Magnetic flux in the solar convective envelope inferred from the initial observations of the sunspots

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ABSTRACT

Different life spans of the sunspots suggest their origin at different depths and by measuring magnetic fluxes from their first observation on the surface, one can estimate the strength of magnetic flux at different anchoring depths. From the SOHO/MDI magnetograms, we infer the strength of magnetic flux and rate of emergence of magnetic flux at different anchoring depths in the solar convective envelope by measuring *initial* magnetic fluxes of the well developed sunspots on the surface. Important findings are : (i) majority of the spot groups that have *first* observation on the surface are bipolar, (ii) irrespective of their sizes, the bipolar spots with different life spans have average magnetic field strengths of $\sim$ 500 G during their first observation, (iii) the average field strength at the site of anchoring depths of the sunspots is estimated to be $\sim 10^6$ G near base of the convective envelope and $\sim 10^4$ G near the surface, (iv) the dynamo-a source of sunspot activity- is distributed through out the convective envelope and, (v) the rate of emergence of *initial* magnetic flux of such a distributed dynamo near base of the convection zone is $\sim$ 6 X 10^{19} Mx/day and is 40% higher than the the rate of emergence of *initial* magnetic flux near the surface.

Subject headings: sunspots – bipolar spots – magnetic field – magnetic flux – rate of emergence of magnetic flux

1. Introduction

The sunspots have been observed since the invention of telescope. Understanding of their evolution and their origin ultimately may give clue to the sun's internal dynamo mechanism that is supposed to be sustaining the solar cycle and the activity phenomena. On the surface though sunspots' dynamical and morphological properties are well understood, recently only helioseismic investigations (Kosovichev 2005; Gizon and Birch 2005) reveal the jelly fish like structure below the surface consistent with Parker's (1979) idea, though stability of such a structure can not be guaranteed (Lites 1992; Chitre 1992 ; Thomas and Weiss 1992).

On the surface, sunspots erupt and are oriented in the east-west direction nearly parallel to the equator suggesting that they are supposed to be formed by the perturbation of the underlying diffused toroidal magnetic field structure. In the convective envelope, such a toroidal field structure may be prone to dynamical instabilities due to buoyancy (Parker 1979; Hughes and Proctor 1988; Hughes 1991). Toroidal field structure is also unstable if it varies continuously in the solar convective envelope (Gilman 1970), although simulations of the compressible numerical convection alleviate the problem of flux storage (Nordlund, Dorch and Stein 2000; Dorch and Nordlund 2001; Tobias *et. al.* 2001). Yet it is not clear whether instability of the underlying toroidal field structure that represents the dynamo activity occurs near base or occurs everywhere in the convective envelope as

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recently proposed by Brandenburg (2005). Moreover it is a unsettled problem whether sunspots are formed due to conventional turbulent dynamo mechanism or formed due to the perturbation of a diffused toroidal field structure in the convective envelope (Hughes 1992). If somehow sunspots are formed below the surface, still a crucial question is what is the magnitude of the magnetic field or magnetic flux at the sites of sunspots' anchoring depths.

