Kodaikanal Obs. Bull. (1986) 6

OPTICAL ASPECTS OF SOLAR ACTIVITY

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Abstract

A review of optical observations of some solar phenomena is presented. From the photospheric observations of the birth, growth and decay of pores, spots and sunspot groups and associated velocity and magnetic field structure have been discussed. Some dynamic phenomena associated with sunspots are also discussed. High resolution H-alpha chromospheric observations offer remarkable advantage to understand the evaluation of solar activity and the associated magnetic field development and decay. A recent observations show evidence of emergence and submergence of magnetic flux tubes. Piddington's (1976) model of twisted flux ropes seems to explain the observed emergence and submergence of field and moving magnetic features. Chromospheric velocity oscillations and wave motion observations in sunspots are discussed.

It will be difficult to discuss all the optical aspects of solar activity in this short review talk. Hence, I shall confine only to some aspects concerning the birth, growth and decay of active regions.

1. Solar Granulations

The white light solar image under good "seeing" conditions resolve into "rice grain" pattern, these are known as solar granulations. A knowledge of the properties of the photospheric granulation would be desirable for an understanding of sunspots. Since the early observations by Janssen, by Hansky, and of Chevalier, made more than 8 decades ago, enormous progress has been made in solar high resolution observational techniques. To overcome the effect of atmospheric "seeing", manned and unmanned observations from balloons have been made by several group (Blackwell et al. (1959), Schwartzschild (1959), Andreiko et al. (1972)) which show solar details comparable with the theoretical resolution of the telescope used (about 0".3 to 0".4 of arc). However, with improved optical telescopes and perseverance, Muller and the Pic du Midi and other observers at Sac Peak, Big Bear and Mt. Wilson Observatories have been able to photograph, from ground-level, solar details comparable to the balloon borne pictures. Of course now with the Spacelab-II on the Space Shuttle and the proposed Space Optical Telescope (SOT) it will be possible to resolve details on the order of 0".1 of arc or better. In Figure 1 is shown a high resolution white light photograph taken by Müller from Pic du Midi.

A number of authors have determined the size, shape and life times of solar granulation from high quality ground based and balloon borne observations. The average size of granules range between 1" to 2" of arc bounded by about 0".4 of arc wide dark intergranulation lanes. The most probable life time of average granule is found between 7to 8 minutes, though individual values as high as 15 to 16 minutes have been also reported. Most of the granules have quasi-polygonal shape and some may appear very irregular and elongated. Macris and Rosch (1983) reported that the mean granule size decreases with increasing solar activity and also that the intensity ratio between granules and intergranule lanes seems to vary from 1.10 during the minimum period to 1.30 at maximum. For greater details readers are referred to a very fine monograph by Bray, Loughhead and Durrant (1984) — on "The Solar Granulation".

High spatial resolution spectra of granulation are available through very careful observations, made during brief moments of exceptional good "seeing" conditions. From the analysis of a fine granulation spectrum generally referred to as "wiggly" line spectrum obtained at the 150-foot solar tower at Mt. Wilson Observatory, Richardson and Schwarzschild (1950) for the first time derived a good correction between the brightness and line-of-sight velocity in the photosphere. The bright areas move upwards while the dark areas downward with about 0.2 km/sec velocity. The observed correlation between brightness and line-of-sight velocity in solar granulation is due to the existence of ordered convection currents, resulting from thermal instability in the sub-photospheric layers.

Several authors have tried to search for possible existence of magnetic field in granule and intergranular regions. From the study of line profile measurements, Unno (1959) obtained an upper limit of 300 gauss while Steshenko (1960) found an upper limit of 50 gauss for possible magnetic field within individual granules. Later studies by Howard (1962) and Semel (1962) gave even lower values of the field. Using the relation between line width and lande g-factor, Howard and Bhatnagar (1969) obtained a value of less than 30 gauss between the granules and intergranular regions. We shall soon be getting results of high resolution magnetic field measurements made from Spacelab-II, by SOUP experiment of the Lockheed Observatory flown in July 1985.

2. Birth and Development of Pores and Sunspots

Good quality photographs of solar granulation show presence of much darker, small regions of a few arc seconds in diameter, which are referred as "pores". Pores are simply small sunspots without any penumbra, which may or may not develop into a regular sunspot. Loughhead and Bray (1961) report that the birth and development of a pore appears to take place by a process involving "individual" photospheric granules. The first indication that a new pore is being formed, is the appearance of a small dark region, no larger than a granule. The growth of the new pore, then seems to occur through gradual alignment in preferred direction and disappearance of individual granules from the region. This is particularly evident during coalesceing of two pores or with an existing sunspot, the granules in the narrow region between the pores gradually dissolve until only a single chain of granules remains.

