# STUDIES OF SOLAR MAGNETIC FIELDS

## II: *The Magnetic Fluxes**

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**Abstract.** Magnetic flux data from the Mount Wilson magnetograph are examined over the interval 1967–1973. The total flux in the north is greater than that in the south by about 7% over this interval, reflecting a higher level of activity in the northern hemisphere. Close to 95% of the total flux is confined to latitudes equatorward of 40°, which means that close to 95% of the flux cancels with flux of opposite polarity before it can migrate poleward of 40°. It is pointed out that a consequence of this flux distribution is that ephemeral regions must make a negligible contribution to the long-term large-scale magnetic flux distribution. A broad peak in the total flux may be seen centered about one year after activity maximum in the north below 40°. In the south there is a very sharp increase in flux about the same time. In the north, several poleward migrations of flux may be seen. Two of these may correspond with the two poleward prominence migrations seen by Waldmeier. In both the north and the south there is a poleward migration of negative flux about the time of activity maximum. Poleward flux drift rates are about 20 m s$^{-1}$.

## 1. Introduction

In Paper I of this series (Howard, 1974) a description of the Mount Wilson 150-ft Solar Tower magnetograph scanning and data systems was given, along with a chronology of changes to the instrumentation. Average magnetic field strengths over a 7-yr interval were presented. Polarity changes in various latitude zones during this interval were discussed.

In this paper the same basic data are separated into magnetic flux measurements and analyzed for large-scale behavior. The same 7-yr interval is used – January, 1967, to December, 1973. The magnetic measurements were all made with the Fe I $\lambda$5250.2 line.

## 2. Magnetic Flux

### 2.1. DEFINITION OF FLUX

The solar magnetograph is basically a flux measuring device. We infer average magnetic field strengths by dividing the measured flux by the area of the aperture. Any single magnetograph measurement is that of the magnetic flux within the aperture.

Naturally these flux measurements are underestimates unless the aperture is equal to or smaller than the characteristic length over which magnetic polarities will be found to be reversed. These observations were made with a 17 arcsec square aperture (using an image slicer.) When the magnetic elements within the aperture are all of the

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same polarity, the flux measurement will be accurate; when the elements are not of the same polarity, the flux will be an underestimate.

The Mount Wilson magnetograph measures only the longitudinal component of the magnetic fields within the aperture. Corrections are made to the raw signal for the brightness, because the magnetic signal is proportional to the brightness. Aside from this, no corrections are made to the data except as noted below. For example, no hidden corrections are made for any geometrical effects of field line orientation or projection, or for the weakening of the $\lambda 5250$ line in magnetic elements (Howard and Stenflo, 1972).

### 2.2. ADVANTAGES OF THE FLUX DATA

Magnetic flux is physically more fundamental a quantity than the magnetic field strength. The true field strength depends upon the element size, which is unknown.

In dealing with the total flux

$$F^T = |F^+| + |F^-|, \tag{1}$$

we have a quantity which is independent of any possible instrumental zero drift. As we mentioned in Paper I, the zero drift is generally less than a few tenths of a gauss for a single magnetogram.

The flux measurements allow us to treat separately the fields of each polarity. Each individual measurement gives us either a positive or a negative flux determination of some magnitude, and these may be summed separately for each polarity over the various zones of the solar disk.

### 2.3. NOISE

The principle disadvantage of the flux data is that it may be affected more by signal noise than is the average field strength. In an area of the Sun where there is no magnetic field, the measured average field strength will be zero, as it should be, but the signal noise will contribute both positive and negative flux values. In regions of the Sun where there are magnetic fields, the signal noise should not significantly affect the results since the total flux of any polarity over an area should contain as many points made accidentally higher by the noise as those made accidentally lower, and the sum will be unaffected. Estimates will be made below of this contribution to the flux values.