Present consensus is that the sunspots originate below the solar surface. In the convective envelope, owing to differential rotation and cyclonic turbulence, the *dynamo mechanism* is supposed to wind the poloidal magnetic field structure into a toroidal magnetic field structure leading to formation of the sunspot structures. It is believed that the solar cycle and the activity phenomena are produced and maintained by such a dynamo mechanism (Parker 1955b; Babcock 1961; Steenbeck, Krause and Raddler 1966; Leighton 1960; Wang, Sheelay and Nash 1991; Fan, Fisher and Deluca 1993; Caligari, Moreno-insertis and Schussler 1995; Durney 1997; Choudhuri 1999; Stix 2002; Ossendrijver 2003; Dikpati 2005; Charbonneau 2005; Gilman 2005; Browning *et. al.,* 2006; Solanki, Inhester and Schussler 2006). Due to very high conductivity of the solar plasma (and assuming that rising flux tube does not acquire extra flux from the ambient medium), sunspots isorotate with the internal plasma and due to buoyancy raise towards the surface along the path of rotational isocontours. This implies that sunspots are very good tracers of the internal dynamics and magnetic field structure of the solar convective envelope. Hence if the sunspots with different life spans that originate at different depths have first and second observations on the surface and if one computes their initial rotation rates, then one can infer rotation rate of the internal solar plasma where the sunspots' foot points are anchored. Infact recent studies (Gokhale and Hiremath 1984; Javaraiah and Gokhale 1997; Javaraiah 2001; Hiremath 2002; Sivaraman *et. al.* 2003; Zuccarello and Zappala 2003; Meunier 2005) substantiate this fact and show that the variation of initial rotation rates of the sunspot groups with different life spans is almost similar to the radial variation of internal rotation as inferred from the helioseismology. By matching the profile of variation of initial rotation rates of the sunspot groups for different life spans and the radial variation of the internal rotation of the solar plasma as inferred from the helioseismology (Antia, Basu and Chitre 1997), it is possible to estimate different anchoring depths of the flux tubes in the convective envelope. Based on the analysis of rate of change of initial rotation rates of the sunspot groups and the radial gradient of rotation inferred from the helioseismology, Hiremath (2002, see the sections 3.3 and 4) further concludes that the spot groups that have life spans of $\geq$ 12 days may originate near base of the convective envelope and spot groups that have life spans $\leq$ 3 days may originate near the surface. However, the spot groups that have life spans 4-11 days may originate at different depths in the convective envelope.

Aims of the present study are two fold : (i) after measuring strength of magnetic flux of the sunspots that have their first and second observations on the solar disk, estimate the magnitude of magnetic field and the rate of emergence of the magnetic flux at different anchoring depths of the flux tubes in the solar convective envelope by using *anchoring depth-life span* information from the Hiremath's (2002) analysis and, (ii) to confirm whether the dynamo activity is distributed in the entire convection zone or confined to near region of the base of the convective envelope. In section 2, we present the data used and the method of analysis. The results are presented in section 3. In section 4, we present a discussion with overall conclusions that emerge from this study.

2. Data and Analysis

For the period of seven years (1999-2005), we use full disk SOHO/MDI primary (at 1.8 level) calibrated 1 minute magnetogram data for estimating the magnetic flux of the individual spots. The SOHO/MDI magnetograms are observed in Ni I 6768 i$\mathring{A}$ line (Scherrer *et. al.* 1995). We consider non-recurrent sunspots that are born and vanish on the visible part of the solar disk. The combined data set for both the solar hemispheres and in the range of 0-15 degree latitude range is considered. The reason for combining the data set in this latitude range is that the information of anchoring-depth (Hiremath 2002) of the sunspots is available. We follow the following criteria (Balthasar, Vazquez and Wohl 1986; Hiremath 2002) in selecting the spot groups. On the visible solar disk : (i) the spot groups that occur in the latitude belt $\leq \pm 15$ degrees, (ii) in order to avoid the projectional effects (especially for the life spans of 10-12 days as they emerge near the limb), the spot groups that emerge within 65 degree longitudinal distance from the central meridian are considered and, (iii) the initial rotation rates of the spot groups (computed from the first and the second observations) should lie between 11-16 degree/day in order to safeguard from the effects due to either torsional oscillations (Howard and La Bonte 1980) or due to abnormal rotation rates (Hiremath and Suryanarayana 2003) that are associated with the development of the abnormal magnetic flux and the flares. We define *life span* τ of a spot group as the total number of days between the first and the last observation on the same part of the solar disk satisfying the afore mentioned criteria. We bin the life span data in the range of 2-3 days, 3-4 days, *etc.* Further we collect the number of sunspots and their life spans in each bin and average life span is computed. In Fig 1, we illustrate the number of selected spots versus different averaged life spans. For the same period 1999-2005, we also use the positional measurements (such as latitude and longitude from the central meridian) and time of observations (the first, the second and the last observations during life time of a spot on the same part of the solar disk) from the Solar Geophysical data (USA).

