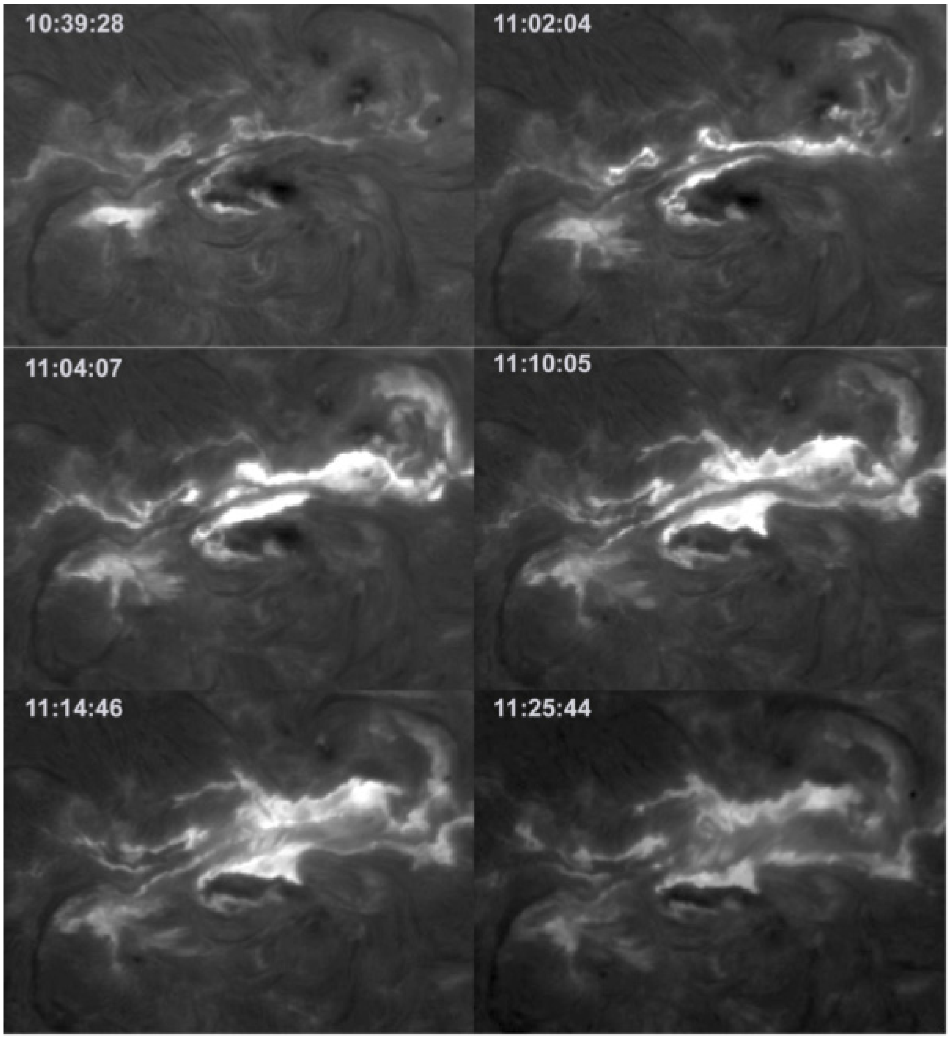

Figure 16. A class 4B flare observed in H-alpha from Udaipur Solar Observatory on 28 October 2003.

7. Helioseismology

Until now we have been discussing and seeing views of the upper and outer layers of the solar atmosphere. Now we will have a glimpse of the solar interior. During the last two decades a new technique has emerged to probe the solar interior called *helioseismology*. This branch of science is the offshoot of Leighton's discovery in 1960 that certain areas or regions on the Sun oscillate with a period of about 5 minutes. These regions may oscillate for about 5 to 6 cycles. Then the oscillations die out but during this time at some other place on the Sun, new sequences of oscillations start. It was realized by Roger Ulrich and by John Leibacher and Robert Stein (Leibacher & Stein 1970) that these observed oscillations are in fact due to the standing pressure p-waves generated inside the Sun. During the last two decades, helioseismology has unraveled several

