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Latitudinal Profiles of the Photospheric Magnetic Field in Solar Cycles 19–21

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Abstract—For various groups of photospheric magnetic fields differing in strength, averaged synoptic maps have been obtained from the data of the Kitt Peak National Solar Observatory (1976–2003). The latitudinal profiles of magnetic field fluxes are considered individually for each 5-G field strength interval. Changes in the maxima of the latitude profiles and their localization in the latitude are studied. The results are evidence that the latitudinal distribution of the magnetic fields changes significantly at field strengths of 5, 15, and 50 G. The magnetic flux for groups of fields differing in strength decreases monotonically as the strength increases, starting from $B > 5$ G; the fluxes of the southern hemisphere exceed those of the northern hemisphere. A very special group is formed by the weakest fields with $B < 5$ G, which are opposite in phase to stronger fields in terms of localization and time changes.

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1. INTRODUCTION

The study of the latitudinal distribution of solar activity is of interest because of such important problems as the shift of the sunspot zone during an 11-year cycle, the periodic appearance of polar faculae in high latitudes, the evolution of polar coronal holes, etc. (see review and references in (Hathaway, 2015)). The latitudinal distribution of sunspots and its variation during an 11-year solar cycle are the most studied. In accordance with Spoerer's law, the average latitude of sunspot groups gradually decreases from the beginning to the end of an 11-year solar cycle, i.e., the sunspot zone is shifted from the middle heliographic latitudes to the solar equator. It was found by Li et al. (2001) that the migration rate of sunspot groups is the largest at the beginning of a solar cycle and decreases with the cycle development. The width of the sunspot zone and their relation to the solar cycle was studied in the literature (Ivanov et al., 2011; Miletsky et al., 2015).

Another manifestation of solar activity, which is clearly associated with a certain range of latitudes, is polar faculae (e.g., (Sheeley, 2008)). They appear at higher latitudes than sunspots, and their development runs ahead of sunspots by about 6 years (Makarov and Makarova, 1996). Another study (Deng et al., 2013) has shown that polar faculae are ahead of sunspots by 52 months. Measurements of polar faculae show good agreement with polar magnetic fields (Muñoz-Jaramillo et al., 2012).

The variety of manifestations of the solar activity is associated with magnetic fields of different strength and their localization on the Sun's surface. The evolution of the zonal distribution of the solar magnetic field was considered on the basis of magnetograms from the WSO observatory (Hoeksema, 1991). It has been shown that the total magnetic flux is closely connected with the level of activity and is similar to the Maunder butterfly diagram, which shows the sunspot distribution. Temporal and latitudinal variations in magnetic fields were considered by Akhtemov et al. (2015). A strong difference in the variations in the total magnetic flux at low and high latitudes is revealed. The analysis of the evolution of latitudinal distributions of magnetic fields of different strength in solar cycles 12–23 shows that the sunspot zone width strongly correlates with the total magnetic flux of sunspots (Miletsky, 2015).

In our paper (Vernova et al., 2016) the latitudinal distributions of magnetic fields were studied on the basis of synoptic maps of the photospheric magnetic field from the Kitt Peak National Solar Observatory (1976–2003). For our study we used the method of synoptic maps superposition. As a result, one averaged synoptic map was constructed for the whole period of 1976–2003. We summed up the magnetic fields with respect to latitude and found the latitudinal profile of the solar magnetic flux for three solar cycles. Thus, stable regularities of the latitudinal distribution of the magnetic field manifest itself which are maintained with averaging over several solar cycles.

The averaged latitudinal profile showed two regions of concentration of magnetic fields, at sunspot latitudes and in the polar faculae zone. The flux in the sunspot zone significantly exceeds the flux in the polar faculae zone. It should be noted that there is a certain lower threshold of the flux of $\sim 1.3 \times 10^{21}$ Mx, below which the latitudinal profile does not drop throughout the latitude range. The maximal flux in the sunspot zone exceeds the threshold by about five times.

Our results show an approximately symmetric latitudinal distribution of the magnetic field modulus relative to the equator. However, it was shown that the flux in the southern hemisphere averaged over three solar cycles slightly exceeds the flux in the northern hemisphere.