The magnetograms of the first and second observations are used for measurement of initial fluxes and rate of emergence of the magnetic flux. The times of observations of the first and last observations from the Solar Geophysical data are used for estimation of different life spans of the spot groups. With the positional measurements alone, ambiguity arises especially if the two spot groups are too close. Thus it is very difficult to match the positions of the sunspots on the magnetograms. Hence in order to locate the sunspots' position on the magnetograms, we manually match with the sunspots' positions on the active region maps from the Mees Solar Observatory (http://www.solar.ifa.hawaii.edu/ARMaps/Archive/). Once we locate the position of a sunspot group on a magnetogram and keeping in mind the noise level in the MDI magnetograms is of $\sim$ 20 G (Scherrer *et. al.* 1995), from the threshold of 20 isogauss contours, we determine the boundary of a sunspot group. The MDI magnetograms provide the line-of-sight magnetic field in Gauss. Using FV interactive FITS file editor (http://heasarc.gsfc.nasa.gov/docs/software/ftools/fv/), we estimate the *average magnetic field* (with errors) that is averaged over total number of pixels considered in the detected boundary of a sunspot. Correspondingly, we determine the area of a sunspot group within a region of 20 isogauss contour. The *average magnetic flux* of a spot group is determined by multiplying the average magnetic field and the area. Irrespective of their life spans, Harvey (1993) mainly concentrated on measuring the magnetic flux of the active regions during their maximum developmental stage. Meunier (2003) computed flux-area relationship for the regions at any time during their lifetime. However present study is different in the following two crucial aspects. For different life spans : (i) the determination of strength of the *initial* average magnetic field/flux of the bipolar regions and (ii) the rate of emergence of the flux at the initial stage of development.

Since the line formation of the observed magnetograms occurs at 200 Kms above the photosphere (Jones 1989; Meunier 1999), there is every possibility that the measured sunspot flux partly contains the plage flux also. Assuming that Parker's (1955a) flux tube model is valid (i.e, strength of the flux tube is directly proportional to square root of the ambient plasma pressure; as this idea is used in the following discussion) and by knowing the observed average magnetic field and the pressure (Vernazza, Avrett and Locsa 1981) at the height of the line formation ($\sim$ 200 Kms above the photosphere), we compute average magnetic field and the flux at the photosphere. Here onwards, we call the computed average magnetic field/flux measured from the first two observations on the surface as *initial* magnetic field B_i $(i = 1, 2)$ and *initial* magnetic flux F_i $(i = 1, 2)$ of the spots. It is to be noted that time interval between the two *initial* observations are considered from the observations compiled from the Solar Geophysical Data and it is not 96 min time interval as considered in the MDI magnetograms. However, the magnetogram data is considered when the time of observations from the Solar Geophysical Data are very close to the time of observations of the magnetograms. Using *initial* two observations, we compute the *rate of emergence of the magnetic flux* (REF) from the following relation

$$REF = \frac{(F_2 - F_1)}{(t_2 - t_1)} \,, \tag{1}$$

where t_1 and t_2 are the time of observations for the first and second *initial* observations respectively. For different life spans, the time difference between the second and the first observations are collected and averaged over each life span bin. For different life-spans, the averages of such observed time differences dt with their error bars along both the axes are presented in Fig. 2. The errors are determined using the formula $\sigma/(N)^{1/2}$, where N is the total number of observed events in different life span bins and, σ is the standard deviation. One can notice from Fig 2 that, for different life spans, on average the time difference between initial two observations are $\sim$ 12 ± 2 hours.

3. Results

We find that majority of the sunspots during their initial observation on the surface are bipolar. Thus we compute the strengths of initial magnetic field and magnetic flux for each of the leading and following bipolar spots respectively. Keeping in mind the Hale's law (*i.e* in a particular solar cycle, polarities of the leading and the following sunspots in both the northern and southern hemispheres are in opposite signs) of magnetic polarity, irrespective of their polarities in the northern and southern hemispheres, we collect the strengths of initial magnetic field for the leading and the following spots separately. We adopt a similar procedure and collect the strength of magnetic fluxes for the leading and the following spots in the northern and southern hemispheres respectively. For the sake of statistical significance, both the leading and following spots data set is merged.

For the first and the second observations, after classifying into different life spans, we compute the measured strength of average magnetic field and the flux values with their respective average errors. We compute a linear least square fit to the form $y = C_1 + C_2\tau$ to both the observed data set, where y is the observed initial magnetic field/flux values, τ is the life span of the spots and, C_1 and C_2 are the unknown coefficients to be determined. For different life spans, in Fig 3, we illustrate variation of strength of the measured *initial* average magnetic field and in Fig 4., we illustrate *initial* average magnetic fluxes that are derived from *initial* two observations of the bipolar spots on the surface. The corresponding law of fits, the rank correlation coefficients and significance of the rank correlation coefficient are computed from IDL software and are over plotted on each of the figures. According IDL, the significance of the rank correlation coefficient is the two-sided significance of its deviation from zero.