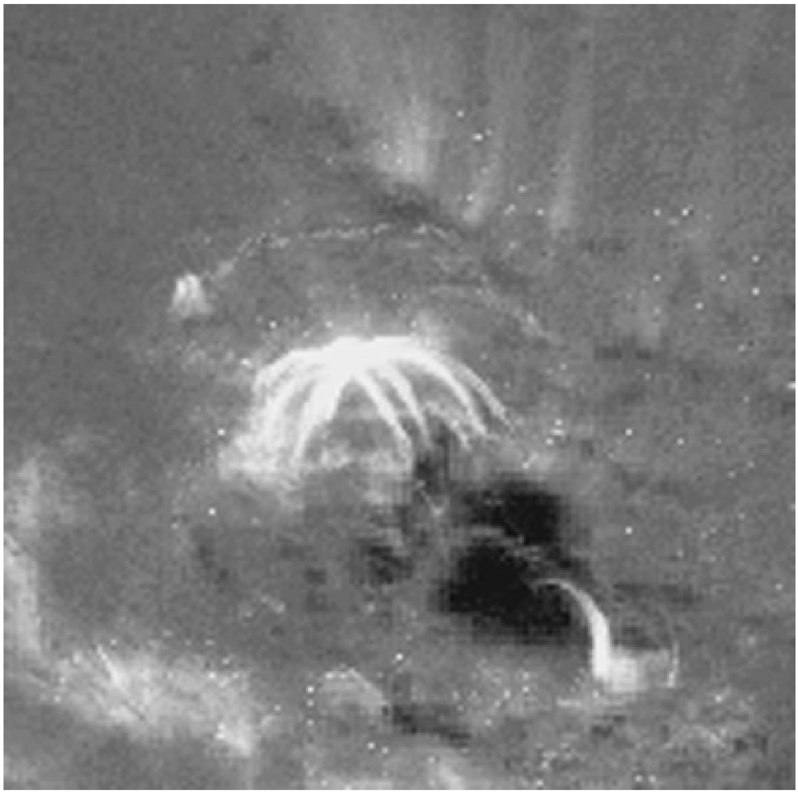

Figure 17. A peculiar flare observed from TRACE on March 17, 2000 showing reconnecting loops.

secrets of our solar interior, solving many puzzling questions like the problem of solar neutrino, Standard Solar Model (SSM), solar rotation, etc. The improved SSM has been put on firm footing through high precision helioseismic observations, and now it does not depend on theoretical assumptions. In Fig. 20 is shown modes of oscillations. Nodes and anti-nodes are shown as dark and bright patches on the solar disk. The cut away portion gives a presentation of p-waves traveling inside the Sun that are reflected at the surface boundary of the Sun. There are more than 10,000 modes of oscillations in the Sun.

The knowledge of rotation of the solar interior is of fundamental importance. Through helioseismic techniques it is now known with a high degree of precision. From the surface down to $0.6R_o$, the Sun shows diffential rotation but in the deeper layers it displays solid body rotation. In Fig. 21 is shown the density and sound speed variation with depth from the surface to the deep interior. It is found that around $0.7R_o$ there is 'bump' in the sound speed and density profiles, this region is called the *tachocline*. Why such a bump appears is of great theoretical interest. What does it represent for the internal structure and dynamics of the Sun?

Streams of fast and slow material flows have been observed on the solar surface by Howard and La Bonte in 1980 (Howard & LaBonte 1980) these are called as *torsional oscillations*. In Fig. 22 fast and slow streams are revealed as dark and bright bands.

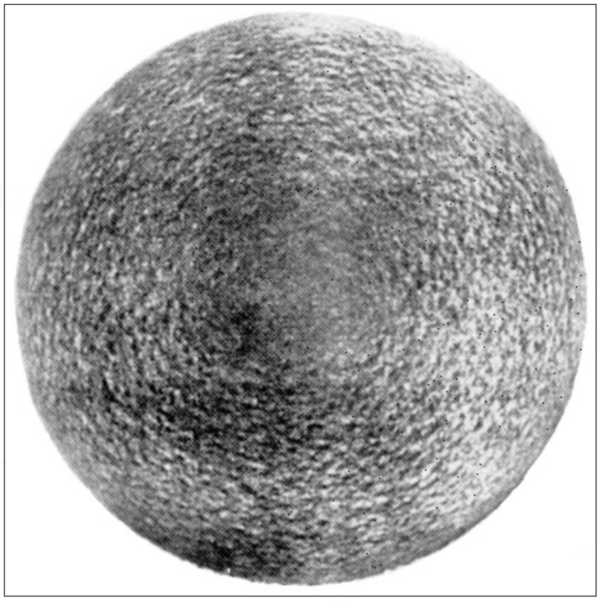

Figure 18. Full disk velocity picture of the Sun displaying supergranulation as cellular structures with dark and white boundaries; away from the central portion the cells are more conspicuous, because the Sun is a spherical body, near the disk centre the cells appear washed out as the motion in the cells is horizontal outwards on the solar surface.

