STUDY OF CALCIUM-K NETWORK EVOLUTION FROM ANTARCTICA

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Abstract. To study the evolution of large convective cells known as supergranules, a solar telescope was set up at Maitri, Indian permanent station in Antarctica region, during the local summer months (December 1989 through March 1990). A continuous sequence of calcium K-line filtergrams for 106 hours spaced at intervals of about 10 min was obtained. The analysis of the data indicates that the most probable lifetime of the calcium-K network is about 22 hours. The lifetime depends upon the size of the cell and is larger for bigger cells. The data also show that cells (of a given size) associated with remnant magnetic field regions live longer than those in the field-free region. This may mean that the magnetic field plays an important role in the confinement of these structures.

1. Introduction

The large-scale cellular system of horizontal motions in the upper photosphere is a fundamental constituent of the structure of the quiet Sun. The study of the evolution, shapes, sizes, and lifetimes of large convective cells may help to reveal the physical characteristics of the deeper convective layers. These large cells, known as supergranules, are enclosed by the chromospheric network, seen in calcium spectroheliograms or filtergrams, and are of various sizes and shapes. Leighton, Noyes, and Simon (1962) and Simon and Leighton (1964) discovered these large cells from the velocitygrams obtained during the summer of 1960 and 1961. They found that these cells have a maximum horizontal divergent flow of 0.5 km s^{-1}. The supergranules have a typical size of 30 000 km and average life 20–24 hours. They also found a strong correspondence between the calcium-K network and the supergranulation pattern and concluded that the supergranulation pattern is a surface manifestation of the convective phenomenon, and may be associated with the He-ionization zone inside the Sun. Singh and Bappu (1981) used a technique to measure the individual cells to study the dependence of their sizes on the solar cycle. Their measurements indicated that the most probable size of this cell is smaller than that estimated earlier by Leighton, Noyes, and Simon (1962). The significant result of this analysis is the variation of cell size with the phase of the solar cycle, the cell size being smaller by 5% at the solar maximum than at its minimum.

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Rogers (1970) estimated the lifetime of the Hα chromospheric network using a nearly continuous sequence of filtergrams of 62 hours duration obtained from Thule, Greenland, 10° above the Arctic circle. The analysis yielded a mean lifetime of 25 $\pm$ 1.6 hours for the Hα chromospheric network. Worden and Simon (1976) investigated the velocity and magnetic field associated with supergranulation using the Sacramento Peak Observatory diode array magnetograph. Their observations indicated that supergranular velocity cells may have lifetimes in excess of the accepted value of 24 hours. To determine lifetimes and the evolution of these large convective cells, we have obtained a continuous sequence of ionized calcium K-line filtergrams from Maitri, the Indian permanent station in the Antarctic region, during the local summer of 1989–1990. We have analysed these data to determine lifetime, size and their relationship for calcium-K network cells.

2. Experimental Arrangement

A heliostat with a 15 cm aperture mirror mounted on a pillar 2 m high was used for tracking the Sun. The flat mirror, driven by a synchronous motor through a worm wheel assembly, collected the light from the Sun and directed it in the direction parallel to the rotation axis of the Earth. A second flat mirror at the bottom of the heliostat tube collected the beam reflected from the first mirror and folded it horizontally to feed an objective of 10 cm aperture and 300 cm focal length. The second mirror has a push-pull arrangement to position and centre the solar image onto the filter. The converging beam from the objective entered a narrow band (1.2 Å passband) K-line filter made by 'Day Star' of U.S. The passband of the filter was calibrated for various temperature settings using the very-high-resolution spectrograph of the solar tower telescope at Kodaikanal. A Minolta X-700 camera mounted on the K-line filter had the facility to record automatically the epoch of every exposure on the corner of each frame of the filtergram. The setup enabled us to obtain the calcium K-line filtergrams with an image scale of 66 arc sec mm^{-1} and a spatial resolution of about 2 arc sec.

