Ripples and Rush-to-the-Poles in the Photospheric Magnetic Field

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Abstract
The distribution of magnetic fields of positive and negative polarities over the surface of the Sun was studied on the basis of synoptic maps presented by the NSO/Kitt Peak (1978–2016). To emphasize the contribution of weak fields the following transformation of synoptic maps was made: for each synoptic map only magnetic fields with a modulus less than 5 G (|B| ≤ 5 G) were left unchanged, while larger or smaller fields were replaced by the corresponding threshold values +5 G or −5 G. Cyclic variations of the magnetic-field polarity have been observed associated with two types of magnetic-field flows in the photosphere. Rush-to-the-poles (RTTP) appear near the maximum of solar activity and have the same sign as the following sunspots. The lifetime of RTTP is ∼3 yr, during which time they drift from latitudes 30–40° to the pole, causing the polarity change of the Sun’s polar field. Our aim is the study of another type of variation that has the form of series of flows with individual flows of 0.5–1 yr with alternating polarity. These flows, called “ripples” by Ulrich and Tran (Astrophys. J. 768, 189, 2013), are located in time between two RTTP and drift from the equator to latitudes of ∼50°. The period of variation of ripples was shown to be 1.1 yr for the northern hemisphere and 1.3 yr for the southern hemisphere. It was found that the amplitude of the variation was higher for the time intervals where the polar field had a positive sign. Within the same flow, fields of positive and negative signs developed in antiphase. Two types of flow – RTTP and ripples – together formed a unique structure that had a close connection to the magnetic solar cycle.

Keywords Magnetic fields · Photosphere · Surges · Solar cycle · Observations

1. Introduction
The magnetic field of the Sun governs all manifestations of the solar activity (SA). Magnetic-field groups of different magnitudes from the strongest magnetic fields to the background

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magnetic fields are connected with certain solar phenomena. Cyclic changes of solar activity reflect periodic changes of the Sun’s magnetic field. The magnetic fields follow the 22-yr magnetic cycle: the polarity change law that manifests itself in the change of the sign of the polar field near the maximum of SA and in the change of the sign of the leading and the following sunspots near the minimum of SA. An important feature of the magnetic-field cycles is the restructuring of the field distribution over the Sun’s surface. The variation of SA with the 11-yr Schwabe cycle manifests itself in the variation in latitudinal distribution of SA in Maunder’s butterfly diagrams, or Maunder butterflies.

Numerous studies deal with the features of magnetic-field distribution over the Sun’s surface, in particular with the asymmetry of the distribution. Such phenomena as active longitudes (Gaizauskas, 1993; Bai, 2003; Bigazzi and Ruzmaikin, 2004 and the references therein), and north–south asymmetry (Ballester, Oliver, and Carbonell, 2005; Deng et al., 2016 and references therein) play an important role in the development of solar activity.

A great impact on the process of the Sun’s polar-field evolution is produced by the transport of the magnetic fields over the Sun’s surface. A special role is played by the “rush-to-the-poles” flows (RTTP), which have direct relation to the polar-field reversal. The RTTP phenomenon was studied in coronal emission features in Fe XIV from the National Solar Observatory at Sacramento Peak (Altrock, 2014). Multiple rush-to-the-poles episodes were found in Gopalswamy, Yashiro, and Akiyama (2016) in the occurrence of high-latitude prominence eruptions. The transport of the photospheric magnetic fields (surges) was studied in Petrie (2015) and Mordvinov et al. (2016). It was found that RTTP are the product of the decay of the following sunspots, causing a change in the sign of the polar field. In Sun et al. (2015) magnetic flux from active regions migrating poleward and the reversal process during Cycle 24 were studied. In Wang, Jiang, and Wang (2022) a statistical method to analyze the poleward flux transport during Solar Cycles 21 – 24 was proposed. Using a surface-flux transport model Yeates, Baker, and van Driel-Gesztelyi (2015) studied the origin of a poleward surge and its contribution to the polar field in Cycle 24.

A new phenomenon that consisted in wave-like structures with periods around 2 yr was described in Vecchio et al. (2012), Ulrich and Tran (2013). In Vecchio et al. (2012) magnetic fields were studied on the base of NSO/Kitt Peak magnetic synoptic maps. The radial field component, for each heliographic latitude, has been decomposed in intrinsic mode functions through Empirical Mode Decomposition. Poleward magnetic-flux migration around the maximum and descending phase of the solar cycle was discovered that the authors connected with a manifestation of quasibiennial oscillations (QBO). This result was studied in detail in Ulrich and Tran (2013), who introduced the term “ripples” for such magnetic flows. In Ulrich and Tran (2013) where the data of the Mt. Wilson Observatory were used, the ripples were discovered by differentiating the time–latitude diagram. On the differentiated diagram the ripples are clearly seen, and, moreover, they exist constantly and independently of the solar-activity level. A different treatment of the time–latitude diagram (deviation from the trend) also allows us to obtain a new time–latitude diagram that shows the alternation of the ripples of opposite signs regardless of the solar-activity level. Thus, a number of similar results were obtained while treating the different data sets and using various methods of treatment (Vecchio et al., 2012; Ulrich and Tran, 2013): a new phenomenon was observed that manifested itself in the emergence at low latitudes and propagation to the poles of large-scale wave-like features of magnetic field having periods of quasibiennial oscillations (solar QBOs). In our study (Vernova et al., 2018a) we analyzed the distribution of the positive and negative magnetic fields in the photosphere using synoptic maps produced at the NSO/Kitt Peak. Each pixel of the synoptic map was assigned a value of +1 or −1 in accordance with the sign of the field in this pixel. Taking into account only the sign of the magnetic field
and ignoring its magnitude we observed the imbalance of positive and negative fields. The results of this study showed the cyclic alternation of magnetic-field flows of the opposite polarities.