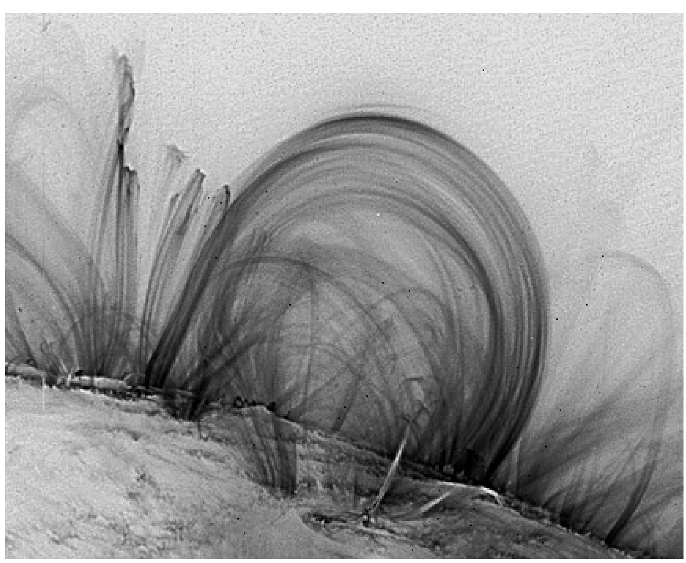

Figure 19. Extremely fine structure coronal arcade of loops observed by TRACE on November 6, 1999.

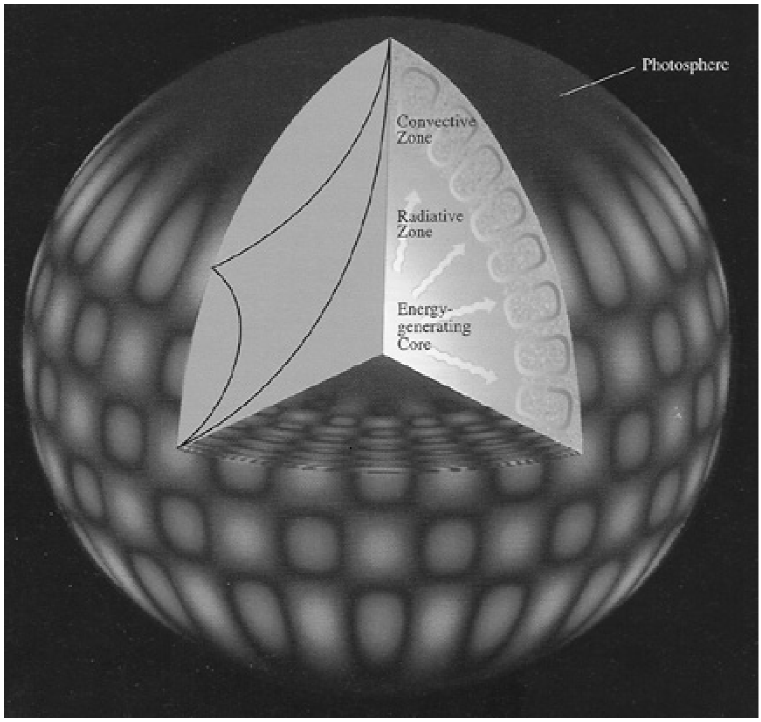

Figure 20. A cutout view of the Sun showing modes of velocity oscillations as dark and gray areas on the solar surface and p-wave traveling inside the Sun, being reflected at the solar surface.

