# SURFACE MAGNETIC FIELDS DURING THE SOLAR ACTIVITY CYCLE*

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**Abstract.** We examine magnetic field measurements from Mount Wilson that cover the solar surface over a $13\frac{1}{2}$ year interval, from 1967 to mid-1980. Seen in long-term averages, the sunspot latitudes are characterized by fields of preceding polarity, while the polar fields are built up by a few discrete flows of following polarity fields. These drift speeds average about 10 m $s^{-1}$ in latitude – slower early in the cycle and faster later in the cycle – and result from a large-scale poleward displacement of field lines, not diffusion. Weak field plots show essentially the same pattern as the stronger fields, and both data indicate that the large-scale field patterns result only from fields emerging at active region latitudes. The total magnetic flux over the solar surface varies only by a factor of about 3 from minimum to a very strong maximum (1979). Magnetic flux is highly concentrated toward the solar equator; only about 1% of the flux is at the poles. Magnetic flux appears at the solar surface at a rate which is sufficient to create all the flux that is seen at the solar surface within a period of only 10 days. Flux can spread relatively rapidly over the solar surface from outbreaks of activity. This is presumably caused by diffusion. In general, magnetic field lines at the photospheric level are nearly radial.

## 1. Introduction

Using early Mount Wilson magnetograph data, Bumba and Howard (1965) demonstrated that the weak magnetic fields resulting from the breakup of active regions coalesce on a large scale to form global patterns of unipolar magnetic fields. These slowly expand, are stretched by differential rotation, and drift poleward to form the polar fields. Stenflo (1972) and Yoshimura (1976) used later Mount Wilson data to confirm these results and demonstrate other characteristics of the large-scale pattern, such as the latitude drift during the sunspot cycle.

Other studies of the large-scale magnetic field distribution include Levine *et al.* (1977) and Svalgaard and Wilcox (1978), both of which are concerned with the extended coronal and interplanetary fields.

Recent years have seen considerable improvements in the quality of the Mount Wilson data. A re-reduction of all the data on a uniform basis has been completed, and new parameters have been measured; for example, the distribution of weak (<2 G) magnetic fields. It is appropriate to reexamine the global properties of magnetic fields with this improved data set. All the magnetic data shown here were taken in the 5250 Å line of Fe I.

## 2. Magnetic Field Observations

### 2.1. Field strengths

Figure 1a is a plot of the latitude distribution of magnetic fields on the Sun over the last $13\frac{1}{2}$ years. The disk average field has been subtracted because instrumental bias,

* Proceedings of the 14th ESLAB Symposium on *Physics of Solar Variations*, 16–19 September 1980, Scheveningen, The Netherlands.

*Solar Physics* **74** (1981) 131–145. 0038–0938/81/0741–0131 $02.25.

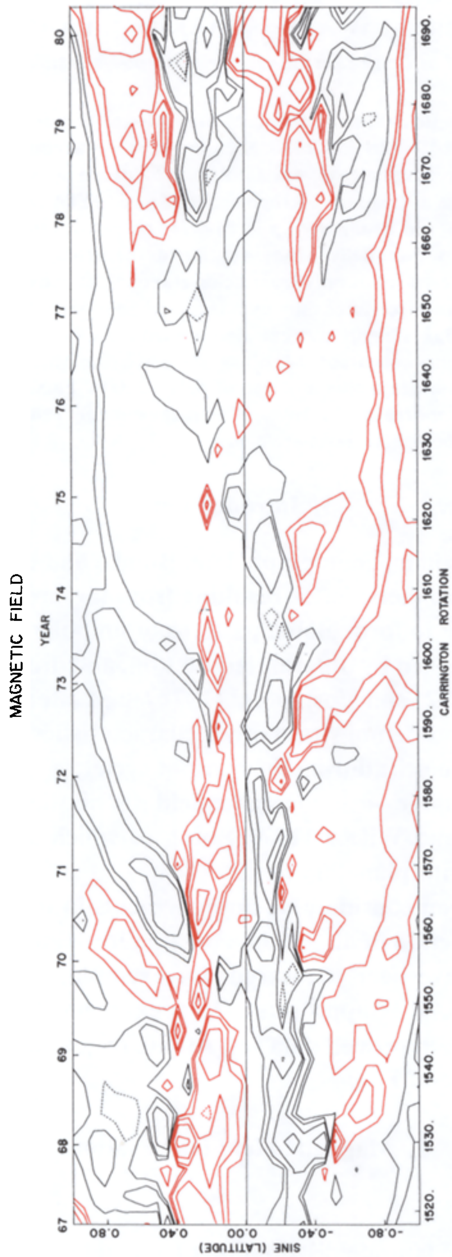
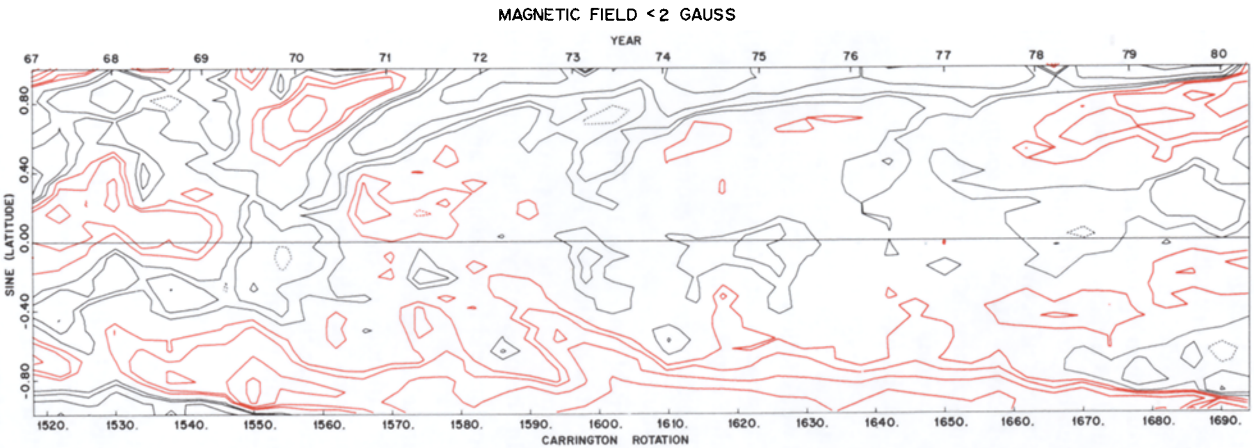