Weak magnetic fields and their distribution on the surface of the Sun are of great interest, since they occupy a significant proportion of the solar surface. As shown by our calculations based on NSO/Kitt Peak data (1978–2016), 65% of the solar surface are fields $|B| \leq 5$ G and 18% are fields with $5 \, \text{G} < |B| \leq 10$ G; in general, 83% of the total surface of the Sun is occupied by fields $|B| \leq 10$ G.

During the solar cycle, the relative number of pixels in an interval of the field strength does not remain constant. Two groups of fields display opposite behavior: while the number of pixels with magnetic fields from 5 to 5000 G follows the solar cycle, the weakest fields (0 to 5 G) develop in antiphase with the change of the solar activity. The same results were obtained in Vernova et al. (2018b) where instead of the pixel number we considered the time variation of fluxes for groups of magnetic fields differing in strength. The magnetic flux of the weak magnetic fields ($|B| \leq 5$ G) varied in antiphase with the solar cycle and with the flux of the strong fields. This is consistent with the conclusions of Jin and Wang (2014), who found that magnetic low-flux structures change in antiphase with the solar cycle.

In Vernova et al. (2018b) the time variations of the magnetic flux were compared with the variations of the nonaxisymmetric component of the magnetic-field distribution for magnetic fields of different strengths $B$. Unexpectedly, the variations in the nonaxisymmetric component of the magnetic field (longitudinal asymmetry) of the weak fields follow the general course of the solar cycle. Thus, the longitudinal asymmetry of the weak fields $|B| \leq 5$ G varies in antiphase with the magnetic flux of these fields.

The time–spatial development of the weak photospheric fields was discussed in Getachew, Virtanen, and Mursula (2019a,b), Mursula, Getachew, and Virtanen (2021). On the basis of various data sets the distribution of the weak photospheric magnetic fields was studied (Getachew, Virtanen, and Mursula, 2019a). The obtained results show that weak-field asymmetries are most pronounced in medium- and low-resolution synoptic maps, being a real feature of the weak fields. The asymmetry of weak magnetic-field distribution was considered separately for the two hemispheres in Getachew, Virtanen, and Mursula (2019b) where it was found that the northern and southern hemisphere shifts are as a rule opposite to each other.

The purpose of our present work is to study in more detail the distribution of the weak magnetic fields of positive and negative polarity over the surface of the Sun. In Section 2 we discuss the used data and method of their treatment. Section 3 considers the phenomenon of ripples using time–latitude diagrams both for various magnetic-field values and for positive and negative magnetic fields separately. In Section 4 the main conclusions are formulated.

2. Data and Method

Synoptic maps of the photospheric magnetic field produced by the National Solar Observatory/Kitt Peak were used for this study. Data were obtained for 1978–2003 at ftp://nispdata.nso.edu/kpvt/synoptic/mag/ and for 2003–2016 at https://magmap.nso.edu/solis/archive.html. Each map consisted of $180 \times 360$ pixels with magnetic-field values in gauss. Taking into account the sign of the magnetic field we averaged synoptic maps over longitude and constructed the time–latitude diagram that reflected the imbalance of positive and negative fields in the photosphere. In the distribution of the solar magnetic fields, especially of the weak fields ($|B| \leq 5$ G), the influence of random fluctuations of the strength (noise) sets the
limit to the accuracy of results. According to Harvey (1996) this noise in the NSO/Kitt Peak synoptic maps can be as high as 2 G per pixel in the near-pole regions. When constructing a time–latitude diagram, each synoptic map was averaged over 360 longitude values. Due to this averaging, the relative contribution of random fluctuations decreased, so that we can consider the resulting error to be near to the resolution of synoptic maps, i.e., of the order of 0.1 G.

As a rule, strong fields are clearly seen in the time–latitude diagram in the form of Maunder butterflies, while the distribution of weak fields is poorly distinguishable. To emphasize the contribution of weak fields the transformations of synoptic maps were made before combining separate maps into the time–latitude diagram. To study magnetic fields in the selected interval of strength from $B_{\text{min}}$ up to the $B_{\text{max}}$ two different methods of treating the data can be applied. The first method consists of leaving unchanged only pixels with $B_{\text{max}} > B > B_{\text{min}}$. Data outside of the selected magnetic-field interval are cut off by replacing the strength values by zeros. The other method incorporates the saturation of magnetic-field strength at a certain level of $B$. For example, if the threshold is set at 5 G, only pixels with fields $|B| \leq 5$ G are left unchanged, while larger or smaller fields are replaced by the corresponding limiting values $+5$ G or $-5$ G. The first approach will be called “cut-off”, the second one “the saturation”.

3. Results and Discussion

3.1. Time–Latitude Diagrams of the Two Types

We carry out our study mostly with a time–latitude diagram built using synoptic maps with saturation at 5 G ($|B| \leq 5$ G). In this case pixels with magnetic-field strength larger or smaller than 5 G were replaced by the corresponding limiting values $+5$ G or $-5$ G. For comparison, we also plotted a diagram with a cut-off at 5 G, where all pixels with values $|B| > 5$ G were replaced by zeros. Comparison of a time–latitude diagram with cut-off (Figure 1a) and those with the saturation (Figure 1b) shows that the cyclic change of the magnetic-field polarity (ripples) can be seen in both diagrams, yet in the diagram with saturation, the picture is clearer and the details of the field distribution are more pronounced.