One can notice in Fig 4 that the bipolar spots with their first and second observations have strong and significant negative correlations between life span and measured *initial* magnetic fluxes that are in the range of $\sim 2X10^{19} - 4X10^{20}$ Mx over the surface and are consistent with the conclusion of the previous study (Harvey 1993).

Similarly, for the bipolar spots that have first and second observations (Fig 3), we find strong and significant negative correlations between the life span and measured *initial* average magnetic field strengths that are in the range of $\sim 400 - 600$ G.

For all the life spans combined together, the maximum values of the *initial* magnetic flux and the area are determined. In Fig 5., for all the life spans, we present the normalized (with respect to their maximum values) *initial* areas versus *initial* magnetic flux of the bipolar spots for their first and second observations suggesting a strong linear relationship between these variables. We fit linear least square fit of the form $F = C_1 + C_2A$ (where F and A are the normalized flux and area values, C_1 and C_2 are the constants determined from the least square fit). With a very high probability, we find significant correlations between these variables. This area-flux relationship is useful for measuring strength of the initial fluxes for a long stretch of sunspot data set (for example, the Greenwich Photoheliographic results wherein the information of magnetic flux is not available). It is to be noted that, in the previous studies, Harvey (1993) computed the flux-area relationship when the active regions reached their maximum area and Meunier (2003) computed the flux-area relationship for the regions at any time during their life time. However, present study is for the spot groups when they are at the initial stages of the development. Moreover, slope ($log_{10}C_2$ is 2.66 for figure 5(a) and is 1.66 for figure 5(b)) of the area-flux relationship of the present study is much greater than the slopes of area-flux relationship in the previous studies. This result suggests that most of the magnetic flux contribution within the threshold 20 G contour is from the sunspots only.

The rate of emergence (REF) of magnetic flux versus the life span for both the leading and following spots is presented in Fig 6. From the law of least-square fit, the rate of emergence of magnetic flux of the bipolar spots during their *initial* developmental stage is found to be $\sim 6X10^{19}$ Mx/day for the spot groups with 12 days life span (that might originate near base of the convective envelope). However, the spot groups with 2 days life span (that might originate near the surface) emerge with $\sim 4X10^{19}$ Mx/day, nearly 65% of the emergence rate near the base.

All the results related to linear least square fits that are over plotted on different scatter plots ($\tau - B$, $\tau - Flux$, $Area - Flux$ and $\tau - dF$) such as the intercepts, slopes and correlation coefficients with probability of significance of correlation coefficient are summarized in Table 1.

4. Discussion and Conclusions

The sunspot groups have very large concentration of magnetic flux compared to the surrounding medium. Present study shows that majority of the spot groups that have first and second observations are bipolar. This suggests that sunspots that are observed on the surface are parts of emerging Ω-shaped loops from the convective envelope. Our previous study (Hiremath 2002) shows that the initial rotation rate of sunspot groups with respect to their life spans is almost similar to the radial variation of internal rotation of the solar plasma (Fig 3a and Fig 5 of Hiremath 2002) as inferred from helioseismology (Antia, Basu and Chitre 1997) suggesting that the sunspot groups of different life spans are anchored at different depths in the solar convection zone. That is the sunspot groups with life span of ~ 12 days are anchored near base of the convective envelope and the spot groups of life spans < 2 days are anchored near the surface ($\geq 0.96R_{\odot}$). The strength of magnetic field B of the flux tube (at the site of the anchoring depth) is directly proportional to the square root of the ambient plasma pressure (P) (Parker 1955a). To be precise, the relation $B_a = (P_a/P_s)^{1/2}B_s$ yields the strength of magnetic field B_a at different anchoring depths in the convection zone with the ambient plasma pressure P_a (where as B_s is the strength of the flux tube and P_s is the ambient plasma pressure at the surface). From the inferred pressure from helioseismology (Shibahashi, Hiremath and Takata 1998; Shibahashi, Hiremath and Takata 1999) and the results from Fig 3 (average surface field strength B_s of ~ 500 G), we get magnetic field strength of $\sim 10^6$ G near base of the convection zone and $\sim 10^4$ G at $0.96R_{\odot}$. These results are strikingly consistent with the helioseismic inversions (Dziembowski and Goode 1989; Basu 1997; Antia, Chitre and Thompson 2000; Antia 2002) and the MHD calculations (Choudhuri and Gilman 1987; D'Silva and Howard 1994; Hiremath 2001)