It has been well established from visual and photographic observations that all sunspots begin their lives as pores. Although not all pores develop into sunspots, but the transformation from a pore to a large spot may take place rapidly through coalesceing of individual pores. Occasionally, pores appear to move towards already existing spots, which may coalesce with the penumbra or the umbra of the spot. As the pores develop and grow in size to 5" to 10" of arc, they have strong tendency to acquire some kind of rudimentary penumbrae. Observations of the development of penumbrae, indicate that the intergranular lanes begin to show conspicuous darkening in the immediate neighbourhood of the umbrae. For a while the photospheric granulations, in the penumbral region are still visible, but slowly the bright thin penumbral filaments of about 0".35 to 0".4 of arc wide, start appearing in the darker region around the umbrae. It is difficult to say whether the polygonal photospheric granules get transformed into penumbral filaments or they originate afresh, in the dark penumbra, to form the main characteristics of the penumbra.

From a detailed study of evolution of spots and sunspot groups, extending over 25 years, McIntosh (1981) has shown that a simple bipolar spot of class A (Zurich classification) develops into a complex class F group sometimes through rapid emergence of bipolar spots and coalescence of small spots or pore to form large spots in the group. Spots with similar polarity may coalesce to form larger spots of the same polarity. In Figure 2 is shown the evolution of the McMath sunspot group No.8454, through emergence and coalescence of small spots. In this case the velocity of coalesceing motion was 100 m^{-1}. While the spot group is growing some small spots may even decay, however the overall spot group reaches a matured phase of its development, and thereafter the group starts decaying. In some cases the bigger spots, fragments into small pieces, while the small spots gradually disappear at first, the penumbra followed by the spot umbra. In Figure 3 is shown an example of dissolution of McMath region No.8530, through fragmentation followed by decay of individual umbrae.

Several authors have observed proper motion and rotation of sunspot groups in the photosphere. McIntosh (1981) has reported several cases of rotation of spot group around the spot axis. The direction of rotation is generally counter-clockwise for spot group in southern hemisphere, while for northern hemisphere spots — clock-wise. This suggests that the spot group axis orientation follows a coriolis law for voritical systems. It has been observed that spot-groups which show large rotational motion are associated with release of energetic proton flares. These flares occur a day or two after the maximum observed rotational velocity of the spot group.

3. Velocity Fields in Solar Active Regions

Sunspots and active regions are associated with a wide variety of dynamic periodic and aperiodic phenomena. We shall not discuss here all the various types of dynamic phenomena, but confine to only a few types of mass motions. The systematic horizontal outward motion, at the photospheric level in the penumbra was discovered right here in Kodaikanal Observatory in 1907 by John Evershed and is now known as the Evershed Effect. I would like to show a picture (Figure 4) of a line drawing of visual observations of the C-line (H-alpha) over a sunspot made by George Hale on May 26, 1892. This drawing was taken from Hale's observing note book, available at the Mt. Wilson Observatory's archives. In this drawing you can distinctly see the Doppler shift of the C-line in the penumbral region, shifted in opposite directions on the two sides of the penumbra. Another interesting feature is the conspicuous line asymmetry, the "flag" phenomenon and even sallite lines is seen which was reported in 1960 by Bumba (1960). From this record it may be noted that Hale, had in fact observed in 1892 Doppler Shifts in sunspot penumbra, but failed to interpret as mass motion, which was left for Evershed to discover, after 15 years! Since the discovery of the Evershed effect, number of authors have greatly contributed through spectroscopic study of mass motion in spot penumbrae. Two-dimensional high resolution time lapse doppergrams, photoheliograms and filtergram observations of sunspots obtained by Sheeley and Bhatnagar (1971), Muller (1973), Zirin and Stein (1972), Giovanelli (1972) have revealed very interesting dynamic phenomena in spot penumbrae. According to Sheeley and Bhatnagar (1971) the Evershed outflow starts from or near the inner umbra-penumbral boundary and terminates in spoke like structures that constitute the ragged outer boundary of the penumbra. Beyond the penumbral outer boundary, spatially averaged horizontal flow extending to nearly 10,000 km is observed. This extra-penumbral velocity field is quite distinct from the Evershed flow, which seems to end at the penumbral spokes. Typical Evershed velocities at photospheric level range between 1 to 2 km/sec, but occasionally higher values have been also reported. Doppler observations of spot penumbrae with enough spatial resolution to distinguish the bright filaments from dark lanes, obtained by Bhatnagar (1966), Beckers (1968) and Abdusamatov and Krat (1970) indicate that the Evershed outflow is strongly concentrated in dark lanes. From very high resolution while light spot observations, Muller (1973 a, 1973 b, 1976, 1979) showed that penumbral bright grains of about 0".36 of arc move inward towards the umbra of the spot, reaching a speed of 0.5 km/sec at the penumbra-umbral border. Thus in the photospheric penumbra, two streams motion is observed, which is directed in opposite directions, one outwards in the dark regions, while the bright grains move inwards.