## 3. The Fluxes Averaged over the 7-Year Interval

### 3.1. THE NORTH-SOUTH DIFFERENCES

In Table I the total flux values from Equation (1) are listed for the various latitude zones, separately for the north and south hemispheres. The second and third columns are the measured flux values. The next two columns give the measured values divided by the cosine of the average latitude of the zone. This corrects the flux approximately, assuming that the fields are radial to the Sun. The last two columns give the percent-

TABLE I

Daily average of total magnetic flux (January, 1967–December, 1973) Mx × $10^{20}$

| Latitude (deg) | $F^T$ measured | | $F^T/\cos B$ | | % for each hemisphere | |
|---|---|---|---|---|---|---|
| | N | S | N | S | N | S |
| > 70 | 1.20 | 0.83 | 6.91 | 4.77 | 2.3 | 1.7 |
| 61–70 | 3.76 | 3.15 | 8.90 | 7.45 | 2.9 | 2.6 |
| 51–60 | 7.41 | 6.85 | 12.92 | 11.94 | 4.3 | 4.2 |
| 41–50 | 12.26 | 11.88 | 21.37 | 20.71 | 7.0 | 7.4 |
| ⩽ 40 | 238.0 | 222.3 | 253.3 | 236.6 | 83.5 | 84.1 |
| Totals | 262.6 | 245.0 | 303.4 | 281.5 | 100 | 100 |

ages of flux in each latitude zone from the previous two columns, separately for each hemisphere.

On the whole the activity in the north was greater than that in the south during this interval. This is reflected in the 7% difference in total flux values between the two hemispheres. This percentage difference between the hemispheres is greatest at the highest latitudes. Above 70° there is about one third more flux in the north than in the south. In the 41°–50° range the difference is only about 3%.

One may from Table I make an estimate of the influence of noise on these total flux values. About 6% of the surface area is found poleward of 70° lat. From columns 2 and 3 of Table I we find that about 0.4% of the total measured flux is found there. If this flux were *all* noise, and the same noise were spread over the entire disk, then about 6% of the total flux for the whole disk would be due to noise. This is a gross overestimate for two reasons: (1) The flux poleward of 70° lat. is not due entirely to noise, as will be seen below in the analysis of the poleward drift of flux. (2) The noise level is higher at the high latitudes than at the low latitudes because of the lower light level near the limb. It is fair to estimate that 1 or 2% of the total flux results from noise.

### 3.2. LATITUDE DISTRIBUTION

From Table I it is clear that nearly 85% of the total flux is confined to latitudes equatorward of 40° in both hemispheres. This value is an *underestimate* for several reasons. (1) The $\lambda 5250$ line underestimates fluxes near the disk center by nearly a factor 2 (Howard and Stenflo, 1972). Fluxes near the limb are unaffected. This raises the flux below 40° by nearly 5%. (2) In the active-region latitudes we are more likely to find mixed magnetic polarities within the 17″ aperture of the magnetograph, thus we are more likely to neglect to measure such flux. (3) In the active region latitudes the actual field strengths are greater, including sunspot fields. The $\lambda 5250$ line is very sensitive to magnetic fields, and strong fields will tend to saturate the signal so that such flux will be lost.

It is difficult to estimate the systematic differences in flux at high and low latitudes from the second and third explanations above, but considering everything it seems fair to guess that close to 95% of the magnetic flux is found between ±40° latitude.

This indicates that close to 95% of the magnetic flux that emerges in active regions cancels with fields of opposite polarity and disappears from the solar surface before these fields have a chance to migrate to latitudes higher than 40°. This assumes a model such as the Babcock dynamo model (Babcock, 1961), discussed also by Leighton (1964). The fields are assumed to emerge at the surface at the birth of an active region and later migrate to high latitudes and reinforce, or early in the cycle cancel, the polar fields. Babcock for his model assumed a polar flux of about $8 \times 10^{21}$ mx, which was that observed at the minimum of 1954.

### 3.3. THE ROLE OF EPHEMERAL REGIONS

Ephemeral regions are small short-lived bipolar features that appear to be like tiny active regions (Harvey and Martin, 1974). Harvey and Martin estimate that the total flux appearing at the surface from the two thousand or so ephemeral regions that are born each day is at least comparable to the flux that appears in active regions per day.

The influence of this ephemeral region magnetic flux on the total flux values listed above must be quite small, however. The ephemeral regions have a much broader latitude distribution than do the active regions, and a significant fraction of the ephemeral regions form poleward of 40° (Martin, 1974). Since more than one third of the surface area of the sun lies above 40°, but only about 5% of the magnetic flux is found there, the influence of the ephemeral regions on the permanent flux distribution must be small. This seems reasonable since these features have a small amount of flux with the flux of opposite polarities in close proximity. Thus the ephemeral region fields must cancel with themselves or with nearby fields within a day or two and leave no net effect on the flux distribution.