3. Observing Conditions and Observations

The Indian department of ocean development in 1988 set up a second permanent station at a logistically good location in the Schirmachar hill range in the Antarctica region. This station known as Maitri is situated at latitude S 70°45′39″ and longitude E 11°44′49″. After reaching Maitri on December 27, 1989, the expedition team surveyed the area around the station and the nearby hills with the help of an IAF helicopter to select a site for the telescope from which the Sun can be observed for a maximum number of hours per day. Keeping in view the logistics and time available for observations it was decided to put up the telescope on the southern side of a lake and close to the Maitri station. During our stay of 50 days there were 10 full days with clear sky. On 5 of these days there was negligible wind but on the other 5 days the wind speed was in the range of 30–50 km per hour. It was possible to obtain filtergrams in calcium K-line on 7 of the 10 days. On each day sunshine at the telescope was available for 21.5 hours during the second week of January and for about 18 hours towards the end of January. Polar ice at the southern horizon obstructed the view of the Sun for about 2 hours each day. These filtergrams, recorded on 35 mm Kodak 2415 film, were developed in D-19 developer at 20 °C for 5 min. The data on four days are of good quality representing quiet and steady atmospheric conditions while the remaining data were obtained under moderate seeing. In all, we have been able to obtain about 1200 filtergrams of the Sun in calcium K-line with an interval ranging from 5 to 10 min. In addition, we have obtained about 800 filtergrams at the rate of one photograph every 30 s on three days to study the solar activity. The longest sequence spans a period of four and half days during January 9–13, 1990. This sequence of filtergrams obtained on 4 days with good seeing and half a day with moderate seeing has been used in the present study.

4. Data Analysis

Each filtergram belonging to the above-mentioned longest time sequence of 106 hours was enlarged to a size of 283 ± 1 mm. The peak emission on the boundary of the cells was marked to delineate the nearly complete calcium-K network cells. The selected network cells were identified on frames 10 min apart. To determine the lifetime of a supergranule, we have adopted the following procedure: suppose a cell with complete boundaries is just seen at an epoch t_2. Then we looked at the same region in the prints of filtergrams obtained earlier than this epoch. A careful examination of the filtergrams showed that a configuration of bright points similar to the boundary of the network cell appeared at time t_1. The same configuration later formed the complete boundary of the cell at time t_2. The difference between these two epochs t_1 and t_2 is about 1–2 hours. The epoch $(t_1 + t_2)/2$ has been taken as the time of formation of the cell. Similarly the epoch of decay has been found for the cell by observing the epoch of beginning of disintegration and complete decay. The difference between two epochs has been taken as the lifetime of the cell.

As an example we show the evolution of a calcium network cell in Figures 1(a) and 1(b) which contain part of the filtergrams obtained on January 11 and January 12, respectively. The epoch of each filtergram, representing the same region on the solar surface, with small differences due to different foreshortening factors at different times, has been written below the filtergrams in UT. In Figure 1(a), a circle marked in the filtergram recorded at 02:00:33 UT shows the region in which a network cell develops. In each filtergram, N has been written on top of the network cell under study. The filtergrams at 02:59:05 (t_1), 04:20:00 and 05:10:00 (t_2) UT show the beginning, intermediate, and complete state of formation of the network cell. It appears from the filtergrams, recorded at 11:29:55 UT on January 11 and 19:21:16 UT on January 12, that the network cell increases in size. There