3.2. Time–Latitude Diagram

As described in the previous subsection, a time–latitude diagram (Figure 2) was obtained in which there are no Maunder butterflies and one can see the details of the weak-field distribution. The main feature of this diagram is the alternation of bands with the dominance of a positive (blue) or negative (red) magnetic field. The slope of these bands in the diagram suggests that the dominant polarity shifts in latitude over time. These bands, called “ripples” in Ulrich and Tran (2013), are about 1 yr or less wide, and can be interpreted as magnetic-field flows that start near the equator and drift towards the polar regions.

It is interesting to note that in the southern hemisphere we see a clearer pattern of alternating fields of different polarities, especially distinct for those time intervals where the polar field had a positive sign.

These ripples should be distinguished from the magnetic-field flows called rush-to-the-poles (RTTP). The main properties of RTTP flows are given in the Introduction. The magnetic fields of RTTP always have the same sign as that of the following sunspots and opposite to the sign of the polar field of the given hemisphere.
Figure 1 Time–latitude diagrams of the weak magnetic field ($|B| < 5$ G) constructed in two different ways: (a) pixels with $|B| > 5$ G were excluded from the analysis by setting values $|B| > 5$ G in each synoptic map equal to zero. The time–latitude diagram obtained by this procedure we will call the “diagram with cut-off”; (b) values of pixels with $|B| > 5$ G were replaced by limiting values $+5$ G or $-5$ G according to the sign of $B$. The resulting diagram will be called the “diagram with saturation”.

Figure 2 Time–latitude diagram on the basis of synoptic maps NSO/Kitt Peak (1978 – 2016) with saturation at 5 G. As a result, there are no Maunder butterflies and one can see alternation of bands with the dominance of a positive (blue) or negative (red) magnetic field. Cyclic variations of the magnetic-field polarity can be observed associated with two types of magnetic-field flows in the photosphere: rush-to-the-poles and ripples. Horizontal line segments point to the six time intervals during which the cyclic polarity alternation was observed. These intervals were denoted as N1, N2, and N3 for the northern hemisphere and as S1, S2, and S3 for the southern hemisphere. Reversals of the solar polar field marked by arrows are taken from Pishkalo (2019).
Figure 3  Examples of the RTTP flows in Solar Cycle 23 (1998 – 2001): (a) northern hemisphere; (b) southern hemisphere. RTTP flows begin at latitudes of $30 – 40^\circ$ and propagate to the poles. RTTP flows are about 3 yr wide. The polar field changes its sign on arrival of RTTP to the polar regions. The arrows indicate the direction of latitudinal movement of flows in time.

Figure 4  Examples of ripples in the southern hemisphere (a) 1981 – 1984; (b) 2003 – 2007. Ripples in contrast to RTTP are periodic structures consisting of a set of fluxes with alternating polarities. The width of ripples in the set is from 0.5 yr (a) to 1 yr (b). Ripples appear near the equator and reach latitudes $50^\circ$. In this interval, the ripples’ field sign changes four times, while the field sign in RTTP remains unchanged. The arrows indicate the direction of latitudinal movement of flows in time.

In the time–latitude diagram (Figure 2), RTTPs are clearly visible near the time of solar maxima as rather large bands about 2 – 3 yr wide, which begin at latitudes $\sim 30 – 40^\circ$. The times when these streams reach the poles coincide with the reversals of the polar field.

Unlike RTTPs, which have the form of separate magnetic-field flows appearing once per solar cycle at its maximum, ripples are a set of narrow field flows with alternating polarity. Each series of ripples spans a period of about 10 yr, including decrease, minimum, and rising phases of the solar cycle. We observe such flows looking like wave packets in the time interval between two RTTPs, when the sign of the polar field is constant. In contrast to this result, Vecchio et al. (2012) found similar structures only in years of high solar activity. Another conclusion was reached in Ulrich and Tran (2013) where similar flows were registered during all phases of solar cycle.

In the data array under consideration represented by the diagram of Figure 2 we selected six time intervals between neighboring RTTPs: three in the northern hemisphere (N1, N2, N3) and three in the southern hemisphere (S1, S2, S3). In these intervals, the alternation of the flow polarity (ripples) can be clearly seen.

To illustrate the difference between RTTP and ripples, the cuts from the time–latitude diagram are presented in Figure 3 (RTTP) and Figure 4 (ripples). RTTP flows are shown for
Figure 5  Change of the magnetic field along the latitude 41° of the southern hemisphere (see Figure 2). Two examples show the position of ripples series relative to the RTTP: (a) period of 1978 – 1994 and (b) period of 1998 – 2016. The data are smoothed by a running average over five points. RTTP are marked with shading.

the Solar Cycle 23 for the northern hemisphere (Figure 3a) and for the southern hemisphere (Figure 3b). As an example of ripples, we chose two sections of the time–latitude diagram in the southern hemisphere, both selected sections (Figures 4a,b) falling on the period of time when the sign of the polar field was positive. The arrows in Figures 3 and 4 indicate the direction of latitudinal movement of flows in time.