Zarin and Stein (1972) and Giovanelli (1972) independently discovered periodic running waves in penumbrae, at chromospheric levels. The waves consist of alternate bright and dark bands, which emerge from and are concentric with the edge of the umbra. These waves propagate horizontally with a speed of 10 to 20 km/sec and display an average period of about 258 seconds. Subtracting, H-alpha filtergrams taken in the red and blue wings, Giovanelli (1972) has shown that the penumbral waves contain vertical velocity oscillations with an amplitude of a few kilometer per seconds.

4. Umbral Granulation, Bright Dots and Oscillations

High resolution white light sunspot photographs show umbral granulations almost similar to photospheric granules, except that they appear more closely packed and have much longer life times (Bray and Loughhead 1959). From umbral photographs, with range of exposures Loughhead et al. (1979) have found bright dots of about 0".5 of arc size and life time of about 30 minutes, in umbrae of all spots and are even present in the darkest parts of the umbra. Both umbral dots and penumbral grains (filaments) have almost similar properties, except that the penumbral grains are elongated while dots are roundish and short lived. Both show upward motion and weaker magnetic field with respect to the surrounding dark region (Beckers and Schröter 1969, Zwan and Buurman 1971, and Kneer 1973). The magnetic field in the umbra is strongly inhomogenous on the scale of umbral dots.

Beckers and Tallant (1969) discovered periodic flashes in H- and K-lines of Ca-II in spot umbrae. The life time of K-line umbral flashes was found about 50 sec, with a tendency to repeat every 145 seconds and size of nearly 2000 km in diameter. In a medium size umbra, at any instant one could see, on an average 3 to 5 flashes. These flashes also display Doppler velocity of about 6 km/sec and even horizontal shift in position. Many flashes repeat for more than 18 cycles while some for a few cycles only. During the post flash phase, strong blue shifts is also noticed for 100 to 200 seconds, but changes rapidly to red shift just before the flash repeats. In H-alpha chromosphere the umbral flashes are less conspicuous, however, Giovanelli (1974) and Moore and Tang (1975) have observed vertical velocity oscilaltions in H-alpha, with period ranging between 134 to 170 sec and cell size of about 3" to 10" of arc and amplitude of 3 km/sec. It has been well established that the vertical oscillations of the umbral chromosphere observed in H-alpha and those observed in K-line are one and the same. Giovanelli (1974) also observed wave front originating from near the centre of the umbra, which seems to progress outwards towards the penumbra. He finds close relation between the umbral oscillations and the running penumbral waves, it seems that the umbral oscillations are in some manner responsible for the penumbral waves. Velocity oscillations in the umbral photosphere have been observed by Beckers and Schultz (1972) using Fe 5434 non-Zeeman lines and peak-to-peak amplitude of 1 km/sec and period of 178 sec at the umbral centre and longer period of 255 seconds near the umbra-penumbra border. Bhatnagar et al. (1972) using lines formed in the umbra only and with zero-Zeeman splitting found peak-to-peak amplitude of 0.5 km/sec and periods ranging from 310 to 448 seconds. Readers are referred to an excellent review by Moore (1981) on "Dynamic Phenomena in Spots".

5. Moving Magnetic Features Around Sunspots

The first evidence of motion of small magnetic features outflowing from spot penumbral boundary came from the time-lapse observations of CN-bright points by Sheeley (1969), as CN bright points correlate well with magnetic regions. However, no idea of the magnetic polarity could be obtained from these observations. From careful high resolution time-lapse magnetograms, using Leighton's (1959) spectroheliograph technique Vrabec (1971) prepared a movie of magnetic features, which distinctly showed motion of magnetic features of 2" to 4" of arc size, flowing outwards from the outer periphery of sunspots with an average velocity of about 1 km/sec. Vrabec (1974) observed that magnetic features of both polarities occur in the outflow around spot of either polarity. Further, some spots not only show outflow but also "inflow" of magnetic features towards the spot. The outflow continues approximately along radial paths from sunspots, some fade and disappear, while other may merge with the pre-existing field and may form new-network structure. Harvey and Harvey (1972, 1973) have reported that half of the sunspots observed with the 40-channel magnetograph exhibit outflow of magnetic features from sunspots, Michalitsanos and Bhatnagar (1975) reported outward moving magnetic ridges from time-lapse longitudinal video-magnetographic observations. The "ridges" could be resolved into individual knots of flux of 2" to 3" arc seconds size, moving in unison with speeds of 0.2 to 0.3 km/sec. Successive magnetic ridges were also observed to originate from the penumbral border. In Figure 5 is shown moving magnetic ridge indicated by arrows on a video-magnetogram.