MAGNETIC FIELD
YEAR
67 68 69 70 71 72 73 74 75 76 77 78 79 80
SINE (LATITUDE)
0.80 0.40 0.00 -0.40 -0.80
CARRINGTON ROTATION
1520. 1530. 1540. 1550. 1560. 1570. 1580. 1590. 1600. 1610. 1620. 1630. 1640. 1650. 1660. 1670. 1680. 1690.

Fig. 1a.




15058

Fig. 1b.

Fig. 1a-b. Latitude distribution of solar magnetic fields. There are 34 independent zones of equal interval in sine (latitude). Plotted values are independent averages of daily observations over 4 Carrington rotations (109.1012 days). Black contours are positive; red contours are negative. Observations run from January 1, 1967 to July 3, 1980. (a) Magnetic field. Average field of all original data points in the latitude zone, minus the average of all points on the disk. Contour levels are ±0.25, 0.5, 1, 2, and 4 G. Random magnetograph noise is <0.01 G per plotted point. (b) Weak magnetic field. Average field of all original data points in the latitude zone with observed field strengths between −2 G and +2 G, minus the average of all such points on the disk. Contour levels are ±0.025, 0.05, 0.1, 0.2, and 0.4 G. Random magnetograph noise is ~0.01 G per plotted point.

particularly in the earlier years, is large enough to affect a four-rotation average. Since 1971 the instrumental bias has comprised a constant field of +0.25 G and an annual sinusoid of 0.2 G peak to peak. The origin of these components is unknown. All latitudes are equally affected by this background zero variation.

The sunspot latitudes are characterized in each hemisphere by the preceding spot polarity for that hemisphere and spot cycle. The magnetic field gradient is larger on the poleward edge of the active zone than on the equatorward edge. The following spot polarity is usually absent, but does appear on the poleward edge of the active zone during the rise in spot number from minimum to maximum (e.g., since mid-1977) and during major outbreaks of activity (e.g., June and July 1970 in the north, August 1972 and May to October 1974 in the south). The strength of the preceding field marking the sunspot zones also increases at these times. A plot of Stanford Solar Observatory data covering the past 4 years appears similar to the same interval of Mount Wilson data (Hoeksema *et al.*, 1980).

Magnetic flux is equally balanced between positive and negative when it emerges at the surface. One might expect the average field in the active latitudes to be zero, rather than strong preceding and weak following. The explanation is that preceding flux is distributed over a narrower range of latitudes than following flux. Thus, the field strength (flux per area) is higher in preceding areas than in following areas, and the average field is as observed. The classic $\alpha$p spot group configuration is a simple example of the required flux distribution.

The polar fields are also clearly visible in Figure 1a. The polar field reversals of spot cycle 20 are at the epochs reported by Howard (1974a), mid-1969 in the south and mid-1971 in the north. The south polar field also reversed before the north in spot cycle 19 (Babcock, 1959). In the present cycle, the north polar field has just reversed (mid-1980). The south polar field is weakening and will probably reverse within one year (mid-1981).

Figure 1a shows that the polar fields are entirely formed by the movement of magnetic field from the sunspot latitudes to the poles. This formation is not continuous, but episodic. Poleward moving fields originate only at those few times when following spot polarity is seen near the sunspot latitudes.