Magnetic-field flows forming ripples (Figure 4) appear, as a rule, near the equator and reach latitudes ∼ 50°. In contrast, RTTP flows (Figure 3) begin at latitudes of 30 – 40° and propagate to the poles.

The width of the flow (the duration of constant field sign at a fixed latitude) is noticeably different for ripples and RTTP. The width of the flows with positive or negative polarities forming the ripples ranges from 0.5 yr (Figure 4a) to 1 yr (Figure 4b). Thus, the total period including the flows of both polarities is approximately 1 – 2 yr. RTTP flows are significantly wider (Figure 3) – their width is about 3 yr. We estimated the average life time of the RTTP from eight streams at latitudes +50° of the northern hemisphere and −50° of the southern hemisphere. This time proved to be 3.2 ± 0.3 yr.

The selected sections of the time–latitude diagram in Figures 3 and 4 have a time length of ∼ 50 Carrington rotations. In this interval, the ripples’ field sign (Figure 4) changes four times, while the field sign in RTTP remains unchanged (Figure 3).

Both ripples and RTTPs can be observed in the same plot displaying a time change of the magnetic field at some selected latitude. Figure 5 shows the magnetic-field variations at the latitude of 41° of the southern hemisphere for two intervals: 1978 – 1994 (Figure 5a) and 1998 – 2015 (Figure 5b). It can be seen that the periodical change of the magnetic-field polarity (ripples) persists between two successive RTTPs. This variation was observed for 9 yr in Figure 5a and for 10 yr in Figure 5b. During these periods the maxima and minima of the magnetic-field curve in Figure 5 corresponded to the positive and negative magnetic fields of the ripples.

The RTTP flows are marked in Figure 5 by shading. The first RTTP in each of the two pairs (Figures 5a,b) has positive magnetic-field polarity that is opposite to the sign of the polar magnetic field and coincides with the polarity of the following sunspots. Accordingly, the pair of the second RTTP in Figures 4a,b displays negative polarity just as the field of the following sunspots.
3.3. Mount Wilson and Wilcox Solar Observatory Synoptic Maps

Two papers considering the ripples phenomenon (Vecchio et al., 2012; Ulrich and Tran, 2013) use different methods for isolating cyclic structures of the magnetic field of the photosphere. This significantly increases the reliability of the results obtained in these works. Moreover, the initial data of these works are also different. The work Vecchio et al. (2012) uses observational data from Kitt Peak Observatory (KP), and the article (Ulrich and Tran, 2013) analyzes the data obtained by Mount Wilson Observatory (MWO). Our work uses synoptic maps produced by NSO Kitt Peak. Some works (Getachew, Virtanen, and Mur-sula, 2019a) noted insufficient reliability of measurements made by the NSO Kitt Peak before 1990. We found no difference between the results derived from the data from this period and from the rest of the data array. However, to avoid the possible appearance of artifacts, we included data of the Mount Wilson Observatory (MWO) and the Wilcox Solar Observatory (WSO) in the study.

For the convenience of comparing the results, we considered for these observatories approximately the same time period as the KP measurement period we used: from 1978 to 2017 (the corresponding ranges in Carrington rotations were 1670 – 2190 for WSO and 1670 – 2132 for MWO).

The Mount Wilson Observatory data can be accessed at ftp://howard.astro.ucla.edu/pub/obs/synoptic charts. MWO synoptic maps contain $512 \times 971$ pixels with magnetic-field values in gauss, and the latitude scale in the maps is linear in degrees. The data for the near-polar regions of MWO were not suitable for analysis, since a strong 1-yr variation is present in them. In this regard, 62 lines of pixels in the synoptic maps ($\sim 22^\circ$) at each of the poles were excluded by us based on this consideration.

The data of Wilcox Solar Observatory were obtained at http://wso.stanford.edu/synopticl.html. Synoptic maps of WSO contain 72 steps of $5^\circ$ in the longitude and 30 steps along the sine of the latitude. The data used to construct synoptic maps are limited to latitudes of $\pm 70^\circ$. Synoptic maps of KP do not have such restrictions, but due to the fact that the map is built on the sine of the latitude, the contribution of the near-polar regions is insignificant.

To compare the results of observations of different observatories, the MWO and WSO synoptic maps were processed using the same method as in the case of the Kitt Peak synoptic maps, as a result of which the contribution of weak fields was emphasized in each map (see Section 2). The time–latitude diagrams based on the synoptic maps of the two observatories are presented in Figure 6 for MWO and in Figure 7 for WSO.

In the same manner as in the time–latitude diagram for Kitt Peak Observatory (Figure 2), these diagrams show the distribution of weak magnetic fields. Maunder butterflies are not visible in these charts, but photospheric magnetic fluxes drifting from the equator to the poles are clearly distinguishable. In general, diagrams for the three observatories show a similar distribution of magnetic fields, despite some differences.