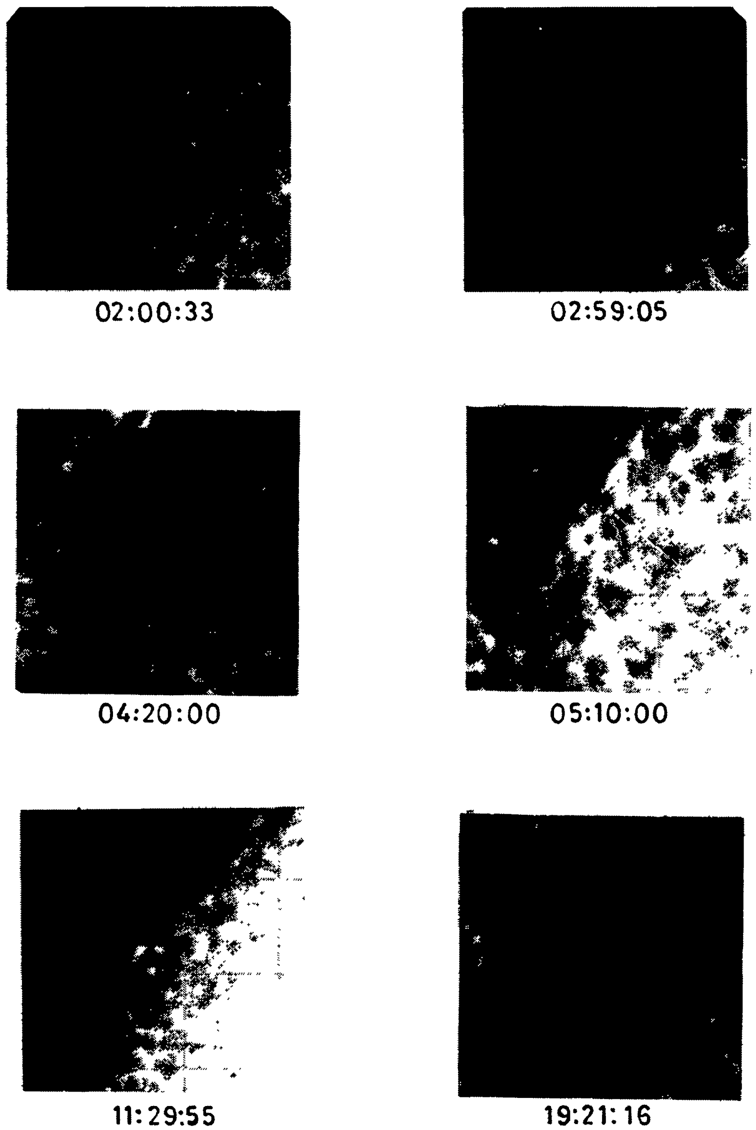

Fig. 1a. Time sequence of calcium K-line filtergrams covering the same region on the solar surface obtained on January 11, 1990. It shows the evolution of the network cell marked by 'N' in the region enclosed by a circle in the filtergram recorded at 02:00:33 UT.

are two reasons for this: (i) it looks bigger because of the decrease in the angular distance of the network cell from the centre of the image due to solar rotation and (ii) an actual increase in area by about 30%. The filtergrams obtained at 12:30:15 and 13:09:31 UT show the beginning and final state of disintegration of the network cell. The circle, enclosing the area of the cell under analysis, marked in the filtergrams at 14:20:00 UT, indicates the complete disappearance of the calcium