The main goal of this study is to trace the features of the latitudinal distribution of magnetic fluxes for various magnetic field strengths. The main attention is paid to weak magnetic fields ($B < 50$ G). The most significant differences in the latitudinal profiles of the photospheric magnetic fields are observed just for such fields.

2. DATA AND METHOD

In the work, synoptic maps of the photospheric magnetic field from the Kitt Peak National Solar Observatory (1976–2003) are used (http://nsokp.nso.edu/). The synoptic maps of the photospheric magnetic field have a resolution of 1° in longitude (360 steps) and 180 equal steps in the sine of latitude. Thus, each map contains 360 × 180 pixels of the magnetic field in gauss.

To distinguish stable features of the latitudinal distribution, synoptic maps were averaged over three solar cycles with the use of the method of superposition of synoptic maps, which allowed us to receive a synoptic map averaged over the entire period 1976–2003. Only the absolute values of the longitudinal component of the magnetic fields were considered, without regard for their polarity.

To estimate the contribution of fields of different strength into the total magnetic flux, each synoptic map before summation is transformed in such a way that only pixels in a certain field strength range remain on it, while the other pixels are replaced by zeros. Thus, we get a summary map for three solar cycles for a certain range of strengths of magnetic fields. The number of nonzero pixels shows the fraction of fields of a certain group in the total magnetic field flux.

The synoptic maps were constructed for various intervals of the field strength: from 0 to 5 G, from 5 to 10 G, and so on. The averaging of such a map over longitude gives the latitudinal profile of the magnetic field in the chosen strength range.

3. RESULTS AND DISCUSSION

Figure 1a shows the latitudinal profiles of a magnetic flux averaged over solar cycles 21–23 for three field strength ranges: 5–10, 10–15, and 20–25 G. The latitudinal profile for 5–10-G fields sharply differs from the profiles of stronger fields (Fig. 1a): the former is almost constant from –60° to + 60° and never drops below 0.39×10^{21} Mx. In polar latitudes, the magnetic flux increases by more than two times. Despite the approximate constancy of the flux in midlatitudes, a slight increase in the sunspot zone is already visible in the latitudinal profile. With a further increase in the strength ($B > 10$ G), the latitudinal profile starts gradually changing the shape. In low latitudes, magnetic fields concentrate in the sunspot zone more evident. In polar latitudes, the flux maximum is shifted from the poles toward the faculae zone. Moreover, for the group of 10–15 G, the flux in polar latitudes considerably exceeds the flux in the sunspot zone, but the fluxes in the sunspot and faculae zones become very close when the field strength increases up to 20–25 G (Fig. 1a).

Another feature of the latitudinal profiles for weak fields is the presence of several regions of the minimal field concentration, which become more pronounced as the field strength increases. One of the flux minima is observed in the near-equatorial region, and the other two are seen at latitudes 40°–60° in every hemisphere. The position of the equatorial minimum is constant for all groups of fields, while the shift of the minimum is seen in the latitude range from 40° to 60° with an increase in the field strength (straight lines in Fig. 1a).

For the groups of fields 25–30, 35–40, and 45–50 G (Fig. 1b), all latitudinal profiles are close in shape and have two maxima: in the sunspot zone (sp) and in the polar faculae zone (pf) near 70°. The flux maximum in the sunspot zone significantly exceeds the flux in the polar faculae zone. The flux is vanishing in the polar faculae zone for fields of 45–50 G in strength. Thus, a field strength of 50 G is the boundary above which only the sunspot zone is seen on the latitudinal profile. It is typical that the flux maximum decreases monotonically in both zones with an increase in the field strength.