When moving field or like polarity arrives at the pole, the polar field strengthens. Between times of new field arrival, the polar field slowly decays. If field were not supplied to the pole from the spot latitudes, the polar fields would disappear in a time of 10 to 20 years.

The transport of field poleward does not occur by diffusion. The center of gravity of the field moves poleward, not just the leading edge. After the moving field passes, the lower latitudes are devoid of field; field strengths are $<\frac{1}{4}$ that in the moving band. In the south at Carrington rotation 1535 and in the north at rotation 1575, for example, following polarity fields are moving poleward, but the field gradients are equal on both poleward and equatorward edges. The fields should diffuse in both directions at equal rates. Because the fields move only poleward, diffusion is not the motive process. Rather, the fields must be carried poleward by some form of meridional flow.

The apparent velocity of poleward motion of magnetic fields is not constant during the spot cycle. During the rising phase of the cycle, when the poleward moving field is of opposite polarity to the existing polar field, the apparent velocity is 5–10 m $s^{-1}$. During the declining phase of the cycle, when the poleward moving field is of the same polarity as the existing polar field, the apparent velocity is 15–20 m $s^{-1}$. This change may be a real variation in the velocity of the flow transporting the fields, but is more likely an artifact of the differing polarity relation of polar and moving fields. As Bumba and Howard (1965) pointed out, the magnetic fields of the Sun move on large scales as if like polarities attract and opposite polarities repel. Their explanation still seems valid: opposite polarities appear to repel because field elements cancel at the polarity boundary. By comparison, like polarities then appear to attract.

### 2.2. Weak magnetic fields

Figure 1b shows the latitude distribution of weak magnetic fields on the Sun. The weak fields are defined as those original data points of the daily magnetograms with measured fields between −2 and +2 G. Published Mount Wilson magnetograms usually do not display fields weaker than 5 G, but Howard (1974a) has shown that 2 G plots of the Mount Wilson data do have large-scale order. Random magnetograph noise has a root-mean-square amplitude of 0.5 to 1.0 G, as measured from magnetograms with the KD*P modulator turned off. Again, the daily disk average of all weak field points has been subtracted from the data in Figure 1b. In this case, the instrumental bias has a constant value of +0.05 G and an annual sinusoid of ~0.08 G peak to peak.

The contour levels of Figure 1b are one-tenth those of Figure 1a, as the total flux in the weak fields is much less than in the strong fields, even when averaged over large intervals in space and time.

In Figure 1b the field strengths of the spot latitudes are relatively weaker compared to the polar latitudes than in Figure 1a. The weak fields in the active zones must be more uniformly distributed than the strong fields.

The polar fields are very prominent in the weak field, as are the episodes of poleward moving field. Between injections of new field, the polar field is observable to latitudes as low as 40°, at the 0.025 G level. Only one episode of moving field is seen in Figure 1b that was not obvious in Figure 1a, in the south at Carrington rotation 1575.

The relatively high ratio of weak field to measured average field strength in the polar field (as large as 0.4 throughout 1971–1974) is evidence that the true average polar field strength is low. Howard (1977) reached this conclusion from a more detailed analysis. Note also the polar field strength maximizes in the weak field plot about 2 years before the maximum in the average field. This implies the polar field slowly builds in strength over a period of years.

Perhaps the most interesting result of Figure 1 is that large-scale magnetic fields on the Sun originate only in the spot zones. This is true for both average field and weak field structures. No other source of fields produces large-scale organization in the surface fields.