If the source of formation of the sunspots, *viz.*, the dynamo activity is confined to base of convection zone, one would expect that all the spot groups irrespective of their size and life span should have same strength of magnetic field over the surface. However, both the results of Fig 3 that are derived from the *initial* two measurements show a strong negative and significant correlation suggesting that , irrespective of their sizes on the surface, the spot groups that have longer life spans have small magnetic field strength compared to the spot groups that have shorter life spans. This is possible only when the dynamo activity is distributed everywhere in the convective envelope. This result is also consistent with the recent argument for the case of a distributed dynamo (Brandenburg 2005) in the whole region of convective envelope.

If we accept this fact that the source of dynamo activity is distributed everywhere in the convective envelope, the results presented in Fig 6 show that the rate of flux emergence from the dynamo activity varies at different depths. For example, the spot groups that have longer life spans with their foot points anchored near base of the convection zone emerge with more flux compared with the spot groups that have shorter life spans and whose foot points are anchored close to the surface. This implies that dynamo activity produces more flux near base of the convection zone compared to the dynamo activity near the surface. It would be interesting to know whether models based on the turbulent dynamo and full MHD simulations reproduce these inferred results.

It is not surprising that the sun has such a source of distributed dynamo activity in the convective envelope. The recent analysis (Donati *et. al.* 2003) of brightness and magnetic surface images of the young K0 dwarfs AB Doradus and LQ Hydrae, and of the K1 subgiant of the RS CVn system HR 1099, reconstructed from Zeeman-Doppler imaging spectropolarimetric observations shows that the dynamo activity is distributed throughout the entire convection zone.

In the present study, we measured the initial magnetic flux of the sunspots from their first observation on the surface. However, the line of sight component of the magnetic field is a combination of poloidal and toroidal parts of the magnetic field that are computed in the previous studies (Shrauner and Scherrer 1994; Ulrich and Boyden 2005). Using Mount Wilson line of sight magnetic data averaged over each carrington rotation, Ulrich and Boyden (2005) computed both the poloidal and toroidal parts of the global magnetic field structure. It would be interesting to know both of these magnetic field components from the initial magnetic field measurements for the localized field structure such as sunspots used in this study.

To conclude, analysis of the initial magnetic field/flux of the sunspot groups derived from the SOHO/MDI magnetograms yields the following results : (i) majority of the sunspots that are observed initially on the surface are bipolar, (ii) irrespective of their sizes, bipolar spots have average initial magnetic field strength of $\sim$ 500 G for different life spans, (iii) the field strength at the sites of the anchoring depths is estimated to be $\sim 10^6$ G near base of the convective envelope and $\sim 10^4$ G near the surface ($\geq 0.96 R_\odot$) and, (iv) the dynamo-a source of sunspot activity-is distributed everywhere in the convective envelope and, (v) the rate of emergence and hence the dynamo activity is strong near base of the convective envelope compared to near the surface.

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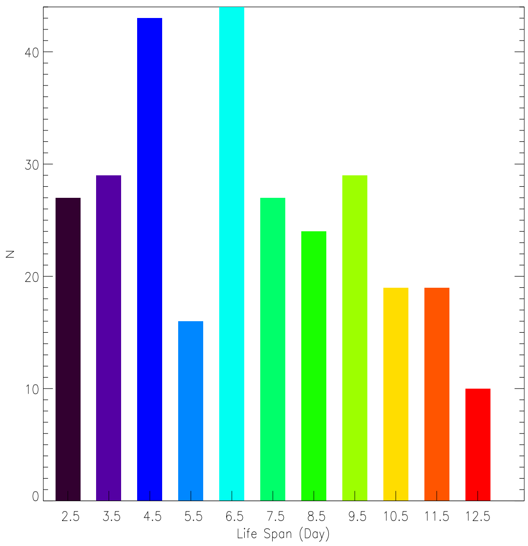

Fig. 1.— The selected number N of sunspots for different life spans are considered for the analysis.