## 4. Variations of the Flux Distribution with Time

Figures 1 and 2 show the distribution of magnetic flux of both polarities as a function of time in the various latitude zones. The Zürich sunspot number is also plotted, along with the number of spot groups in the northern hemisphere ($N_N$) and in the southern hemisphere ($N_S$). The magnetic flux data represent daily average values taken over successive Carrington rotations. The Zürich sunspot numbers are monthly averages, and the group numbers for each hemisphere are the quarterly averages published by M. Waldmeier in the *Astronomische Mitteilungen der Eidgenössischen Sternwarte Zürich*.

### 4.1. ACTIVITY-CYCLE-RELATED VARIATIONS

The maximum of the activity cycle may be seen roughly in early 1969 in the sunspot curves in Figures 1 and 2. A maximum in the magnetic flux below 40° may be seen also in the north data (Figure 1). This maximum appears centered on late 1969 or early 1970, delayed approximately a year from the spot maximum. The variations of the daily flux appear to be from about $1.75 \times 10^{22}$ Mx for each polarity near maximum to about $0.75 \times 10^{22}$ Mx in 1973. In the south there is not the same broad maximum that is evident in the north equatorward of 40°. Instead there is a very steep rise in measured

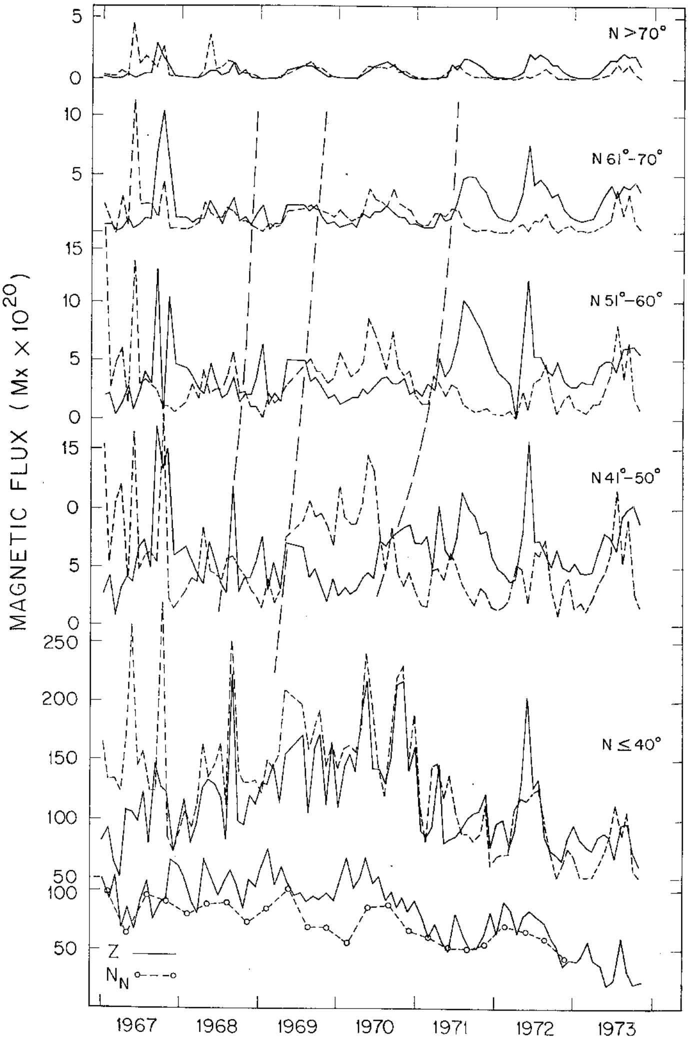

Fig. 1. Positive polarity magnetic flux (solid lines) and negative polarity magnetic flux (dashed lines) in various latitude zones as a function of time in the northern hemisphere. Each point is the daily average over one solar rotation. The lowest solid curve is the Zürich full-disk sunspot number, and the lowest dashed curve represents the number of spot groups per quarter in the northern hemisphere. The three long sloped dashed lines represent successively the positive, negative, and positive flux migrations. The first is quite weak. Note that the flux scale for the zone below 40° is 10 times that of the other latitude zones.

flux for a short interval early in 1970. The maximum for this brief peak was nearly $3 \times 10^{22}$ Mx for each polarity.

At higher latitudes the maximum peak is not so evident, although it can be seen in the interval 40°–60° in both hemispheres. In the north the largest flux measurements poleward of 60° are found in the last three years of the interval.