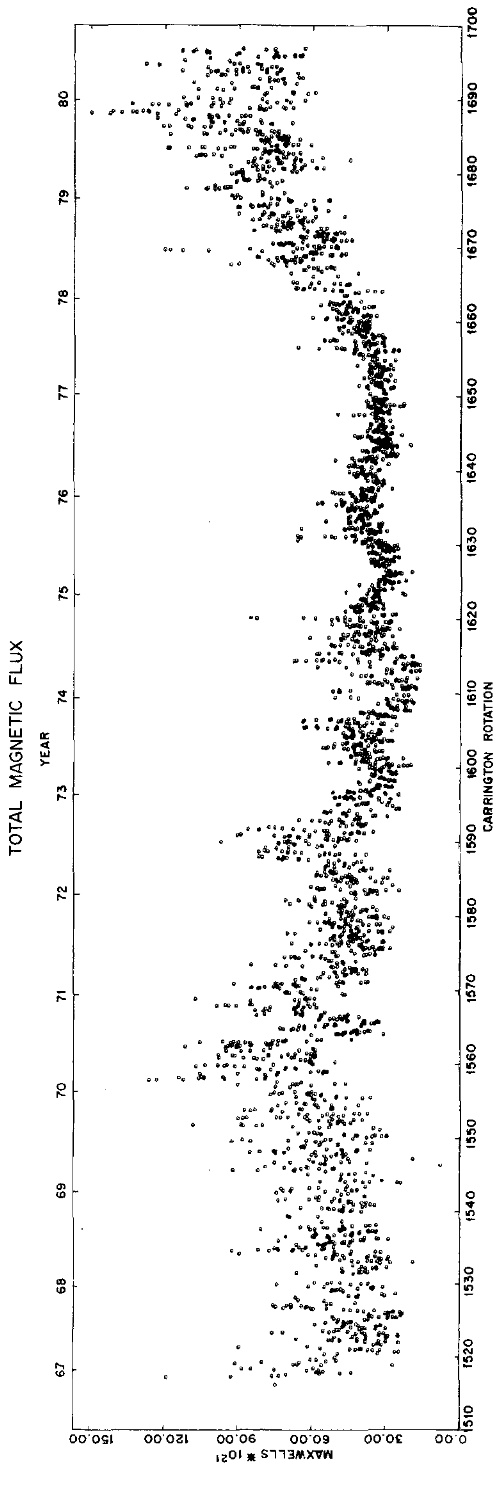

TOTAL MAGNETIC FLUX
YEAR
CARRINGTON ROTATION
MAXWELLS * 10^21

Fig. 2a.

15060

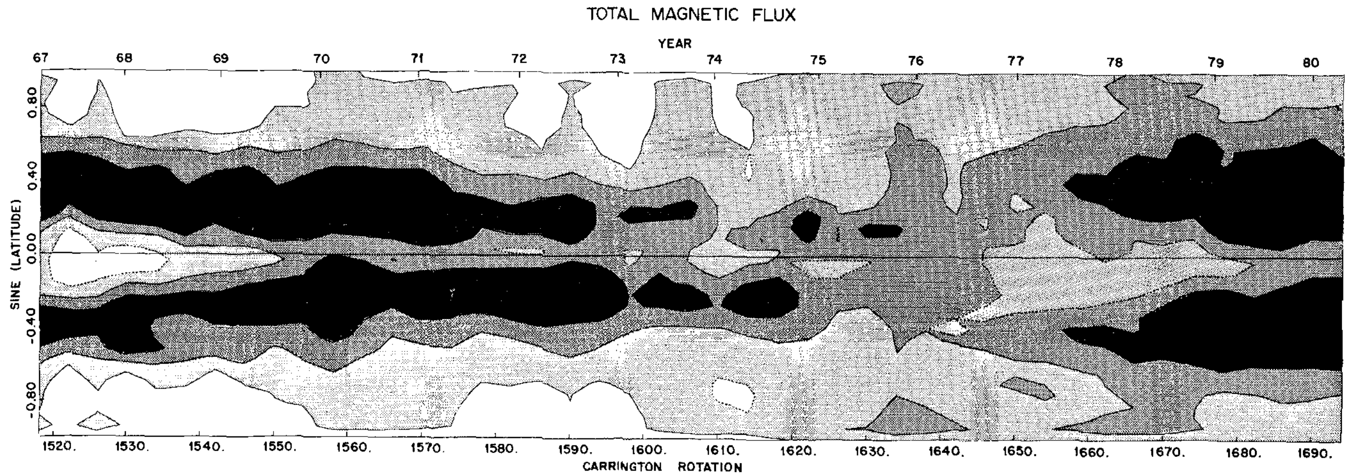



Fig. 2b.

Fig. 2a-b. Magnetic flux on the solar surface. (a) Daily observed magnetic flux. Total flux $F(=|F_+|+|F_-|)$ observed on the disk. No corrections are applied. Decreases in the magnetograph aperture (Howard, 1976) increase the amplitude of the fluxes after January 1975 by ~20% relative to fluxes before October 1974. (b) Latitude distribution of total flux. Plot format is the same as Figure 1. The total flux $F(=|F_+|+|F_-|)$ in each of 3 longitude bins (W32.0–44.9, W6.8–E6.8, and E32.0–44.9) is corrected for the disk average magnetic field and the projection angle of the magnetic field lines (assumed radial). The corrected flux in the 3 bins is summed and multiplied by a constant to represent the total flux in the latitude zone over 360 degrees of longitude. Contour levels are 2, 4, 8, 16, and $32 \times 10^{21}$ Mx.

### 2.3. Total flux

Figure 2a shows daily values of the measured full disk total magnetic flux for the $13\frac{1}{2}$ year interval. Total flux is defined as $F_T = |F_+| + |F_-|$, with $F_+$, $F_-$ the positive and negative fluxes. Instrumental improvements in September 1969 and July 1974 reduced the magnetograph noise level and lowered the variation of the flux values.