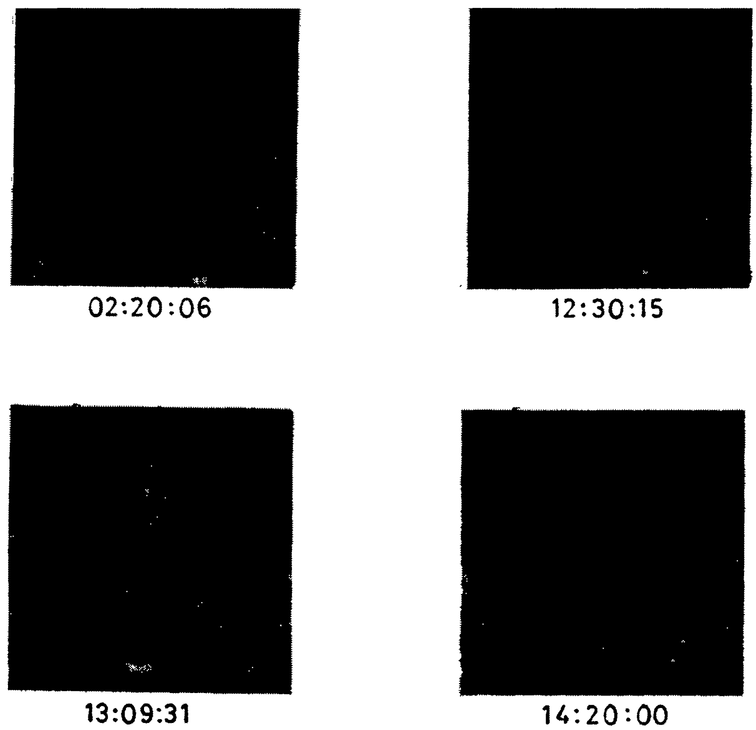

Fig. 1b. Same as Figure 1(a) but obtained on January 12, 1990; it shows the disappearance of the cell.

network cell. From the above-mentioned times we find that the epoch of formation is 04:05 UT on January 11 and 13:25 UT on January 12 as the time of decay of the cell. Thus the lifetime of this cell comes out to be 33 hours 20 minutes. This cell, belonging to the quiescent region category, has an average area equal to 8.7×10^8 km^2.

The measurement of areas on the enlarged prints was done by use of a 1 mm grid. The values of the areas have less than a 3% variation caused by the measuring technique. The areas of the cells were corrected for foreshortening using the following method: the centre of each print of the filtergram was marked by matching the positions of sunspots visible on the calcium K-line filtergram with those on the full-disc, white-light picture of the Sun obtained at the Kodaikanal observatory. In case of non-availability of a corresponding photoheliogram, the position of the centre of the filtergram was interpolated, using the two adjacent filtergrams. The distance from the marked centre and the area of each network cell were measured using a mm scale and a mm square grid, respectively. The angular distance, θ, of the cell from the centre of the disc was computed using the relation

$$\sin\theta = d/R ,$$

where d is the distance of the cell from the centre and R the radius of the solar image. Then the cell size, given by $A \sec\theta$, A being the measured area of the cell, was converted into actual area on the surface of the Sun.

Our analysis began with 76 well-defined calcium network cells. Two of the cells, very close to the active region, lived for more than 3 days and could not be traced further due to the limited length of the data available. These cells appear to belong to the category of magnetic 'pukas' studied by Livingston and Orrall (1974). We have excluded these cells in our present analysis. The lifetimes of another 10 cells could not be determined accurately because some of these appeared to split into two and others made bigger structures by merging with the neighbouring cells. Finally we were left with 64 well-defined network cells whose lifetimes could be determined without any ambiguity.

5. Results and Discussion

We have divided all these calcium network cells in two groups depending upon their distances from the calcium plage region. A cell seen close to the periphery of a plage with boundary emission larger than the average has been labelled as an active region cell (marked A in Figure 2). The cells away from the plage region and showing normal boundary emission have been labelled as quiescent region supergranules (cell marked B in Figure 2). Using this method of classification we got 35 cells belonging to the active region and 29 to the quiescent region. In this paper we shall refer to them as 'active cells' and 'quiescent cells'.

We have tried to estimate the lifetimes of the calcium-K network cells by two methods: by finding (i) the mean lifetime and (ii) the most probable lifetime from the frequency distribution curve. The lifetimes of the cells span a range of 10–56 hours. The mean lifetime of an active cell is ~36 hours and ~24 hours for a quiescent cell. We have plotted number against lifetime of the calcium-K network cells in Figure 3. Figures 3(a) and 3(b) show the frequency distribution of lifetimes for active and quiescent cells, respectively. The histogram in Figure 3(b) indicates that the most probable lifetime for the quiescent cell is about 22 hours. It is difficult to say what is the most probable lifetime of the active cell from the histogram in Figure 3(a) because the sample is too small. We have also combined the data of active and quiescent cells and shown the frequency distribution of lifetimes of all 64 cells in Figure 3(c). The histogram in Figure 3(c) indicates that the most probable lifetime of a cell is about 22 hours. The mean lifetime of cells is ~31 hours when all 64 cells are taken together. The large difference between the mean lifetime and the most probable lifetime of a cell is because the frequency distribution of lifetimes is not gaussian. The extended tail due to large values of lifetime for a few cells contributes to the large value of the mean lifetime of a cell.