Figure 2 shows the flux maximum as a function of the strength for the northern and southern hemispheres. We consider separately: (a) low latitudes from 0° to 40° and (b) high latitudes from 40° to a pole. A continuous decrease in the flux maximum with an increase in the magnetic field strength, with the flux in the southern hemisphere being slightly higher than the northern hemisphere, is a common feature for low- (Fig. 2a) and high-latitude fields (Fig. 2b). As the

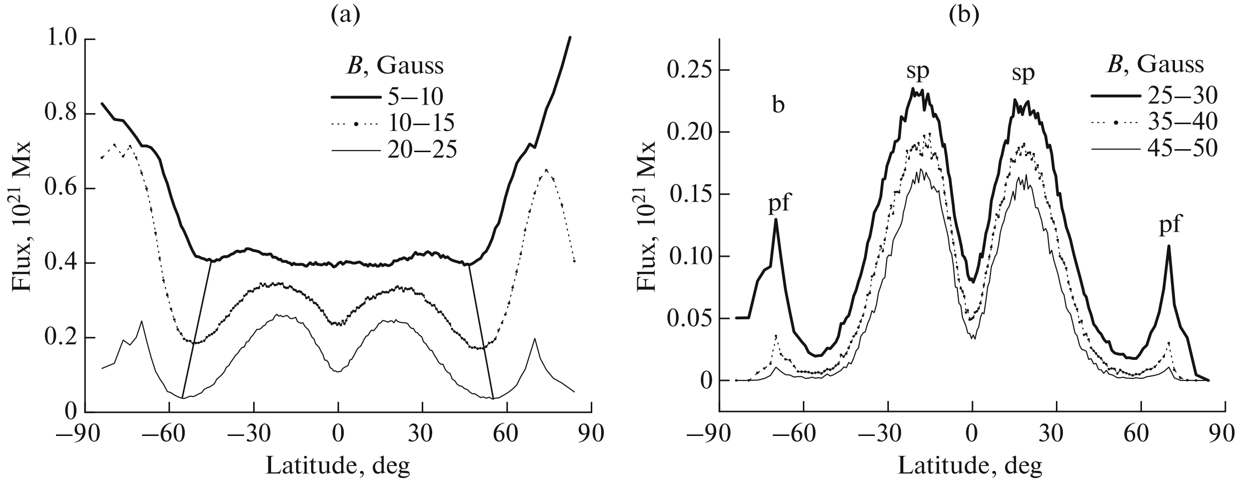

Fig. 1. Latitudinal profiles of photospheric magnetic fields averaged over three solar cycles (1976–2003): (a) magnetic fields with a strength of 5 to 25 G (straight lines show the shift of the profile minimum versus the field strength); (b) magnetic fields with a strength of 25 to 50 G. Regions of magnetic flux concentration are sunspot zone (sp) and polar faculae zone (pf).

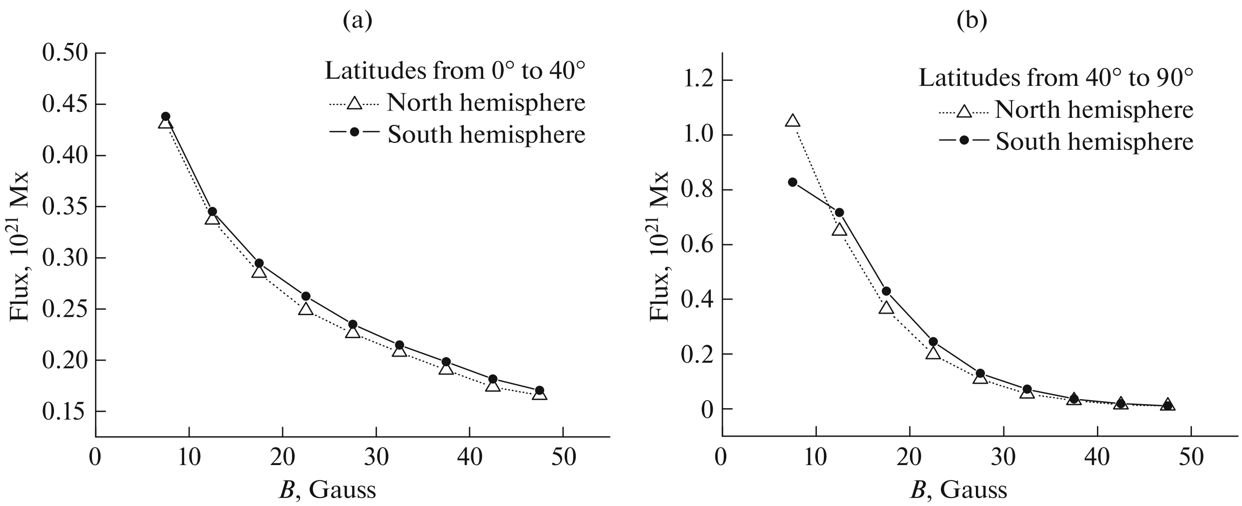

Fig. 2. Variation in the latitude profile maximum for the northern and southern hemispheres versus the magnetic field strength: flux maxima for latitudes (a) ±40° and (b) above 40°.