Also, the measured flux depends on the size of the magnetograph aperture (Howard, 1976). The aperture at Mount Wilson was changed from 17.5 to 12.5 arc sec in early 1975, and the fluxes after that time are systematically ~20% larger as a result. The measured flux varies with aperture because larger apertures have a greater probability of including both positive and negative field elements and thus measuring an incorrect, low field strength. The fraction of flux missed by averaging in the aperture will vary systematically during the spot cycle if the mixing of field element polarities on scales smaller than the aperture varies cyclically.

The total flux varies by only a small factor from spot minimum to maximum. The ratio was ~1:2 in cycle 20 (Howard, 1974b) and ~1:3 in cycle 21, rising from $3\times10^{22}$ Mx in 1976 to $9\times10^{22}$ Mx in late 1979. A similar ratio for cycle 21 was found in the Kitt Peak data (J. W. Harvey, private communication). The dispersion in the daily values changes by a larger factor, ~5 (in Mx) from $6\times10^{21}$ to $3\times10^{22}$ Mx, or from ~18% of the average flux at minimum to ~32% of the average at maximum. This is a natural consequence of the fact that the longitude distribution of active regions is less uniform than that of the quiet network.

Figure 2b shows the latitude distribution of the total magnetic flux on the Sun. To construct Figure 2b, data in individual latitude-longitude areas were corrected for disk average magnetic field, the projection angle of the field with respect to the line of sight (assuming radial field lines), and multiplied by a constant to represent the total flux over 360 degrees of longitude. The correction for the disk average field assumes it is an instrumental bias, which is not always true, but the correction is generally only a few percent in any individual area.

Figure 2b is dominated by the spot latitudes. The equatorward drift of the active zones (Spörer's law) is clear. The strong concentration of flux near the equator was noted previously by Howard (1974b); this holds true even during spot minimum. Table I gives the latitude distribution of total flux averaged over the $13\frac{1}{2}$ year interval. It shows 69% of the flux on the Sun is found in the 47% of the area between $\pm28.1$ degrees latitude. The flux distribution peaks at $\pm15$ degrees, where the flux per unit area is 6 times larger than at the pole. Of course, this ratio varies through the spot cycle.

Figure 2b also shows that at times flux spread rapidly to all latitudes. Examples are at Carrington rotations 1555, 1590, and 1600. These events are not caused by changes in the instrument, but correlate well with the numbers of active regions on the Sun. When active regions are more numerous, there is a higher probability of regions appearing at higher latitudes. Also, flux spreads over a broad latitude range as these regions break up. However, this rapid spreading includes both positive and

TABLE I

Average of daily values, January 1, 1967 to July 3, 1980

| Latitude (degrees) | Total magnetic flux ($\times 10^{21}$ Mx) | Flux increase ($\times 10^{20}$ Mx day$^{-1}$) | Flux decrease ($\times 10^{20}$ Mx day$^{-1}$) |
|---|---|---|---|
| 73.0 | 1.8 | 3.6 | −3.8 |
| 65.8 | 2.8 | 3.3 | −3.3 |
| 58.5 | 2.7 | 2.9 | −3.1 |
| 52.6 | 2.7 | 2.8 | −2.9 |
| 47.3 | 2.9 | 2.9 | −2.8 |
| 42.6 | 3.2 | 3.0 | −3.1 |
| 38.1 | 3.8 | 3.7 | −3.6 |
| 34.0 | 4.5 | 4.1 | −4.8 |
| 30.0 | 5.6 | 5.3 | −5.6 |
| 26.2 | 7.3 | 6.8 | −7.2 |
| 22.5 | 8.9 | 9.6 | −9.4 |
| 18.9 | 10.7 | 10.7 | −11.6 |
| 15.3 | 11.5 | 12.6 | −12.6 |
| 11.9 | 10.7 | 11.6 | −12.5 |
| 8.5 | 8.5 | 9.6 | −9.9 |
| 5.1 | 6.3 | 7.0 | −7.5 |
| 1.7 | 4.5 | 5.0 | −4.9 |
| −1.7 | 4.3 | 5.0 | −4.4 |
| −5.1 | 5.8 | 7.6 | −6.5 |
| −8.5 | 7.9 | 10.4 | −9.9 |
| −11.9 | 10.0 | 12.3 | −12.1 |
| −15.3 | 10.8 | 12.0 | −12.1 |
| −18.9 | 9.4 | 9.5 | −9.3 |
| −22.5 | 8.2 | 8.0 | −8.3 |
| −26.2 | 7.1 | 6.5 | −8.5 |
| −30.0 | 5.9 | 5.4 | −6.7 |
| −34.0 | 4.5 | 4.0 | −4.1 |
| −38.1 | 3.5 | 3.4 | −3.5 |
| −42.6 | 3.1 | 3.2 | −3.1 |
| −47.3 | 2.8 | 3.1 | −2.9 |
| −52.6 | 2.7 | 3.0 | −2.8 |
| −58.5 | 2.7 | 3.2 | −3.0 |
| −65.8 | 2.9 | 3.7 | −3.6 |
| −73.0 | 1.9 | 4.1 | −3.9 |
| Total | 191.9 | 208.9 | −213.3 |

negative field elements and contributes nothing to the average magnetic field. These events are not seen in Figure 1 for this reason. There is a difference between this rapid, chaotic motion of flux and the slower, organized redistribution of magnetic polarity. The spreading of flux to the poles looks very rapid in Figure 2b because the data are averaged over 109 days; in plots of 10 day averages, the time for spreading is found to be between $\frac{1}{2}$ and 1 year.