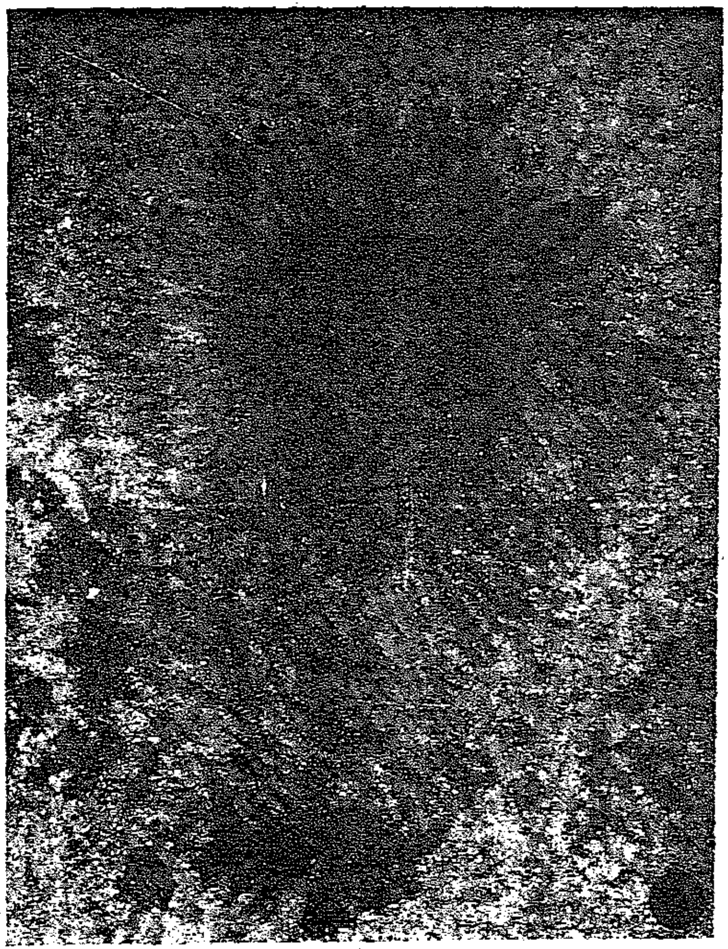

Fig.1. White light granulation picture taken by Müller, from Pic du Midi, *showing granulations* and *penumbral grains*. Round circle on the right lower corner indicates 5 arc seconds in diameter (Courtesy - Dr. R. Müller)

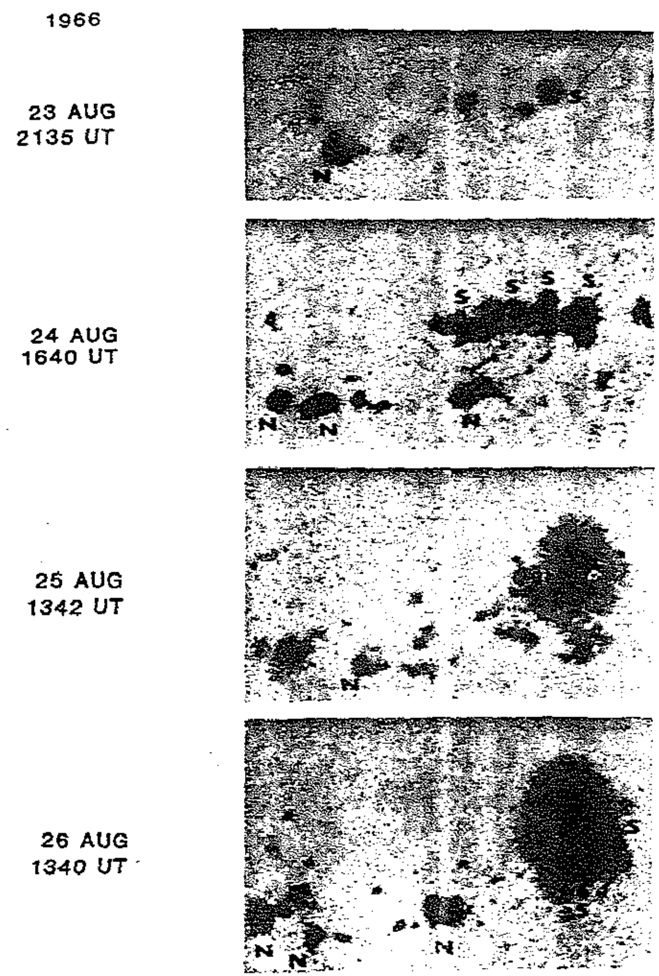

Fig.2. White light pictures, showing growth of sunspot group *and coalescing* of small spots and pores to form large spots (McIntosh 1981)