magnetic field increases, the rate of the flux weakening slows down. In comparison with 5–10-G fields, the magnetic flux decreases by a factor of 3 for 45–50 G fields (Fig. 2a).

The low- (Fig. 2a) and high-latitude fluxes (Fig. 2b) differ in the following: the flux maximum for high latitudes, which corresponds to the group of 5–10-G fields, is twice as large as for low latitudes. In addition, unlike low latitudes, where for the strongest fields (45–50-G group) the flux drops only to 0.17×10^{21} Mx, the flux drops almost to zero as the field strength increases in high latitudes.

Figure 3 shows changes in the latitude of the profile maximum with respect to the magnetic field strength in the northern and southern hemispheres. For low latitudes (Fig. 3a), the positions of the maxima in the two hemispheres coincide for the weakest fields of 5–10 and 10–15 G. Then the northern and southern fields develop differently, but the latitude variations are small and range from 15° to 22°. Thus, the flux maxima of these fields are in the sunspot zones. For high latitudes (Fig. 3b), weak fields (5–10 and 10–15 G) are localized in the highest latitudes and are obviously associated with coronal holes. In both hemispheres starting from 15–20 G, one latitude equal to 70° is dominant which is associated with the localization of polar faculae here.

It is of interest to consider the latitude regions where the magnetic flux is minimal. Figure 4 shows the magnitude and localization of the flux minimum

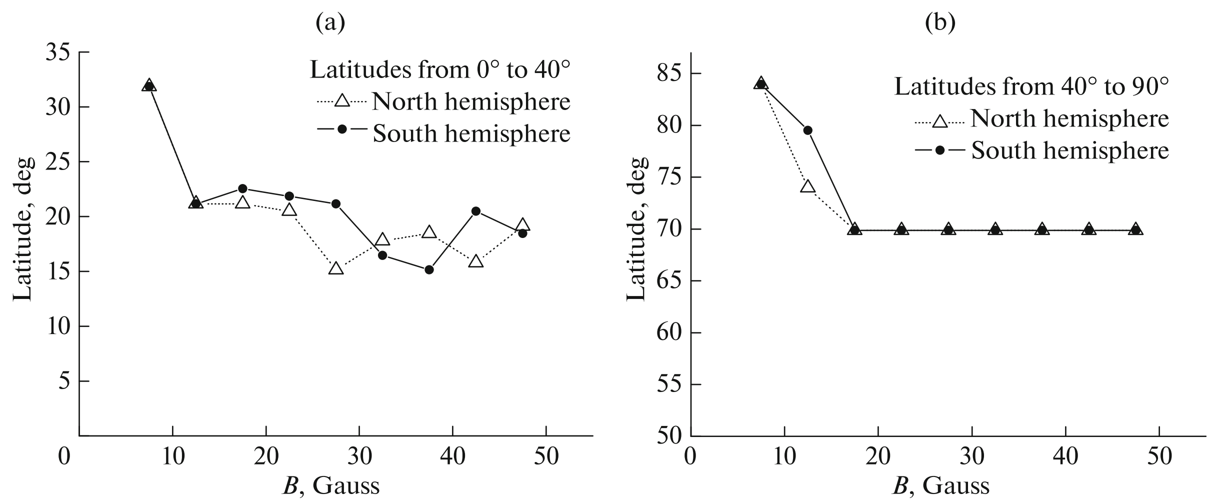

Fig. 3. Regions of the highest concentration of magnetic fields of different strength: the dependence of the position of the latitudinal profile maximum on the magnetic field strength for latitudes (a) ±40° and (b) above 40°.