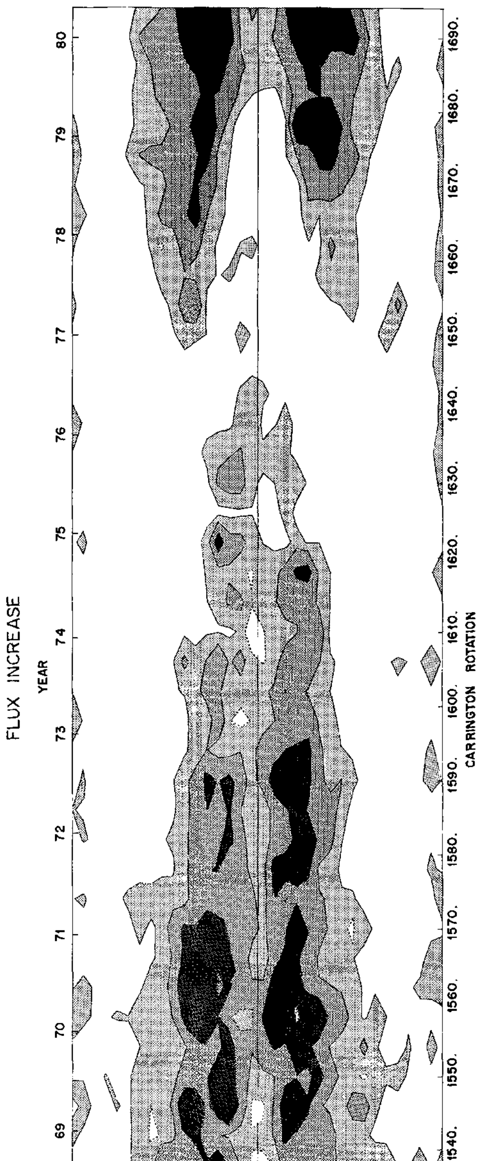



Fig. 3a.

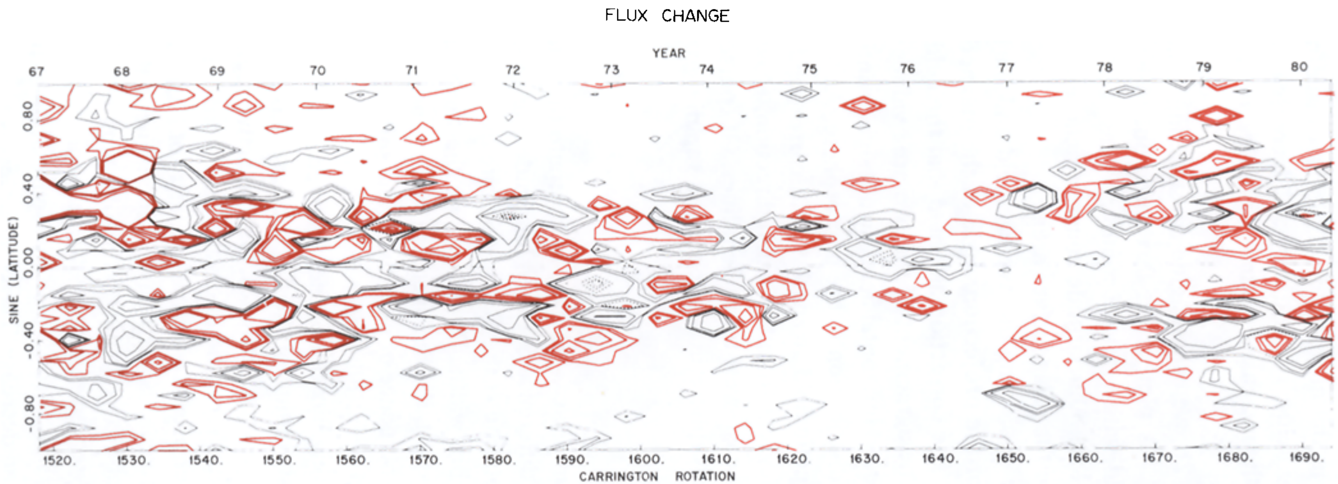



Fig. 3b.