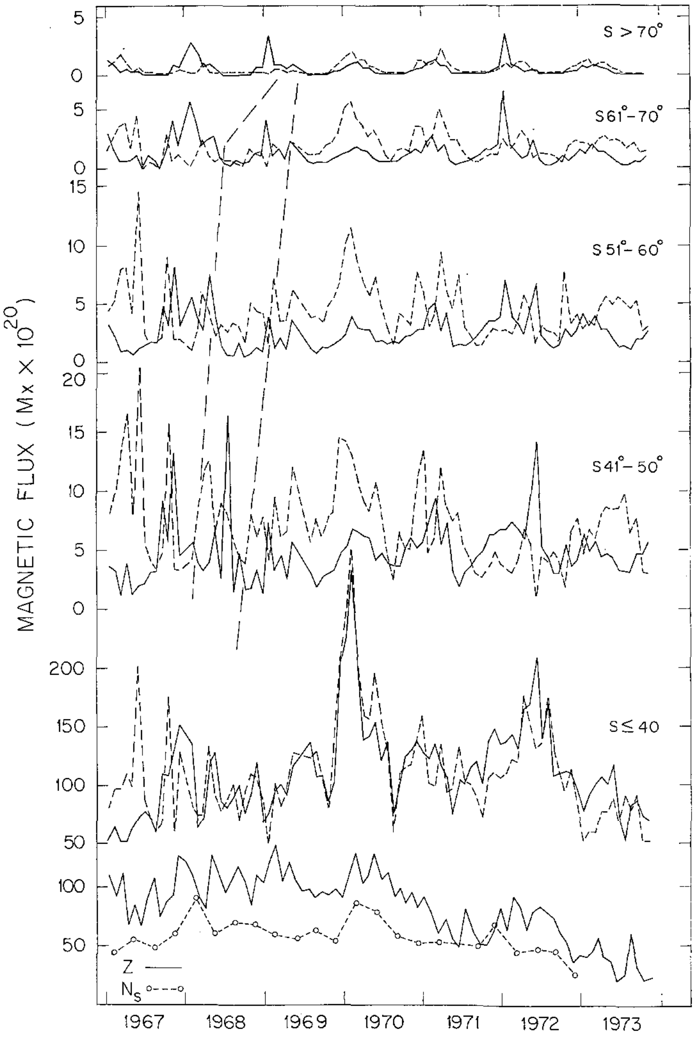

Fig. 2. The same as Figure 1 but for the southern hemisphere. Here two poleward migrations are noted. The quarterly numbers of regions at the bottom of the figure refer to the southern hemisphere only. The sunspot curve is the same as in Figure 1.

In both hemispheres negative flux predominates in the interval 40°–70° around the time of solar maximum. Equatorward of 40° there is also the same tendency but proportionately smaller. Ambrož *et al.* (1971) have noted that high levels of activity are generally correlated with predominantly negative magnetic fields. This positive correlation is confirmed here. Apparently, near activity maximum, the activity increases at all solar longitudes, and as a consequence the fields averaged over a whole rotation become negative. The strong negative flux at high latitudes may be the result of the poleward drift of fields. In the south the polarity of the following spots was negative in this period. The following polarity is believed to drift poleward more readily than the preceding polarity, and, indeed, more negative flux is seen at high latitudes in the south than in the north in this interval. In the north the large-scale poleward migration of these negative fields could have been responsible for the late polar field reversal (to positive polarity.)

### 4.2. THE POLAR POLARITY REVERSALS

At the high latitudes one may see the effects of the inclination of the solar rotation axis to the ecliptic. There is a clear annual variation of the amount of magnetic flux of both polarities, especially poleward of 70°. These two curves are 180° out of phase between the north and the south, as one would expect.

The polar field polarity reversals were described in Paper I as seen with the magnetic field strength data. In the north (Figure 1) the polarity reversal and its poleward drift are clearly seen as both an increase in the positive flux and a decrease in the negative flux. The polar fields reversed in the north in mid-1971. As mentioned above, the poleward drift of negative flux that reached the highest latitudes about the beginning of 1970 may have erased an earlier negative-to-positive polarity reversal in the north. Without that drifting negative flux, a case might have been made for a negative-to-positive polarity reversal early in 1969, or about the same time as the south pole polarity reversed. The dashed lines in Figure 1 indicate the various poleward flux drifts in the north. The drift rates are about 20 m $s^{-1}$.