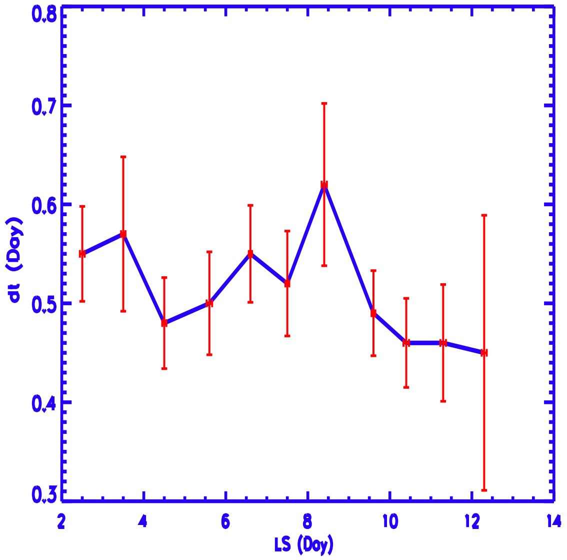

Fig. 2.— For different life spans, the average time difference dt between the initial two observations.

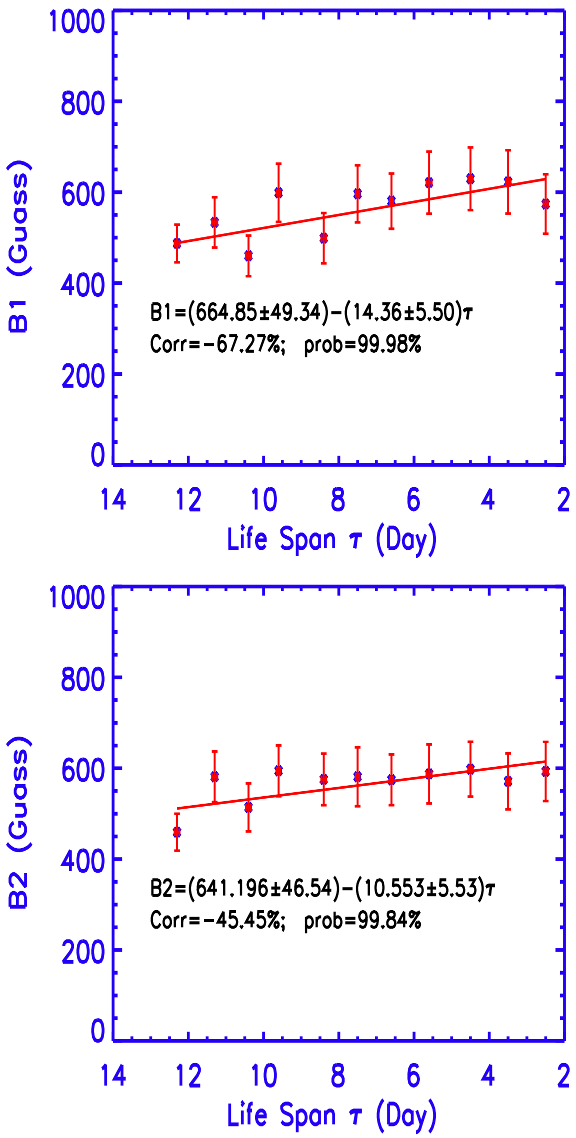

Fig. 3.— For different life spans, measured initial magnetic field strength of the bipolar spots. **(a)** The upper figure represents variation of the magnetic field strength of the bipolar spots during their first observation on the solar disk. **(b)** The lower figure represents variation of the magnetic field strength of the bipolar spots during their second observation on the solar disk. In both the illustrations, the red continuous line represents the linear least-square fit with a law $B_i = C_1 + C_2\tau$ (where $B_i, i = 1, 2$, are the measured initial magnetic field strengths,τ is life span in days and, C_1 and C_2 are the coefficients determined from the fit) is fitted to both the data set.