Fig. 3a-b. Rate of change of magnetic flux on the solar surface. Plot format is the same as Figure 1. (a) Flux increase. The total flux ($F_T = |F_+| + |F_-|$) in each of 3 longitude bins (W32.0–44.9, W6.8–E6.8, E32.0–44.9) is corrected for the disk average magnetic field and the projection angle of the magnetic field lines (assumed radial). The west flux is then reduced by the center flux measured 3 days previous and the center reduced by the east of 3 days previous. The sum of the positive differences obtained is multiplied by a constant to represent the total flux increase in the latitude zone over 360 degrees of longitude. Contour levels are 4, 8, 16, and $32 \times 10^{20}$ Mx day$^{-1}$. Random magnetograph noise is $\sim 1 \times 10^{20}$ Mx day$^{-1}$ $\times$ secant (latitude) per plotted point. (b) Flux change. The sum of positive and negative flux differences obtained by the procedure described above is multiplied by a constant to represent the net change in flux in the latitude zone over 360 degrees of longitude. Contour levels are $\pm 1$, 2, 4, $8 \times 10^{20}$ Mx day$^{-1}$. Random magnetograph noise is $\sim 5 \times 10^{19}$ Mx day$^{-1}$ $\times$ secant (latitude) per plotted point.

The polar fields seen so clearly in Figure 1 do not appear in the total flux plot. This is a further statement of the fact that the polar fields contain only a small amount of flux. The strong appearance in the magnetic field plot is caused by the nearly unipolar composition of the polar fields. The equatorward decrease of field strength and increase of total flux shows the increased mixing of positive and negative fields at lower latitudes.

From the data used in Figure 2b, we can imagine constructing a plot of the net flux $F_N$, defined as $F_N = F_+ + F_-$. A plot of net flux turns out to be identical to Figure 1a, the plot of average field, with a ratio of contour values of $\sim 1.6 \times 20^{21}$ cm$^2$ (0.25 G corresponds to $4 \times 10^{20}$ Mx). Our latitude zones are chosen to have equal areas of $1.8 \times 10^{21}$ cm$^2$, 1/34th of the solar surface area.

The only significant difference in plotting the average field and the net flux was that the fluxes were corrected for the projection angle of the magnetic field lines with respect to the line-of-sight. The correction assumed that the field lines in the photosphere are purely radial. The agreement of the two area values within 10% shows that this assumption is correct. Horizontal fields do not significantly contribute to the large-scale magnetic field distribution in the photosphere. At 60° latitude, a 10% variation in measured magnetic field strength would correspond to a north–south field line tilt of only ~10 degrees from the radial direction. Howard (1974c) found even smaller angles for the east–west tilt of field lines. Of course, horizontal field lines are present in the photosphere in sunspots and rapidly growing active regions.

### 2.4. Flux change

The corrected fluxes used in Figure 2b can be used to compute the rate of change of flux on the Sun. The longitude difference between longitude bins (38°.2) is nearly equal to that produced by solar rotation at the Carrington rate over a 3 day interval (39°.6). The error is 10% of the bin width. By comparing the fluxes in the same area of the Sun measured 3 days apart, the flux increase or decrease is found.

Flux increase is caused by the emergence of new flux at the surface or the motion of existing flux into the observed area. Flux decrease is caused by the decay of existing flux or the motion of existing flux out of the observed area.

Figure 3a shows the latitude distribution of the flux increase. Like total flux, the flux increase is concentrated in the sunspot latitudes. Only in active region latitudes do large quantities of flux appear in short time intervals. This is true in a long term average (Table I) and in the short term, as seen in the similarity of Figures 2b and 3a.

The ratio of total flux to flux increase is ~10 days. The magnetic flux seen at a given time is equal to the amount of flux eruption on the Sun summed over a 10 day interval. Because the total flux observed remains relatively constant, existing flux must be decaying at an equal rate. This is confirmed by Figure 3b, which shows the flux change – the sum of increase and decrease. The contour levels are $\frac{1}{4}$ those of the flux increase plot. The equality of flux increase and decrease rates lead to low net values. This is also shown in Table I.

It is obvious that the long term average rates of flux increase and decrease must be equal or the total flux on the Sun would change monotonically. It is possible that this balance may arise from, for example, a mixture of occasional large flux increases followed by frequent small flux decreases. That is, the relative frequencies of occurrence of increases and decreases may differ. We find that increases and decreases occur in equal numbers and with equal amplitudes. There is no systematic bias in the ratio of increases to decreases. Figure 3b in effect shows what little variation from uniformity there is in flux change.

## 4. Conclusions

(1) The active region latitudes are characterized by the preceding spot polarity for each hemisphere and spot cycle.

(2) The polar magnetic fields are built and subsequently reversed by isolated episodes of magnetic field drift from the active latitudes.

(3) Poleward field drifts average about 10 m $s^{-1}$ in latitude. They are slower early in the spot cycle and faster later in the cycle.