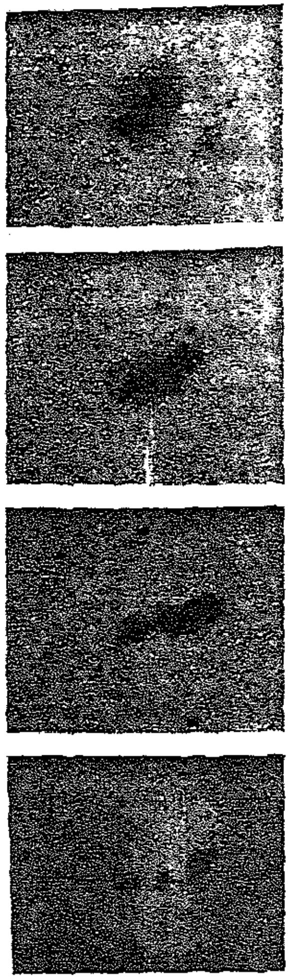

Fig.3. Day-to-day sequence of white light pictures, showing dissolution and fragmentation of sunspots (McIntosh 1981).

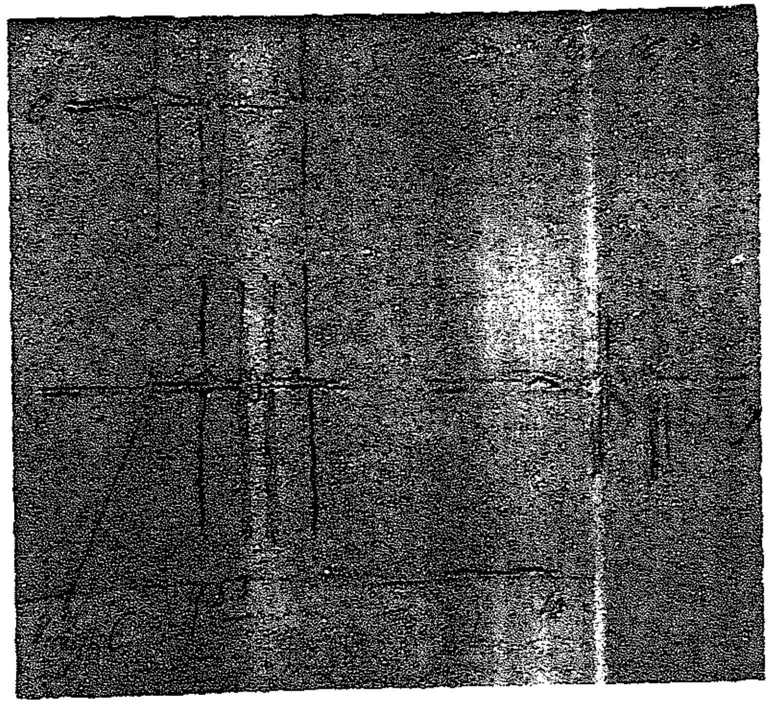

Fig.4. Line drawing of visual observations made by George Hale on May 26, 1982 at 09.50 and 09.53 of the C-line (H-alpha) over sunpots. One can distinctly see the strong Doppler shift and line asymmetry – "flag" and even the satellite line, copy obtained from Hale's observing note book.