Several lifetime studies of supergranules have been performed referring to the velocity field or to associated phenomena like network or magnetic field structures. Lifetime estimates for supergranules of about 20 hours were derived from obser-

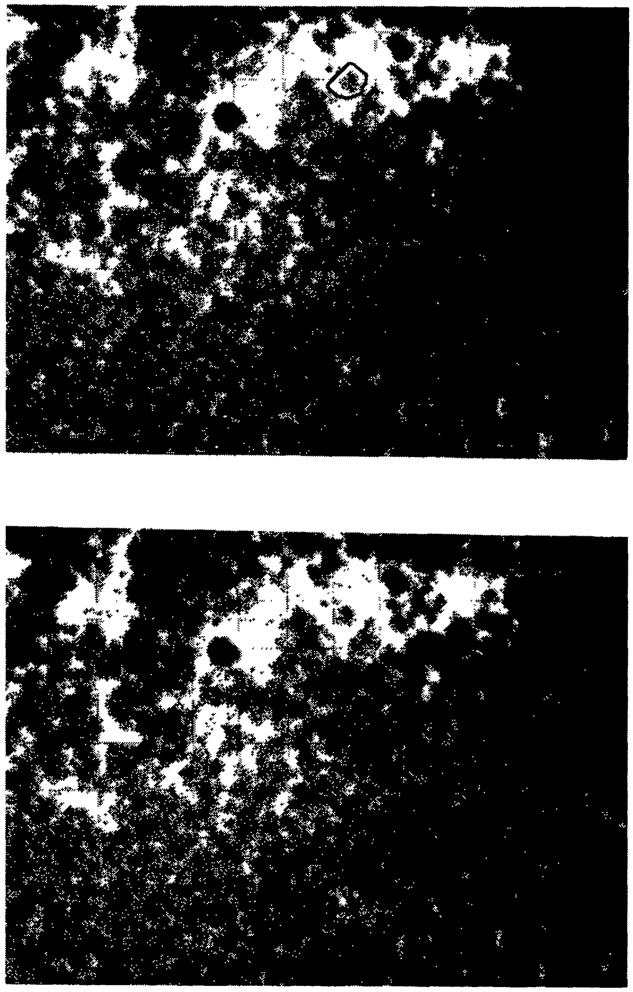

Fig. 2. Duplicate photographs of the calcium-K filtergram of same region, one with marking of calcium network cells and the other for comparison. Typical examples of active and quiescent cells are marked as 'A' close the periphery of the plage and 'B' away from the active region, respectively.

vations of calcium-K network by Simon and Leighton (1964) and from the time sequence of Hα filtergrams by Rogers (1970) and Janssens (1970). On the other hand, Smithson (1973) and Worden and Simon (1976) inferred a mean lifetime for supergranules near 40 hours from magnetic observations. Duvall (1980) also estimated a mean lifetime of about 40 hours from velocity observations. Wang's (1988) study of velocity fields of a small number of supergranules indicates lifetime in excess of 50 hours. Most of these estimates of lifetime for supergranules are deformation time scales (Schrijver, 1989), i.e., correlation times over which the feature used to trace the supergranule (e.g., the area of downdraft, or the chromospheric