(4) The poleward motion is not a diffusion process. Field is moved bodily by a directed flow.

(5) The weak ($<2$ G) fields show basically the same patterns as the stronger fields. All organized large scale magnetic fields originate in the active latitudes.

(6) The true field strength of the polar fields is no more than a few gauss.

(7) The variation of total flux on the Sun is only about a factor of 3 from spot minimum (1976) to an active maximum (1979).

(8) Magnetic flux is highly concentrated toward the equator. The flux in the polar fields is a small fraction ($\sim 1\%$) of the total flux on the Sun.

(9) Flux can spread rapidly (50–100 m $s^{-1}$) over the solar surface from outbreaks of active regions without segregating into separate unipolar latitude zones.

(10) Horizontal (non-radial) fields are not important to the large-scale organized magnetic fields in the photosphere.

(11) The rate at which flux appears on the Sun is sufficient to replace the total flux present in about 10 days.

## 5. Discussion

In this paper we have examined the Mount Wilson solar magnetic data over the past $13\frac{1}{2}$ years in one way only. We have ignored all longitude differences and possible short-term variations in order to study gross, long-term aspects of the activity cycle. This gives us a view of the cycle that is somewhat incomplete, and we plan more detailed studies in the near future. Nevertheless, this analysis has provided us with new results which relate to the physics of magnetic field appearance, motion, and dissipation at the solar surface.

Ephemeral regions appear to contribute a large fraction of the magnetic flux that appears at the solar surface (Golub *et al.*, 1979). Because the ephemeral regions have a much broader latitude range than do active regions, we are able to distinguish their contribution to the large-scale magnetic field patterns from that of the active regions. In Figure 1 we see no contribution to the field patterns from any place on the Sun other than the active region latitudes, so we conclude that the contribution of ephemeral regions to any patterns seen in Figure 1 – even the weak fields of Figure 1b – is negligibly small. This is understandable since the scale of the ephemeral regions is so small. It seems likely that a region that small will disappear by cancelling a portion of the pre-existing field before it can coalesce with other regions to form large patterns.

The large-scale flow of fields to the poles, which is seen in Figure 1, is the motion of the extended, high-latitude unipolar regions described by Bumba and Howard (1965). Since the fields do not spread out in latitude but move toward the poles with little decrease in magnitude (the weaker fields in Figure 1b actually increase in magnitude as they approach the poles because of the breakup of the stronger fields), we conclude that there is a movement of the field from low to high latitudes, not a diffusion of field elements as has been proposed (Leighton, 1964). We may speculate that the motion of the field lines – only those of following polarity – results from a large-scale circulation pattern, perhaps below the surface, that has a meridional component. Whatever forms the polar field is a directed motion, not the accidental effect of random motions at the surface.

We presented above further evidence that the polar field is quite weak – a few gauss – not 6 G or more proposed previously (Svalgaard *et al.*, 1978; Suess *et al.*, 1977). It is also of interest to note that the total flux in the pole-most zone of Table I corresponds very nearly to a field of 1 G. This is also the field strength seen at the poles in Figure 1a. Thus the polar field is to a good approximation unipolar – keeping in mind the definition of unipolar and the size of our aperture (12.5 arc sec).

The high rate of flux appearance and disappearance at the solar surface compared to the flux present is an unexpected result of this work. This ratio is set by the rate of dissipation of fields, and evidently this is greater than had been believed. The amount of energy involved in the field dissipation can be estimated by assuming a length over which the field cancellation takes place. The flux decrease at the surface from Table I is about $2.3\times10^{17}$ Mx s$^{-1}$. This translates to $9.2\times10^{18}\times L$ erg s$^{-1}$, where $L$ is the length over which the fields cancel. (This assumes that all the field exists as 1000 G field-strength bundles.) Spread over the solar surface this is $1.5\times10^{-4}\times L$ erg cm$^{-2}$ s$^{-1}$. If this dissipation takes place over granular or supergranular scales, $10^8$ or $10^9$ cm, then it represents a rather small energy source, about $10^4$ to $10^5$ erg cm$^{-2}$ s$^{-1}$. But if the fields are annihilated over a large fraction of a solar radius, the energy flux at the surface becomes much larger. The field annihilation is concentrated in the active latitudes, where strong opposite polarity fields occur close together. Weak, unipolar fields like the polar fields have much longer lifetimes before decay.

## Acknowledgements

This work was supported in part by the National Science Foundation (Grant AST 77-224652), the Office of Naval Research (Contract N00014-76-C-0113), and the National Aeronautics and Space Administration (Grant NGR 09-140-015). The dataset used in this study could not have been accumulated over the years without the dedicated assistance of the observers: T. A. Cragg, J. M. Adkins, T. S. Gregory, S. P. Padilla, L. S. Webster, and M. G. Utter. Much of the computer programming was done by J. E. Boyden.

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