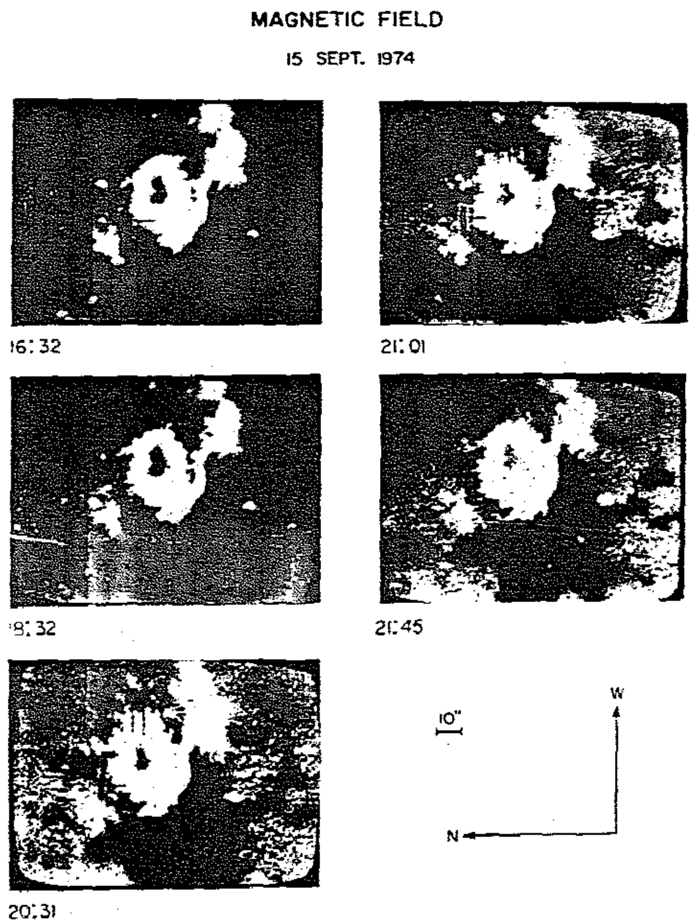

Fig.5. Video-magnetograms taken at the Big Bear Solar Observatory, showing motion of magnetic ridges, away from the sunspots. *Arrows indicate the ridges, moving towards west and north* directions (Michalitsanos and Bhatnagar 1975)

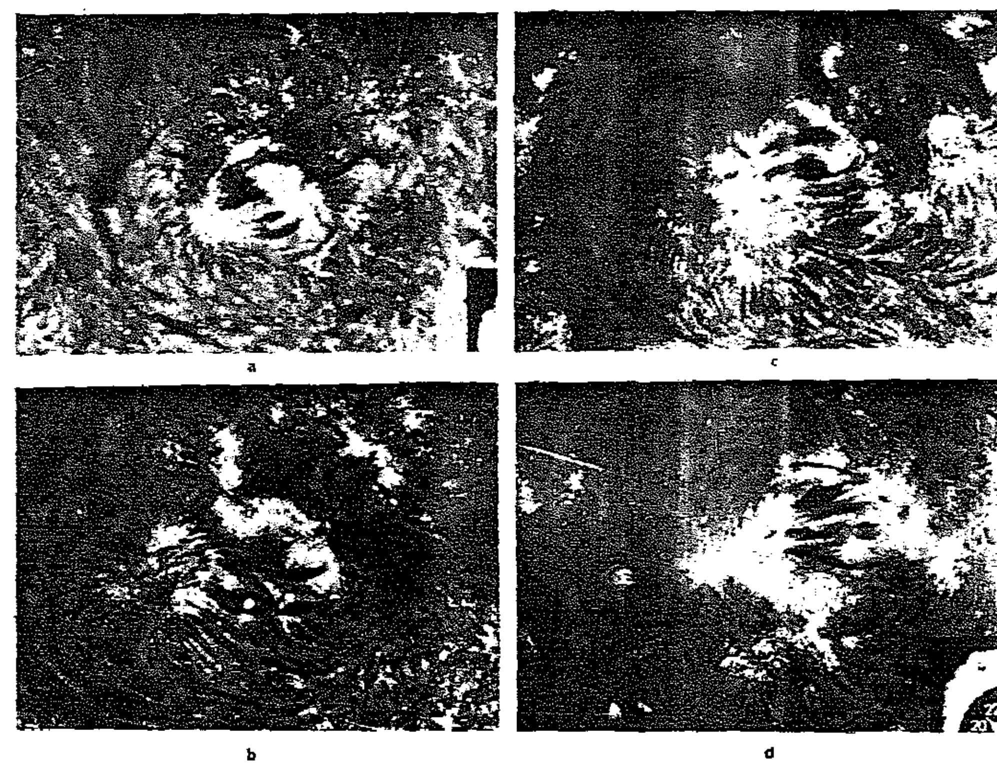

Fig.6. Day-to-day *development* of emerging flux *region* on H-alpha filtergrams taken at Big Bear Solar Observatory
(Courtesy - Prof. H. Zirin, CalTech., Pasadena, 1971 Sept. 1-4)