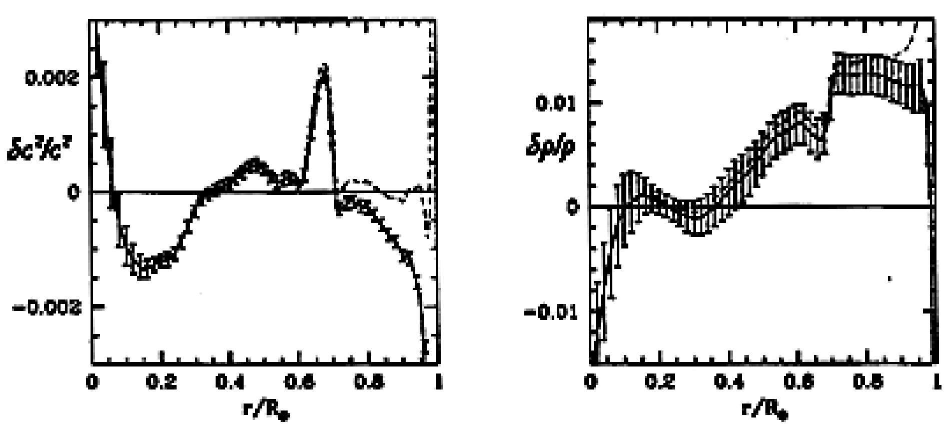

Figure 21. Showing variation of sound speed and density with depth in the solar interior. Note a 'bump' at $0.7R_o$, in sound speed and discontinuity in the density profiles, this region is called as 'tachocline'.

These streams move towards the solar equator with advancement of the solar cycle. These streams have been also detected through helioseismic technique, and found to continue in the solar interior at least down to $0.85R_o$.

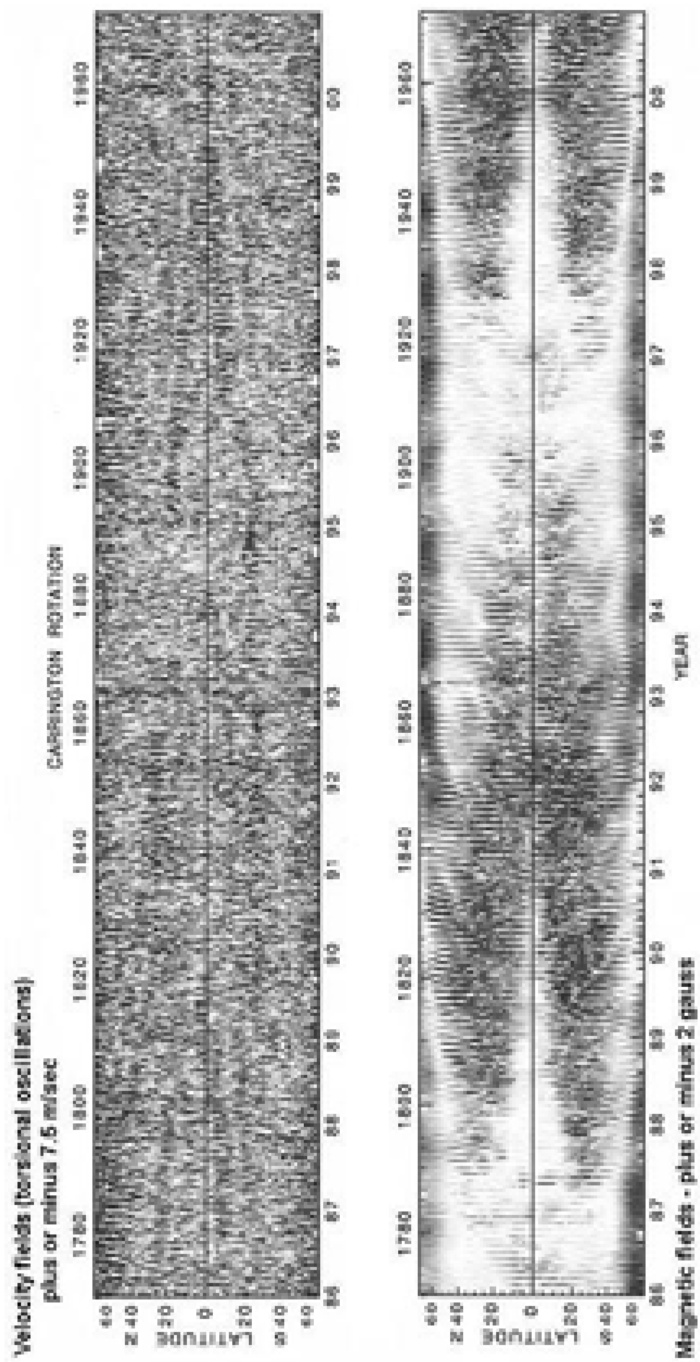

Figure 22. Upper panel shows the torsional oscillations observed on the solar surface during 1986 to 2001 as bright and dark belts, and the lower panel indicates synoptic magnetic field map.