The MWO synoptic map resolution is high, having an array of $512 \times 971$ pixels, which is higher than the Kitt Peak resolution ($180 \times 360$ pixels). The resolution of the WSO synoptic maps is significantly lower: $30 \times 72$ pixels, and, as a result, the distribution of fields of different polarities in the time–latitude diagram of Figure 7 is somewhat blurred compared to the distributions of KP (Figure 2) and MWO (Figure 6). This difference does not interfere with the fact that cyclic changes in the distribution of magnetic fields are equally clearly visible in both cases (Figures 6 and 7). Thus, the analysis of data from the MWO and WSO observatories confirms the results obtained by us from the Kitt Peak data, namely, the presence of cyclic structures with a period of about 2 yr in the weak magnetic fields of the photosphere.
Figure 6  Time–latitude diagram plotted with the Mount Wilson Observatory synoptic maps (1978 – 2012). The resolution of the maps was 512 steps in latitude and 971 steps in longitude. 62 pixels from each of the poles (about $22^\circ$) were removed from the diagram to account for the strong yearly variations at high latitudes. Data were treated in the same way as in Figure 2 (Kitt Peak). Both maps show similar structures of the magnetic-field distribution. Due to suppression of the strong fields, Maunder butterflies are not seen in the diagram, instead of which flows of alternating polarity (ripples) appear.

Figure 7  Time–latitude diagram plotted with the Wilcox Solar Observatory synoptic maps (1978 – 2022). Resolution of the maps was 30 steps in the sine of latitude and 72 equal steps in longitude. The field above $70^\circ$ was not resolved. Data were treated in the same way as in Figure 2 (Kitt Peak). The quality of the diagram is lower in comparison with Figure 2 because of the low resolution of the used synoptic maps. However, the main features of the magnetic-field distribution can be discerned. Ripples with domination of positive (blue) or negative (red) magnetic field are clearly seen.

The reliability of these outputs can be evaluated by comparing the time profiles at the fixed latitude $\sim 40^\circ$ for MWO and WSO in the same time interval 1981 – 1990 as before for KP (Figure 5a). The time dependencies shown in Figures 8a and 8b are clearly similar to Figure 5a. The cyclic structure of the magnetic-field distribution appears quite distinctly in the form of a series of flows with alternating polarity fields (ripples) located between two regions with constant polarity of the magnetic field (RTTP).

For the time interval of about 9 yr from one RTTP to another, fitting the field variations with the sinusoidal function gives the following values of the half-period of variations $w$
Figure 8  Change of magnetic-field strength along the fixed latitude 41°. Two diagrams were used for plotting the graphs: (a) time–latitude diagram based on the MWO data (Figure 6) and (b) time–latitude diagram based on the WSO data (Figure 7). Fitting with the sinusoidal function of the time profiles (a) and (b) as well as that of Kitt Peak for the same time interval (Figure 5a) show nearly identical values of the period of the magnetic-field variation.

Figure 9  Influence of the saturation limit on the change of magnetic field along the latitude 33° of the southern hemisphere. The saturation thresholds are set at $B = 5, 10, 15, 30,$ and $5000$ G; the last one means inclusion of all magnetic fields. One can see that irrespective of the saturation thresholds the magnetic fields change synchronously.

in Carrington rotations: WSO – $w = 10.30 \pm 0.16$, MWO – $w = 10.18 \pm 0.17$, and KP – $w = 10.24 \pm 0.12$ (20 Carrington rotations correspond to the whole period of 1.5 yr). This coincidence of results for the three series of data allows us to conclude that the ripples phenomenon manifests itself even in the data with significantly different resolutions.

3.4. Polarity Variations for Different Strengths of Magnetic Field and Different Saturation Thresholds

To compare the variations of the magnetic fields with different strength we plotted time–latitude diagrams using various saturation thresholds ($B_{lim} = 5, 10, 15, 30, 5000$ G). For these diagrams the change of magnetic field along the latitude 33° of the southern hemisphere is shown in Figure 9. One can see that all curves develop synchronously, yet their behavior during the phases of low and high solar activity is different. From one RTTP to
Figure 10  Contribution of fields of different strength to cyclic variations. Change of the magnetic field along the latitude 41° of the southern hemisphere is shown for each of the field groups. RTTPs are marked with shading. The data are smoothed by running an average over five points.

another a cyclic change of the magnetic-field polarity can be seen (ripples). During 4 yr of low solar activity most of the variation is connected with the weak fields ($B \leq 5$ G). The increase of the threshold value does not produce a significant rise of the magnetic-field variation. On the contrary, for high solar activity periods (where RTTP are present) the increase of the selected threshold leads to a significant rise of the variation. The highest values of $B$ are observed when the threshold is set at 5000 G, which is equivalent to the inclusion of all magnetic fields. Strong fields change their sign at the same time as the weakest fields. This means that there is a common pattern in the alternation of the field signs for all strengths of magnetic fields. Due to the synchronous behavior of magnetic fields of different strengths these fields can be combined into the same time–latitude diagram.

When constructing the time–latitude diagram (Figure 2) for each synoptic map, fields with the modulus greater than 5 G were replaced by the limit values of $+5$ G and $-5$ G. This procedure was applied to each of the synoptic maps that were then longitude averaged and included in the time–latitude diagram. In this way the influence of the strong magnetic fields was suppressed, revealing the periodic variations of the low-strength fields. The strong fields were also accounted for in construction of the time–latitude diagram, yet with the saturation limit of $|B| = 5$ G.

The relative contribution of the different field groups to the distribution of magnetic fields varies according to the field strength. In this connection, the question arises as to which magnetic fields play the main role in the emergence of a periodic structure in the form of the alternating bands of different polarities.

To answer this question we considered the following groups of fields: $0 – 5$ G, $5 – 15$ G, $15 – 50$ G, and $|B| > 50$ G. For the construction of the time–latitude diagrams the transformed synoptic maps were used where only field values in the selected intensity ranges were left unchanged. All pixels not included in these groups of fields were filled with zeros.