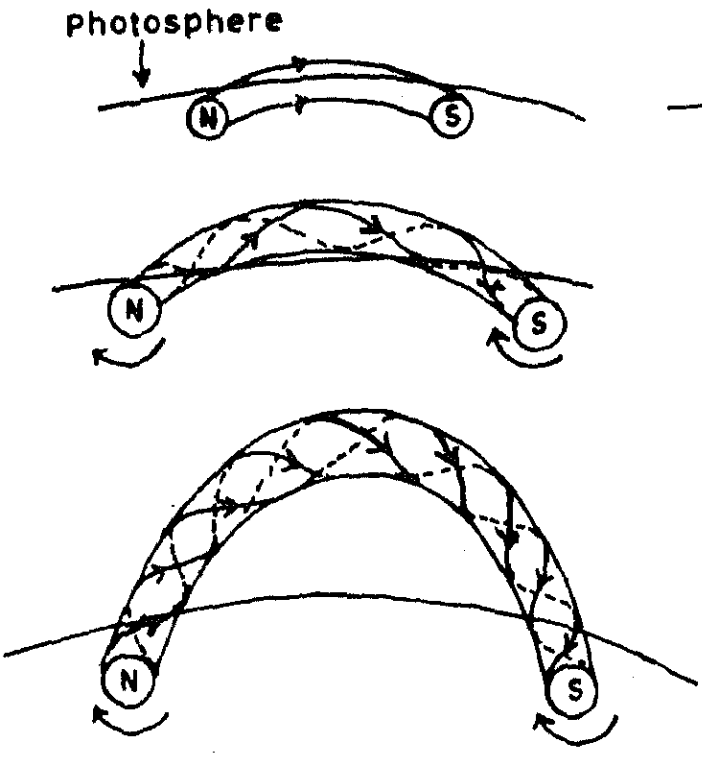

Fig.7. A possible scenario of emerging magnetic flux tubes. N and S indicate the bipolar sunspots

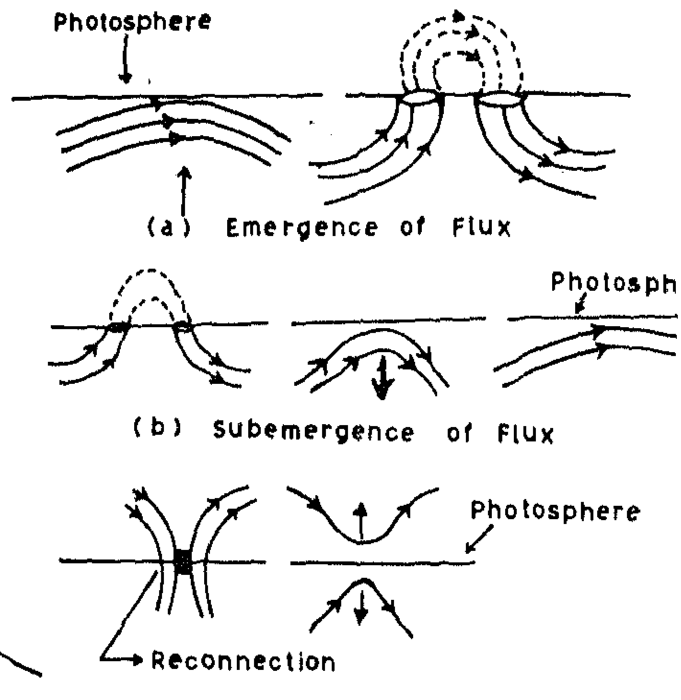

Fig.9. (a) Indicates flux emergence due to r flux ropes, from the sub-photospheric level. appearance of magnetic field due to submerg flux tubes. (c) Magnetic flux removal by poss connection of field lines above and below the sphere.

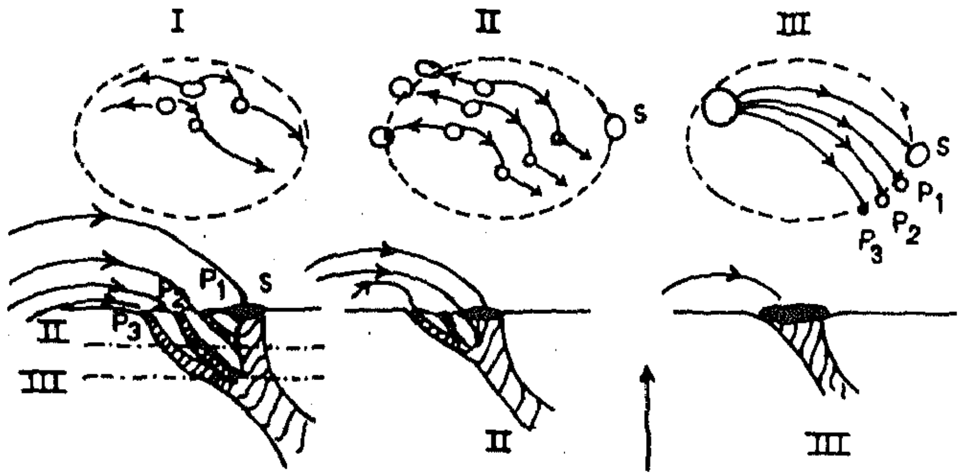

Fig.8. A scenario of moving magnetic features I, II and III indicate the various locations of the magnetic features P_1, P_2 & P_3 based on Piddington's frayed twisted flux rope model, in the lower portion is shown a possible configuration of the frayed flux strands, in sub-photospheric level