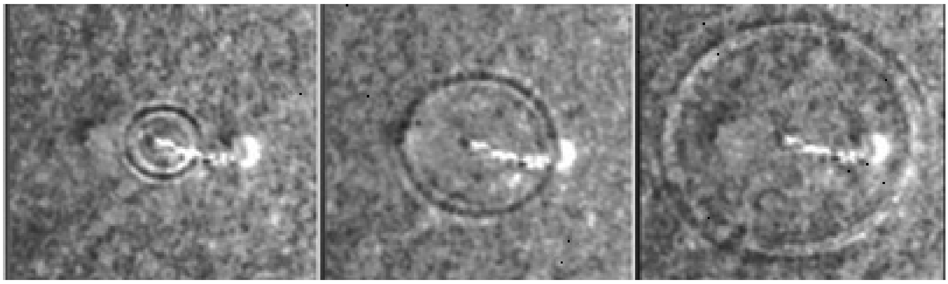

Figure 23. Sun quake observed from MDI on SOHO spacecraft due to a solar flare on 9 July, 1999, note the circular wave-like structure emanating from the flare region.

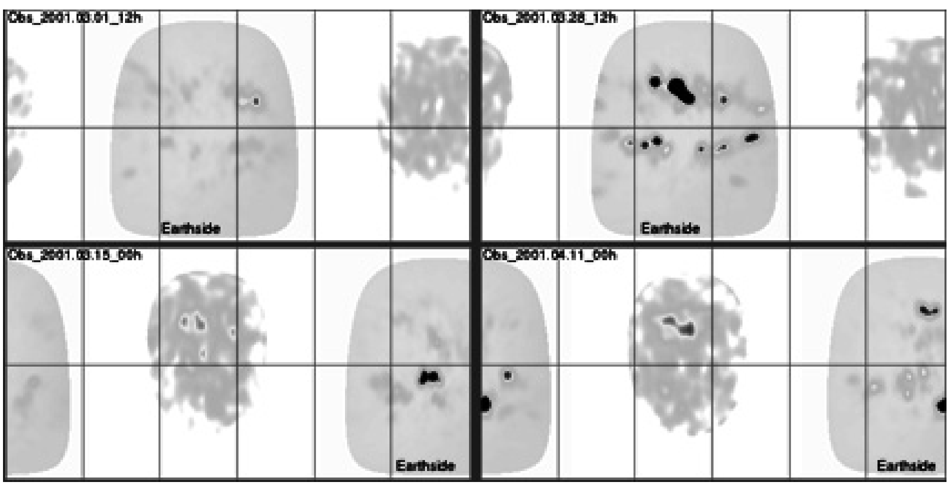

Figure 24. Showing location and structure of active regions on four sample images of the Sun taken from 1 March to 11 April 2001, over a span of 2 rotations. These computed Carrington maps show the magnetic flux on the earth side and inferred flux on the far side of the Sun, was obtained by helioseismic holographic technique at 13.5 days interval.

The effect of flares on solar oscillations have been recently observed in the case of a moderate flare on July 9, 1996 from the MDI instrument on the SOHO spacecraft by the Stanford solar group. This flare produced a 'wave' like pattern on the solar surface around the flare region, as shown in Fig. 23. This phenomenon is now known as a 'Sun quake'. Surprisingly only one such event has been reported in the literature. Helioseismic techniques have helped even to map the 'other side' of the Sun – or the side opposite to the front side facing us. In Fig. 24 is shown a view of both the front and backside of the Sun, as it made 2 rotations. These observations are of enormous importance for Space–Weather forecast and in prediction of solar activity, in interplanetary space.

After seeing all these fascinating pictures of our nearest star – the Sun, and knowing that there are still large numbers of challenging and puzzling secrets to unravel, you should be convinced that our Sun is an object in the sky that needs very dedicated, systematic and persistent observations and study.

For this presentation I have heavily drawn from our recent book, 'Fundamentals of Solar Astronomy' (by Arvind Bhatnagar & William Livingston 2005, Publ. by World Scientific Publishing Company, Singapore), therefore I have not given specific references, as they are mentioned in this book.

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