This earlier north polar field reversal, at least at high latitudes, may have been associated with the first northward migration of polar prominences mentioned by Waldmeier (1973). If so, then it is interesting to note that the two negative-to-positive flux drifts to the north pole had associated with them prominence drifts, but the positive-to-negative poleward flux drift did not have such a prominence drift. These prominence drifts may be seen in Figure 7 of Paper I.

In the south the polarity reversal may also be seen as an increase in the negative flux and a decrease in the positive flux. At the polar latitudes this reversal is in mid-1969. Later surges of negative flux at the south polar latitudes were due to the maximum-related negative flux mentioned above.

In mid-1973 a negative dip could be seen in the polar fields in both hemispheres – strengthening the south polar fields and weakening the north polar fields. From Figures 1 and 2 it may be seen that this is due to an increase of negative flux at almost all latitudes and a corresponding decrease in positive flux at most latitudes.

### 4.3. THE SOLAR 'MONOPOLE'

These flux data allow us to examine in more detail the apparent 'monopole' behavior of the Sun at times. A number of examples may be seen in Figures 1 and 2 of such an appearance of the fields, and this effect was discussed in Paper I.

Some of these features have already been discussed above. One that was mentioned in Paper I is the sudden positive surge in mid-1972. This is seen from Figures 1 and 2 to be predominantly an increase in positve flux with little or no decrease in negative flux in most latitude zones. The same is true of a negative surge early in 1967.

The fact that these field surges occur predominantly in one polarity is a strong indication that the 'monopole' behavior is not an instrumental zero effect. A zero drift in the instrument would raise one polarity by the same amount that the other polarity was decreased in each latitude zone.

## 5. Summary

(1) About 95% of the total magnetic flux of the Sun is confined to latitudes below 40° in both hemispheres. The flux above 60° represents less than 2% of the total flux.

(2) Activity-cycle-related increases in total magnetic flux may be seen in each hemisphere. This effect is strongest in the sunspot latitudes, but may be seen at the higher latitudes as well.

(3) Negative magnetic flux is stronger than positive flux at all latitudes around the time of solar maximum. This effect is proportionately strongest poleward of 40° where a 'wave' of negative flux may be seen moving poleward.

(4) The polarity reversals at the polar latitudes in both hemispheres described in Paper I may be seen to be the result of a combination of an increase of the flux of one polarity and a decrease of the flux of the opposite polarity.

(5) An early weak negative-to-positive polarity reversal is evident at the north polar latitudes. This may correspond to Waldmeier's (1973) first north prominence migration.

(6) From the behavior of the fluxes of the two polarities it appears that the frequent 'monopole' behavior of the solar magnetic fields is not due to instrumental effects.

## 6. Discussion

The magnetic flux determinations, both as total flux from Equation (1) and each polarity considered separately, give us a powerful tool with which to study solar magnetic fields. This tool will be used more frequently as more digital data accumulate from the Mount Wilson magnetograph. Later papers in this series will treat the flux data in more detail, but, as a first glance, this study has uncovered some interesting results.

The fact that nearly 95% the total magnetic flux of the Sun is confined to about $\frac{2}{3}$ of the area, i.e., to equatorward of 40°, indicates that this percentage of the flux cancels with fields of opposite polarity and disappears from the surface of the Sun before it can migrate to higher latitudes. From Figures 1 and 2 it is clear that this average percentage varies somewhat throughout the cycle, being greatest near the activity maximum. This is because the cycle-related total flux changes are greater below 40° than above 40°.

The polarity reversal 'waves' to high latitudes that represent the cycle-related reversals (positive-to-negative in the south and negative-to-positive in the north) appear because of a strengthening of one polarity along with a weakening of the other polarity. The negative 'waves' to high latitudes that appeared to be associated with the activity maximum, on the other hand, appeared mostly to be just a wave of negative flux. This is especially true in the south. This appears to be a qualitative difference between these two types of flux drifts, which may be significant in the large-scale structure of the activity cycle.

The negative 'wave' in the north appeared shortly after what may have been a weak negative-to-positive polarity reversal in the north polar latitudes. This meant that there were two negative-to-positive polarity reversals in the north polar latitudes. This must not be a common occurrence since Waldmeier (1973) points out that the double prominence migration observed in the north in cycle 20 is the first such double prominence drift that has been observed.

Although an instrumental cause for the frequent 'monopole' appearance of the magnetic fields of the Sun appears unlikely now, other reasonable explanations still exist, as discussed in Paper I of this series. These proposed explanations will be examined in more detail with further analysis of these data.

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