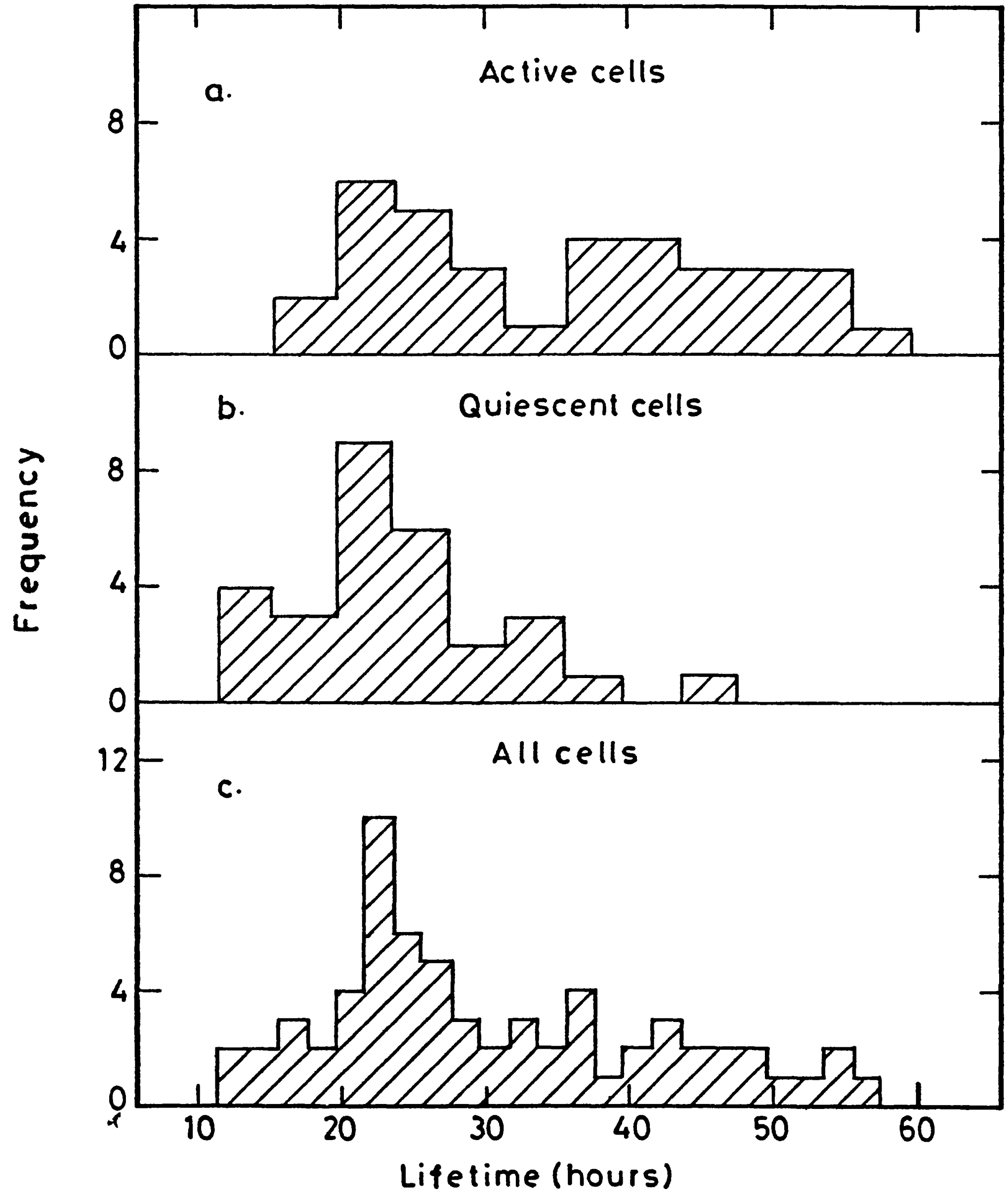

Fig. 3. Frequency distribution of the lifetime of calcium-K network cells. (a–c) are for active cells, quiescent cells and all cells, respectively. In (a) and (b) distribution is shown by making bins of 4-hour intervals and in (c) bins of 2-hour intervals.

or magnetic network) is displaced by its own characteristic dimensions, whereas we have studied the lifetimes and evolution of individual calcium-K network cells. Our value of 22 hours agrees well with the value estimated by Simon and Leighton (1964). Our value of mean lifetime of an active cell is close to the 40 hours derived by Smithson (1973) from magnetic observations.