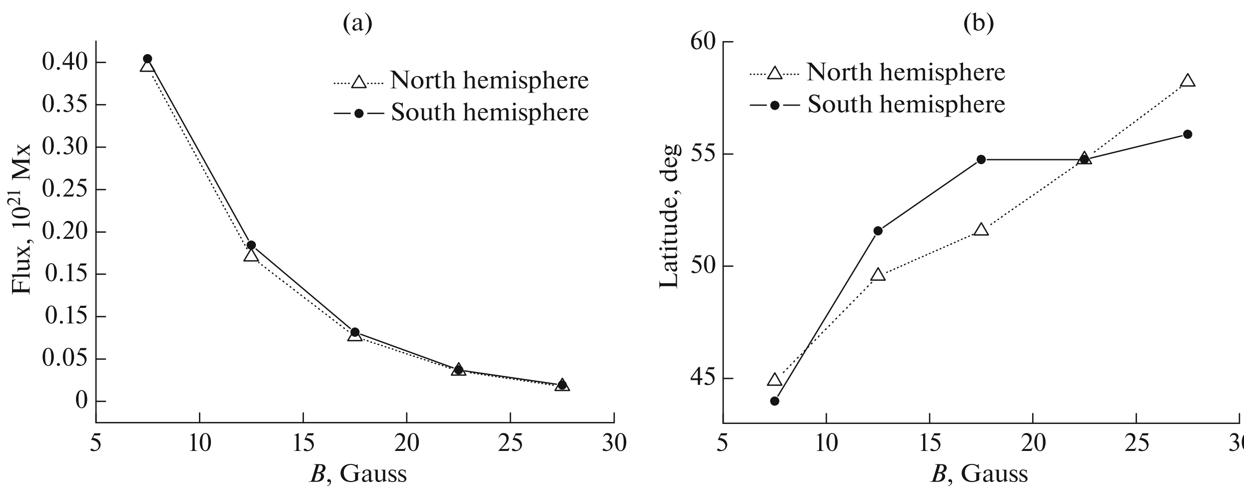

Fig. 4. Regions of low concentration of magnetic fields of different strength: (a) flux magnitude in the latitudinal profile minimum and (b) latitude of the minimum.

versus the field strength. The latitudinal profile minimum (Fig. 4a) decreases as the field strength increases in the same way as the maximum magnitude (Fig. 2a). A monotonic decrease in the flux is seen with strengthening of the magnetic field, and the flux in the S hemisphere slightly exceeds that in the N hemisphere for all points. A shift of the minimum is observed on the latitudinal profiles in the latitude range 40°–60° (Fig. 4b). The flux minimum is at the latitude 45° for 5–10-G fields. When the field strength increases, the shift toward high latitudes also occurs for 25–30-G fields, and the minimum is at latitudes of 56° S and 58° N.

It should be noted that latitudinal profiles for fields of 5–10, 10–15 G, etc. form a family of similar curves, the shape of which gradually changes as the field strength increases so that the curves do not intersect anywhere. A very special group consists of the weakest fields ($B < 5$ G), and it is the most numerous group. Pixels with a field strength of 0–5 G occupied more than 60% of the solar surface in 1976–2003, while strong fields ($B > 50$ G) occupied 3.3% of the solar surface.

In analysis of the weakest fields ($B < 5$ G), the question of the measurement noise of the initial data becomes significant. The measurements of the line-of-sight longitudinal component of the magnetic field are the least reliable in the polar regions of the sun. Harvey (1996) showed that the noise level of the NSO/KP synoptic maps depends on the latitude and is about 2 G for an individual map element in polar regions. The technique used in our work (averaging