For these four field-range groups, the changes of magnetic fields at the latitude 41° of the southern hemisphere are shown in Figure 10. Periodic reversal of the magnetic-field sign is
clearly seen for the fields of 0–5 G (Figure 10a), and 5–15 G (Figure 10b), in the interval from one rush-to-the-pole to another. For the intermediate group of 15–50 G (Figure 10c), the alternation of polarities occurs only at a sufficiently high level of solar activity, and the variations disappear near the minimum. Periodic polarity changes are almost completely absent for fields with $|B| > 50$ G (Figure 10d). Thus, the alternation of the dominant polarity of flows is a characteristic property of weak fields.

As can be seen in Figure 10, rush-to-the-poles flows (shaded in the figure) are present in all field groups. Thus, in the formation of rush-to-the-poles flows, not only weak fields of less than 15 G are involved, but also fields from 15 to 50 G and more. In the formation of RTTP the fields of 50–100 G and even the fields with a strength of more than 100 G (which are not shown in the figure) are present. Thus, one can conclude that in the formation of ripples only weak fields (0–15 G) are involved, while in the formation of RTTP the fields up to 100 G and higher play a role.

On the other hand, the synchronous behavior of different field groups allows their inclusion in the time–latitude diagram while studying the features of ripples. In order to avoid excessive influence of the strongest fields the saturation limit should be chosen and set at a sufficiently low level.

### 3.5. Period and Amplitude of Variations

In the time–latitude diagram (Figure 2), which served as an experimental basis for our analysis of magnetic-field variations, flows with different polarity appear very clearly. However, upon closer examination, it turns out that this phenomenon is quite complex, and over several cycles the variation parameters experience significant changes. To begin with, the lifetime of these variations (the section of the time–latitude diagram in which the variation is constantly present) changes during 1978–2016 from 6 to 11 yr in the northern and southern hemispheres. Approximate estimates of the period and amplitude of the variations also showed that these parameters differ significantly between sections N1, N2, N3, S1, S2, S3. Therefore, to obtain quantitative estimates of the period and amplitude parameters, it was necessary to subject the time–latitude diagram to a preliminary processing that would eliminate both the shortest variations and long-period ones from the primary data, since it was obvious that ripples are associated with variations that have a period from one year to several years.

To isolate these variations, the following data processing technique was adopted. As an example, we consider the change of the magnetic field along the latitude $-33^\circ$ in the interval S1 (Figure 11a, blue curve). The trend of the raw data (Figure 11a, red curve) was determined as a result of a running smoothing over 21 points (a point corresponds to one Carrington rotation). After subtracting the trend (Figure 11b), the data was smoothed over five points (rotations). As a result of such processing, both the slowest and fastest variations of the field were excluded from the data series, and thus the interval of periods of interest was emphasized and we could observe the variation in a “pure” form (Figure 11c). The time dependences of the magnetic-field strength at the latitude of $-33^\circ$ were subjected to such processing for six intervals marked in the latitude-time diagram (Figure 2).

After that, it became possible to estimate the amplitude and period by fitting the “cleaned data” with a sinusoidal function. The magnetic-field variations for the intervals N1, N2, N3, S1, S2, S3 were approximated by a function of the following form:

$$y = y_0 + A \sin \frac{2\pi (t - t_c)}{T},$$  \hspace{1cm} (1)
Figure 11  (a) Change of the magnetic field ($|B| \leq 5$ G) along the latitude $-33^\circ$ in the interval S1 (blue curve). The trend was determined as a result of running smoothing over 21 points (red curve); (b) magnetic field after detrending; (c) magnetic field (b) smoothed over five points.

Figure 12  Approximation of magnetic-field variations by a sinusoidal function: (a) for the entire interval S1; (b) and (c) – the approximation interval is divided into two parts. There is a noticeable difference in the periods of variation for parts (b) and (c).

where $A$ is the amplitude, $T$ is the period of variation and $t_c$ is the shift of the phase. (Figure 12 shows the approximation for the interval S1.) It turned out that the variation period noticeably changes not only from one interval to another, but also within one interval, i.e., over a time of $\sim 10$ yr (in our example, during the interval S1), which leads to uncertainty in the estimation of the period. Therefore, the intervals were divided into two parts (with a split point near the minimum of the solar cycle) and the approximation was performed independently for each of the parts (see Figures 12b,c).

Figures 12b,c show that approximating the two parts separately gives a better accuracy. The data of all six intervals were processed similarly and the period and amplitude of the variations were determined. This analysis showed that the variation period changes during the N1–S3 intervals, and in the northern hemisphere, in each interval before the minimum of solar activity, the variation period was longer than that after the minimum (Figure 13a).
Figure 13  Periods and amplitudes of the magnetic-field variations (ripples) along the $33^\circ$ latitudes in the northern and southern hemispheres. (a) Periods of variation for both hemispheres. The six intervals N1, N2, N3, S1, S2, S3 were divided into two equal parts; the periods were evaluated independently for each of the 12 sections. (b) Amplitudes of the variations for six time intervals (N1–S3). At the top of the histogram the sign of the polar field is shown. The amplitudes were higher for the hemisphere with a positive polar field.

However, in the southern hemisphere, such an effect appeared only in one of the three regions. On average, the period of variation was 1.1 yr for the northern hemisphere and 1.3 yr for the southern hemisphere.