To find the relationship between the size and lifetime of a cell, we have measured the area of the cell at one-hour intervals. The areas of most cells remained unchanged within a variation not larger than 10%. A few cells showed a gradual decrease of 20 to 30% in area during their lifetimes, while some showed area

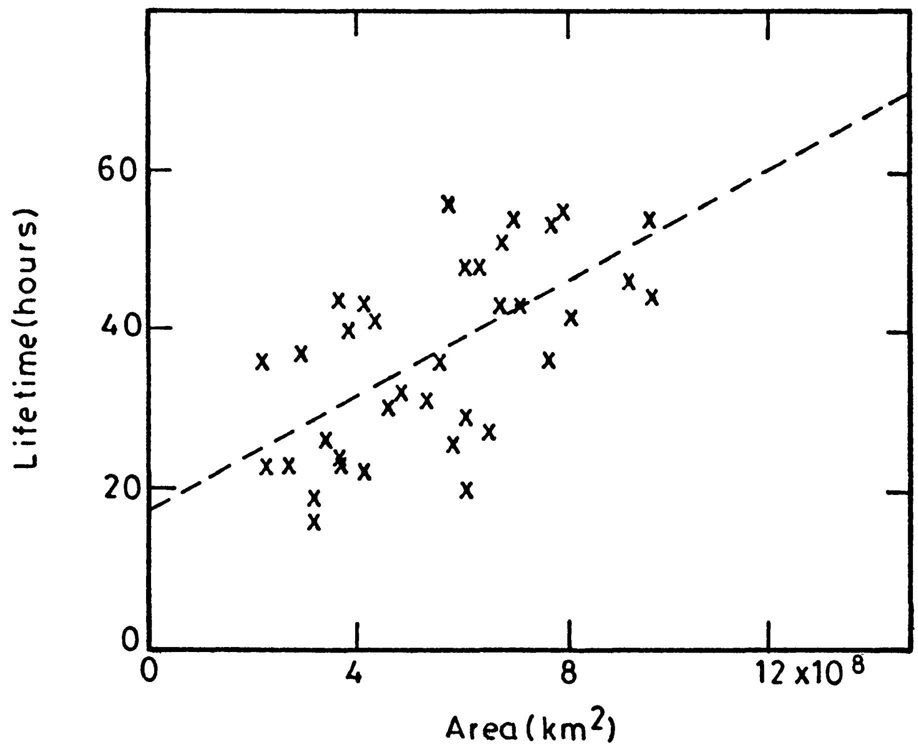

Fig. 4. Observed correlation between the area and lifetime of the 'active cells'. The dotted line is a linear fit to the observed data.