6. Emergence and Submergence of Magnetic Flux

Good quality H-alpha-filtergrams show elongated fibrills joining opposite polarity regions, which mark the transverse magnetic field in a bipolar magnetic region. Comparing H-alpha high resolution filtergram with magnetic bipolar region for these features, Zirin suggested a new name as Emerging Flux Region (EFR), which were earlier called by Bruzek as arch-filament-system (AFS). In Figure 6 is shown the development of an emerging flux region. It will be noticed that as the EFR grows, the H-alpha arches, which are the indicators of the transverse magnetic field lines, grow in length and height. In Figure 7 is given a scenario of possible emergence of flux from the sub-photospheric region. As mentioned in section 2 earlier, it may be recalled that just before the emergence of a "pore", disturbance, realignment and slight elongation in photospheric granulations have been observed. It is suggested that the observed disturbance in the granulation, appearance of spots and "pores" and later the emergence of arch filament system at the chromospheric level, are due to rising of submerged magnetic fields, in the form of helically twisted flux ropes, from the sub-photospheric level to the solar surface. These observations support, the original idea of Babcock (1961) and the model developed by Piddington (1971, 1975, 1976). The rotation of sunspots have been observed which would also increase the magnetic flux through twisting of flux ropes. The twisting of flux tubes can be inferred from the high resolution time lapse H-alpha filtergrams, wherein one could see "winding" and "unwinding" H-alpha filamentary structures, in active regions. Thus the twisting of the submerged flux ropes indeed exists.

The moving magnetic features observed by Sheeley (1969), Vrabec (1971), Harvey and Harvey (1972) and Michalitsanos and Bhatnagar (1975) can be interpreted according to Piddington's frayed twisted flux rope model. In Figures 8 a & b is shown a possible scenario of moving magnetic features, P_1, P_2, P_3 around a sunspot S. Consider the magnetic flux rope as "magnetic tree" whose trunk is a flux rope and branches are the fine frayed flux rope strands. The spot and the magnetic features (knots) appear when the flux tubes open up at the photospheric level. As the twisted and frayed flux strands rise, the photosphere interests at II and then at III (Figure 8b), which would appear as inflow of magnetic features, P_1, P_2, P_3 towards spot S. A reversed situation will appear, if the flux tubes untwist and sink in the photosphere, this would indicate an outflow of magnetic knots from the penumbral boundary.

Recently Zirin (1984) has observed on H-alpha filtergrams and magnetograms a case of disappearance of magnetic flux. No motion of diffusion of flux seems to take place, instead on the filtergrams the H-alpha arches decreased in length and finally vanished within 3 days. A corresponding disappearance was also seen on the video-magnetograms. Rubin et al. (1984) have also observed a similar disappearance of magnetic flux in over night, in Boulder active No.2372 between 6 and 7 April 1980. On 6 April the transverse component over the region was quite strong, but on the next day i.e., on 7 April, no sign of transverse component was visible. Filtergrams obtained at the Udaipur Solar Observatory (USO) on 6 April at 06.00 UT, about 13 hours before, showed no indication of plage brigtening or EFR in the location observed by Rubin et al. But on 6 April at 19.30 UT filtergrams by Rubin et al., and on 7 April filtergrams at 02.30 UT taken at USO, conspicuous brightening and EFR was visible. Later in the day Rubin et al. observed considerable weakening of plage on April 7 at 18.47 UT. From these observations, we conclude that an emerging flux region (EFR) appeared between about 10.00 UT and 19.00 UT on April 6 and disappeared between 09.00 UT and 18.40 UT on 7 April, 1980. These observations suggest that some of the magnetic flux dissipation takes place through reverse process of emergence, that is "submergence" of flux ropes in the photosphere. The flux removal could take place either through submergence or reconnection as shown in Figure 9. In the 6 April case, it appears that the emergence and submergence took place rapidly, in a short time of about one day or so. From these examples we believe that submergence of magnetic flux is much more frequent phenomenon, through which flux dissipation takes place on the Sun.

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