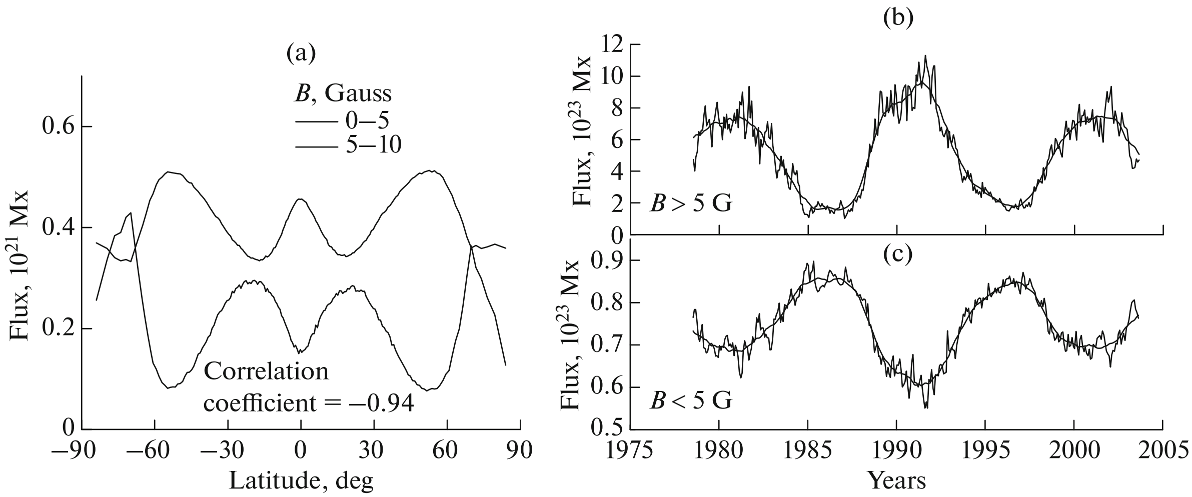

Fig. 5. Features of the weakest fields variations in comparison with stronger ones: (a) latitudinal profiles of 0–5- and 15–20-G fields (correlation coefficient $R = -0.94$); time variations of magnetic fields with (b) $B > 5$ G and (c) $B < 5$ G (correlation coefficient $R = -0.96$). A thick line shows sliding smoothing over 20 Carrington turns.

over longitude and time) allows a significant reduction of the noise contribution.

The latitudinal profiles of the weakest ($B < 5$ G) and stronger fields are compared in Fig. 5a (the latitudinal profile of the group of 15–20-G field is taken as an example). The flux concentration in the sunspot and faculae zones is observed for the latitudinal profile of 15–20-G fields, which is typical for all groups of fields stronger than 15 G. Magnetic fields with $B < 5$ G evolve in antiphase and reveal flux minima just at the latitudes of the sunspot and polar faculae zones. These fields are concentrated at latitudes from 40° to 60° and in the near-equatorial region ±5°. The maxima of the weakest fields are located at latitudes ±53 ° and at the equator. Thus, the two latitudinal profiles (15–20 G and $B < 5$ G) are sharply opposite, with the correlation coefficient of the two curves $R = -0.94$.

Not only the latitudinal profile for the weakest fields ($B < 5$ G) is opposite in phase to stronger fields but also the time variations in these fields develop in antiphase. Figure 5b shows the time variation in the total magnetic flux for fields with the strength $B > 5$ G. A clear 11-year cycle with maxima shifted toward the second Gnevyshev maximum is seen. Figure 5c shows the time variation in fields with $B < 5$ G. It is obvious that weak fields develop in antiphase with strong fields (correlation coefficient $R = -0.96$), but the maximal flux values are about an order of magnitude smaller than for strong fields. This result is consistent with SOHO/MDI data for 1996–2011, the analysis of which showed that magnetic structures with a weak flux vary in antiphase with the solar cycle (Jin and Wang, 2014).

4. CONCLUSIONS

The shape of the latitudinal profile of a magnetic field changes when the field strength increases, and these changes are subject to certain regularities. While the flux magnitude decreases both at the profile maximum and minimum as the field strength increases, the latitude positions vary in different ways in the regions of the highest and lowest flux concentrations. The latitude of the profile maximum is almost constant, whereas the flux minimum monotonically shifts toward higher latitudes as the magnetic field strength increases.

The results prove that the latitudinal distribution of the magnetic fields varies radically for certain values of the field strength, i.e., 5, 15, and 50 G. The magnetic flux for field groups differing in strength monotonously decreases as the field strength increase, and the fluxes of the southern hemisphere exceed those of the northern hemisphere. A very special group is represented by the weakest fields ($B < 5$ G), which are opposite in phase to stronger fields in terms of localization and time variations.

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