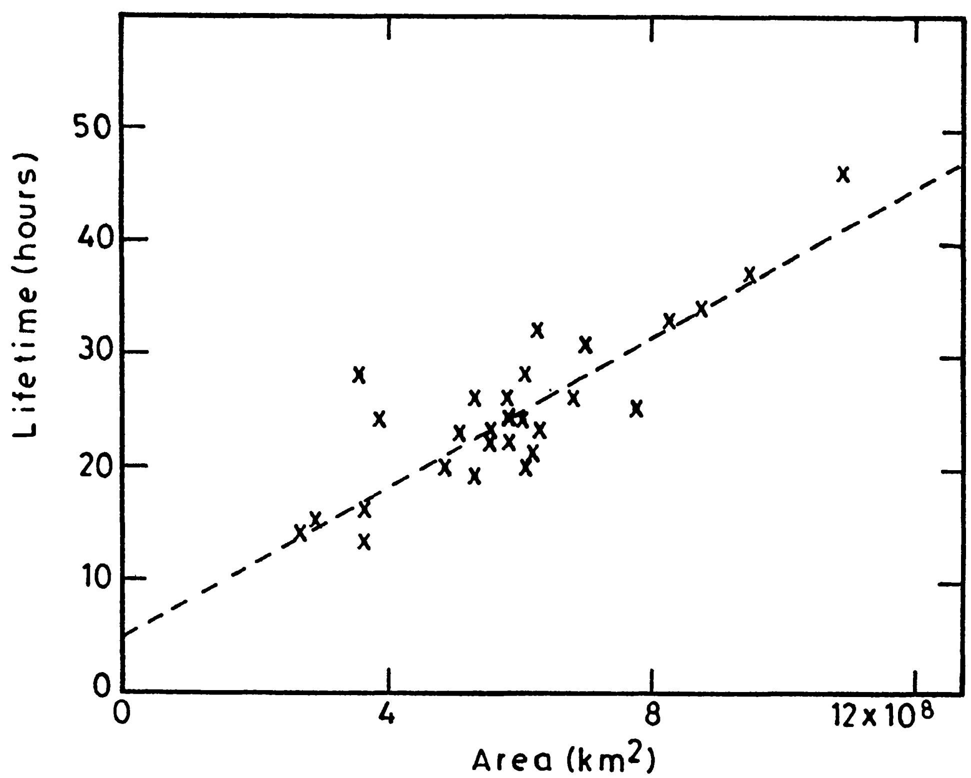

Fig. 5. Observed correlation between the area and lifetime of the 'quiescent cells'. The dotted line is a linear fit to the observed data.

increases of 20 to 30%. The average area of each cell was computed and plotted versus lifetime as shown in Figure 4 for active cells and Figure 5 for quiescent cells. From these figures a correlation between the lifetime and the cell size is apparent; the value of the correlation coefficient is 0.58 for the active and 0.79 for the quiescent cells. These values of correlation coefficients indicate a confidence level above 99% (Snedecor and Cochran, 1967). This means that the lifetime of a cell depends on its size and is larger for the bigger cells. It may be interesting to know the cell size corresponding to the most probable lifetime of the calcium-K network cell. A linear fit to the data of quiescent cells as shown in Figure 5 yields a value of cell size of 26 000 km for the most probable lifetime of about 22 hours. This value of cell size is close to that derived by Singh and Bappu (1981) from the measurement of individual calcium-K network cells.

To compare the lifetimes of quiescent and active cells let us consider a cell, say, of area 6×10^8 km^2. The derived value for the lifetime of this cell is $\sim$25 hours (from the linear fit in Figure 5) if quiescent and $\sim$38 hours (from the linear fit in Figure 4) if active. The linear fits for the active and quiescent cells have slopes of 0.86 and 0.81, respectively, and are approximately parallel, having a separation of about 13 hours. It shows that active cells live longer than quiescent cells of comparable size.

Leighton (1959) and Howard (1959) showed that a close spatial correlation exists between the general pattern of emission in the calcium K line and the magnetic fields in the underlying regions. This relation holds for the chromospheric network as well as for active regions near sunspots. It is, therefore, expected that the active cells, close to the peripheries of plages having larger emissions at the cell boundary, are associated with stronger magnetic field. We speculate that the 'confining properties' of the magnetic field may be responsible for the longer life of active cells. This possibility can be explroed by studying the dynamics of velocity and magnetic field in the cells. One more point to be noted is that the scatter in the lifetime versus cell size plot for the quiescent cells is much less than that for active cells. This may indicate that varying activity plays a role in the evolution and structure of the cells.

To summarize the present work, our analysis of a 106-hour continuous time sequence of calcium K-line filtergrams obtained at the Indian permanent station in the Antarctic region shows that:

(i) The most probable lifetime of a calcium-K network cell is about 22 hours.

(ii) There is a correlation between the lifetime and the cell size such that bigger cells live longer.

(iii) Cells (of a given size) associated with active regions live longer than those in quiescent regions.

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