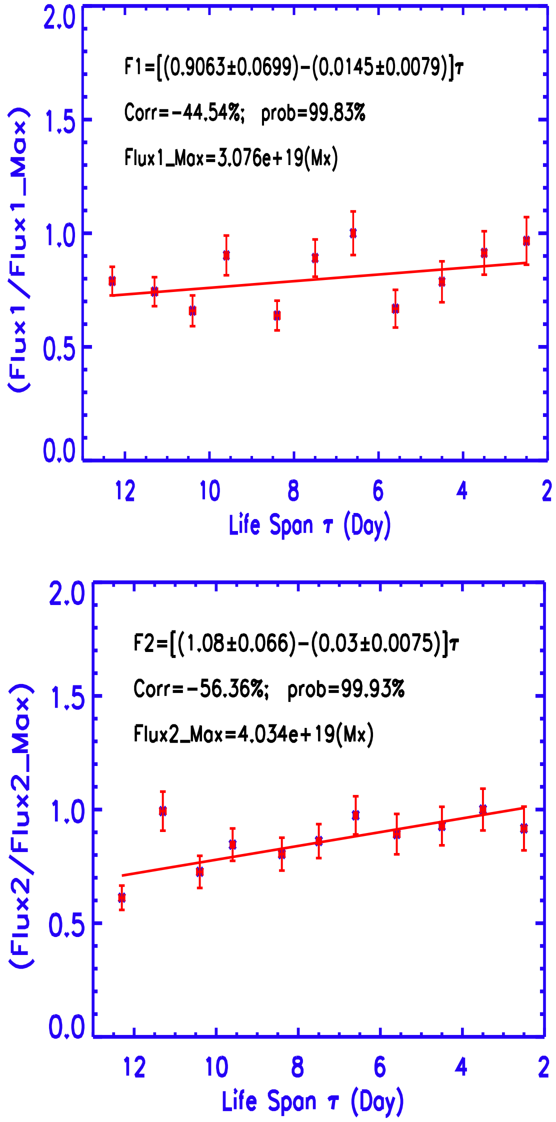

Fig. 4.— For different life spans, measured initial magnetic flux of the bipolar spots. **(a)**The upper figure represents variation of the magnetic flux of the bipolar spots during their first observation on the solar disk. **(b)** The lower figure represents variation of the magnetic flux of the bipolar spots during their second observation on the solar disk. In both the upper and lower illustrations, the normalized (with their maximum values Flux1_Max and Flux2_Max) flux values during their first and second observations respectively are presented. The red continuous line represents the linear least-square fit to the normalized flux values with a law $F_i = C_1 + C_2\tau$ (where $F_i, i = 1, 2$, are the measured initial magnetic fluxes, τ is life span in days and, C_1 and C_2 are the coefficients determined from the fit) is fitted to both the data set.