It should be emphasized that these estimates of the period of variation are obtained for particular latitudes ($+33^\circ$ and $-33^\circ$). For other latitudes, we received slightly different periods. In the work Vernova, Tyasto, and Baranov (2022), averaged period values for the range of latitudes from the equator to $50^\circ$ were obtained by two methods: a) using the method of empirical orthogonal function (EOF) analysis and b) by summing the time profiles of the field taking into account their latitude shift with time. The values of the periods for the two methods turned out to be 1.8 yr and 1.6 yr.

These period values are close to the estimations of other authors. In Vecchio et al. (2012) these variations are considered as one of manifestations of the quasibiennial oscillations (QBO). The period of ripples from 0.8 to 2 yr was found in Ulrich and Tran (2013).

A certain regularity is seen in the change of the amplitude of the variations of the two hemispheres (Figure 13b): the amplitude is higher for the hemisphere in which the polar field is positive (the sign of the field is indicated in the upper part of the histogram). This effect supports the connection of polarity variations with the 22-yr magnetic cycle of the Sun.

3.6. Fields of Positive and Negative Polarity

The contribution of fields of positive and negative polarity to the formation of a cyclic structure of flows with alternating signs of the field is considered.

There are two possibilities for the magnetic-field variations, which lead to a variation of the dominant polarity. The first variant: positive fields and the modulus of negative fields develop in phase with each other, but there is a cyclical change of the ratio between their values. Another variant is that high values of positive fields correspond to low (in the modulus) negative fields and vice versa. The result will be the same: alternate dominance of one of the polarities.

Plotting the time–latitude diagrams separately for positive and negative fields, one can check which of the variants takes place. We used the same value of 5 G as the saturation limit for synoptic maps.
Figure 14 shows the time variation of positive and negative magnetic fields at the latitude 33° of the southern hemisphere. Within the same flow, fields of different signs are closely related to each other and develop in antiphase: the maxima of the positive field (upper curve) are close in time to the minima of the absolute value of the negative field (lower curve). (These points are connected by red lines). To study positive and negative fields of the ripples separately, the same procedure as in Section 3.5 was applied. The change of the positive magnetic-field modulus and of the negative magnetic-field modulus along the latitude −33° is shown, respectively, in Figure 15a and in Figure 15c. The trend of the raw data (red thick curves) for the positive-field modulus (Figure 15a) and for the negative-field modulus (Figure 15c) was determined as a result of a running smoothing over 21 points (a point corresponds to one Carrington rotation). After subtracting the trend (Figures 15b,d), the data was smoothed over five points (rotations). As a result of such processing, both the slowest and fastest variations of the field were mostly removed from the data, so that the interval of periods under study was emphasized and we could observe the ripples free of redundant additions. In Figures 15b,d the periodic structure of the magnetic field can be clearly seen. The half-period of this variation evaluated by fitting with the sinusoidal function was 10.68 ± 0.14 CR for the positive field and 10.98 ± 0.15 CR for the modulus of the negative field. The full period of the variation was about 1.6 yr.

In Figure 16 detrended positive and the modulus of negative fields are plotted together. Good anticorrelation between fields of the opposite signs can be seen, the correlation coefficient being $R = -0.83$ for the interval of 150 rotations and even higher ($R = -0.89$) for a smaller interval of 100 rotations. The pattern of change of the magnitude of positive and negative fields with high anticorrelation leads to successive dominance of one of the polarities and the formation of ripples.

Thus, an increase in the positive field within one flow is accompanied by a decrease in the modulus of the negative field in the same flow and vice versa. This leads to alternate dominance of magnetic fluxes with different polarities.

### 3.7. RTTP and Ripples: Two Different Phenomena or the Same One?

Phenomena observed as surges in the magnetic field of the photosphere are called both rush-to-the-poles (RTTP) and ripples in different works. Historically, RTTPs were discovered much earlier than ripples. The RTTPs were detected in the polar crown filaments and
Figure 15  Magnetic fields of positive and negative polarity considered separately along the latitude $-33^\circ$. Negative fields are plotted as $|B|$. (a) Change of the positive magnetic field (blue curve). The trend was determined as a result of running smoothing over 21 points (thick red line). (b) Positive magnetic field after removing the trend (blue line) and smoothing over five points (thick red line). (c) Change of the negative magnetic-field modulus (blue curve). The trend was determined as a result of running smoothing over 21 points (thick red line). (d) Negative magnetic-field modulus after removing the trend (blue line) and smoothing over five points (thick red line).

Figure 16  Comparison of variations of positive (blue curve) and modulus of negative (red curve) magnetic fields. The same interval as in Figure 14 is displayed after removing the trend (running average for 21 Carrington rotations). The fields develop strictly in antiphase.
Table 1  Main differences between two kinds of surges: rush-to-the-poles (RTTP) and ripples.

| Feature                  | RTTP                                      | Ripples                          |
|--------------------------|-------------------------------------------|----------------------------------|
| Periodicity of appearance| Once during 11-yr solar cycle              | 6 – 10 times during an interval between two RTTP |
| Magnetic-field polarity  | Constant, coinciding with the following sunspot polarity | Alternately positive and negative |
| Life time at the 40<sup>o</sup> latitude | Constant field sign during about 3 yr | Change of polarity every 0.5 – 1 yr |
| Latitudinal drift        | From latitudes of ±30° to the poles       | From the equator to ±50° of latitude |
| Connection with the solar cycle | Near the solar-cycle maximum            | Descent, minimum, and rise phases of the solar cycle |
| Magnetic-field strength  | Up to 100 G and higher                    | Below 15 G                       |

coronal Fe<sub> XIV</sub> emission study (for a review see: Cliver, 2014; Altrock, 1997, 2014). The term ripples was introduced by Ulrich and Tran (2013), which in their turn cited Vecchio et al. (2012) as the first to describe this phenomenon. The new effect became available for the study after applying special techniques of magnetic-data treatment. Vecchio et al. (2012) used the Empirical Mode Decomposition analysis, which showed the existence of two main periods in the photospheric magnetic field: 22-yr and 2-yr, possibly a quasibiennial oscillations (QBO).

Ulrich and Tran (2013) studied the ripples using the parameters $\frac{dB_r}{dt}$ and $\delta B_r$ – the difference between the raw $B_r$ and a smoothed $B_r$. Ripples were observed as wave-like structures at all latitudes and irrespective of the phase of the solar cycle (Ulrich and Tran, 2013). According to Vecchio et al. (2012) the maximal values of the amplitude of QBO (ripples) were reached at solar-cycle maxima and at the decline phases of solar cycle. Some problems concerning ripples remain open. One of these problems is the relative role of magnetic fields with various strengths in the formation of the periodical change of the field sign.

Several papers consider RTTP and ripples as the same phenomenon of surges in the magnetic field produced by the decay of groups of trailing sunspots (e.g., Petrie, 2015; Mordvinov et al., 2016). According to this approach the difference consists only in the scale of the phenomena: large surges form RTTP and, reaching the poles, replace the polar field. The alternating polarity of surges (ripples) is explained by the appearance of spots with reverse polarity that violate Hale’s law.

In contrast, both Ulrich and Tran (2013) and Vecchio et al. (2012) do not support the idea of the ripples being remnants of the dispersing active regions. As a possible source of 2-yr variations Vecchio et al. (2012) point out the processes in the interior of the Sun, may be at the tachocline level.

The results of our work speak in favor of the existence of two types of fluxes – RTTP and ripples, which differ in many respects from each other in terms of characteristic features. We summarize these differences in Table 1.

4. Conclusions

Wave-like structures with periods around 2 yr (the ripples) were found in Vecchio et al. (2012), Ulrich and Tran (2013). We continued the study of this phenomenon using the
time–latitude diagrams constructed on the base of NSO/Kitt Peak data. To emphasize the contribution of weak fields the following transformation of synoptic maps was made: for each synoptic map only magnetic fields with modulus less than 5 G ($|B| \leq 5$ G) were left unchanged while larger or smaller fields were replaced by the corresponding limiting values $+5$ G or $-5$ G. A time–latitude diagram was obtained, in which there are no Maunder butterflies and one can see the details of the weak-field distribution. In the time–latitude diagram, one can see magnetic-field fluxes of two types: rush-to-the-poles (RTTP) and the ripples. The two phenomena have very different characteristics. Magnetic fields of RTTP always have the same sign as the sign of the following sunspots and opposite to the sign of the polar field of the given hemisphere. The times when RTTP reach the poles coincide with the reversals of the polar field. Unlike RTTP, which appear as separate magnetic-field flows one per maximum of the solar cycle, ripples are a set of narrow field flows with alternating polarity. We observe such flows in the time interval between two RTTPs, when the sign of the polar field is constant, i.e., at the decrease, minimum, and rise phases of the solar cycle. RTTP flows begin at latitudes of $30–40^\circ$ and propagate to the poles. In contrast, magnetic-field flows forming ripples appear, as a rule, near the equator and reach latitudes $\sim 50^\circ$. The width of RTTP flows is about 3 yr. The width of the flows with positive or negative polarities of the ripples ranges from 0.5 yr to 1 yr.

One of important differences between RTTP and ripples is that they are produced by magnetic fields of different strengths. The main contribution to the ripples is made by weak fields $|B| \leq 15$ G, while in the formation of RTTP flows mainly the fields from 15 G to 100 G and more are involved.

 Apparently, there are certain regularities in the distribution of weak fields over the surface of the Sun (ripples). These patterns are associated with both 11-yr and 22-yr solar cycles. The connection with the 11-yr cycle is manifested in the fact that ripples occupy certain phases of the cycle: decline, minimum, and rise, which in total last for about 9 yr. The connection with the 22-yr cycle can be seen in the fact that ripples exist only when the sign of the polar magnetic field is constant. This period of time corresponds to a certain wave packet of ripples; when moving to the next interval of the constant sign of the polar field, the ripple structure may change slightly. Such a boundary between two wave packets is the RTTP, which leads to a change in the sign of the polar field. Another connection of ripples with the 22-yr magnetic cycle is that the amplitude of ripples depends on the sign of the polar field and will be greater when the polar magnetic field is positive.

The study of the time–latitude diagram separately for positive and negative magnetic fields made it possible to obtain similar wave-like structures with periods of 1.6 yr for both polarities. Comparison of the periodic structure of positive magnetic fields and the modulus of negative magnetic fields shows a high anticorrelation ($-0.8$ or higher). The change of the relative magnitude of positive and negative fields due to their high anticorrelation leads to successive dominance of one of the polarities and as a result to the formation of ripples.

Two types of flows – RTTP and ripples – together form a structure that appears regularly in the magnetic field of the photosphere and has close connection to the solar magnetic cycle.

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**Declarations**

**Competing interests**  The authors declare no competing interests.

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