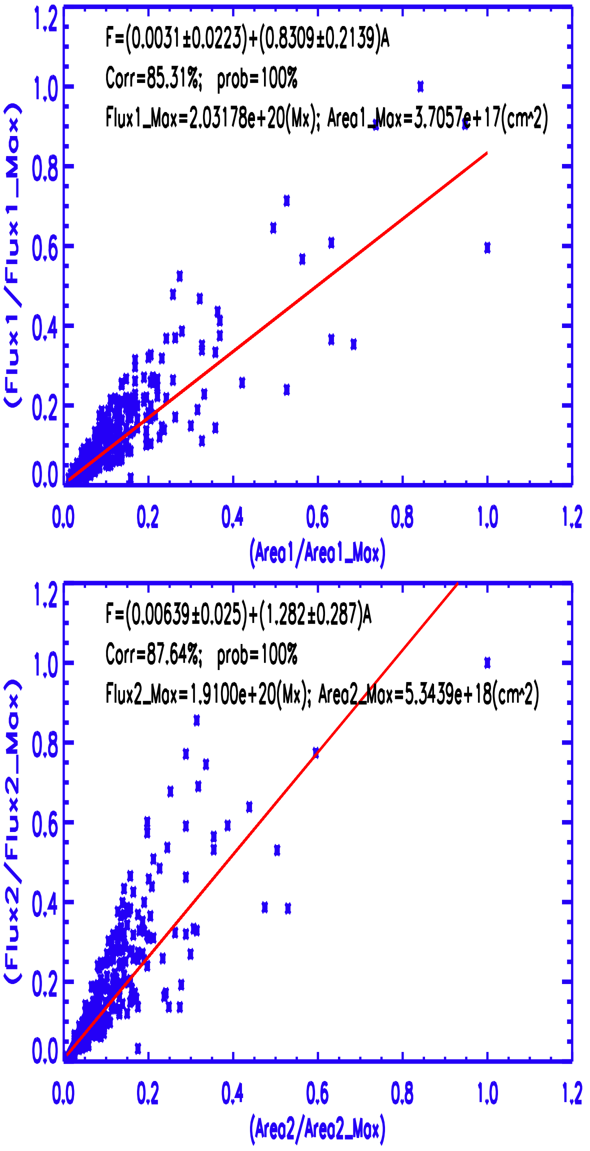

Fig. 5.— Irrespective of their life spans, measured initial area versus initial magnetic flux of the bipolar spots. Both the upper **(a)** and lower **(b)** illustrations represent the normalized (with their maximum area values Area1_Max and Area2_Max and, the flux values Flux1_Max and Flux2_Max) area and flux values during their first and second observations respectively. The red continuous line represents the linear least-square fit with a law $F_i = C_1 + C_2 A$ (where $F_i, i = 1, 2$, and A are the normalized flux and area and, C_1 and C_2 are the coefficients determined from the fit).

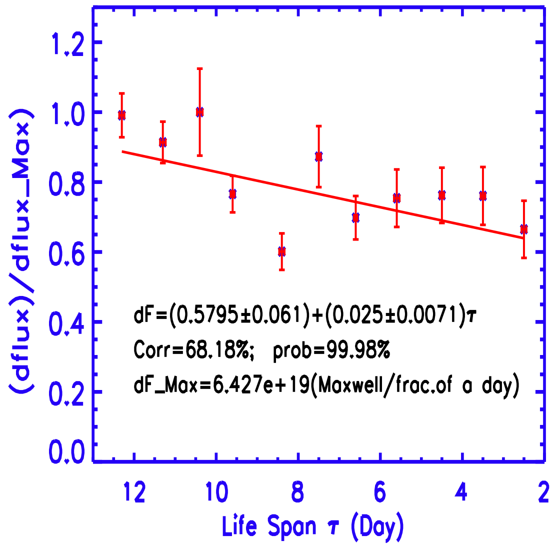

Fig. 6.— For different life spans, the normalized (with the maximum value of dF_Max) rate of emergence of magnetic flux of the bipolar spots respectively. The red continuous line represents the linear least-square fit with a law $dF = C_1 + C_2\tau$ (where dF (in the units of Mx/day) is the rate of emergence of initial flux, τ (in days) is the life span and, C_1 and C_2 are the coefficients determined from the fit) is fitted to both the data set.

TABLE 1

PARAMETERS OF THE LINEAR LEAST SQUARE FIT

Observations	Intercept	Slope	Corr	Prob
$(\tau - B)$ First	654.85±49.34	14.31±5.50	-67.27	99.98
$(\tau - B)$ Second	641.20±46.54	10.55±5.53	-45.54	99.83
$(\tau - Flux)$ First	(2.79 ± 0.22)x10^{19}	(0.04 ± 0.02)x10^{19}	-44.54	99.83
$(\tau - Flux)$ Second	(4.36 ± 0.27)x10^{19}	(0.12 ± 0.03)x10^{19}	-56.36	99.93
$(Area - Flux)$ First	(0.06 ± 0.45)x10^{19}	(455.58±115.43)	85.3	99.99
$(Area - Flux)$ Second	(0.01 ± 0.05)x10^{20}	(45.85±10.27)	87.6	99.99
$(\tau - dF)$	(3.72 ± 0.39)x10^{19}	(0.16 ± 0.05)x10^{19}	68.2	99.98

[a] For the first and second observations of $(\tau - B)$ relationship, the intercepts and the slopes are in the units of Gauss.

[b] For the first and second observations of $(Area - Flux)$ relationship, the intercepts are in units of Maxwell and the slopes are in the units of Gauss.

[c] For $(\tau - dF)$ and the first and second observations of $(\tau - Flux)$ relationships, the intercepts and the slopes are in the units of Maxwell.