Magnetic fields a tracer for studying the differential rotation of the solar corona

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The characteristics of differential rotation of the solar corona for the period 1976-2004 were studied as a function of the distance from the center of the Sun..

In the corona, there are virtually no obvious tracers, such as, for example, sunspots or photospheric faculae, which help us study the rotation of the photosphere by tracing their position on the disk and calculating their speed, i.e., the synodic rotation rate of the Sun.

In this paper we use magnetic field calculations to study the rotation of the corona over a large range of distances from the center of the Sun (i.e.from the base of the corona to the source surface).

Main our tasks

In what follows, we mean by rotation of the corona (unless otherwise specified) the rotation of the calculated magnetic field. This method was proposed in Badalyan and Obridko (2015). It allows us to trace changes in the differential rotation of the corona with distance and with the phase of the activity cycle and to compare them with the rotation parameters obtained from the study of other coronal tracers, *e.g* from the study green-line.

Method for calculating the magnetic field in the corona

We calculated the coronal magnetic field in the potential approximation using the well-known method described in Hoeksema and Scherrer (1986); Hoeksema
(1991) in its classical version without assuming the radial field in the photosphere. We used as the source data WSO (John Wilcox Solar Observatory) measurements of the longitudinal component of the photospheric magnetic field
(http://wso.stanford.edu/synopticl.html) and on their basis built the synoptic charts for each Carrington rotation. The general method for extrapolating the magnetic field in the corona is to solve the boundary problem with the line-of-sight field component measured in the photosphere and strictly radial fild at the source surface. As a result, it becomes possible to calculate three magnetic field components in the spherical coordinates *Br, Bμ, Bθ.*

- After that, the method of periodogram analysis was applied. In this method, the correlation between the daily values of the calculated magnetic field and the test harmonic function with a trial period T_p is determined within the time window of a chosen length L. The correlation coefficient found shows the degree of similarity between the function with the period T_p and the distribution we are examining in this time window. After that, the window is shifted in time by δt and the whole procedure repeats. The periodogram method ensures quite a good resolution in period, which allows a detailed study of the time-latitude characteristics of the coronal rotation.

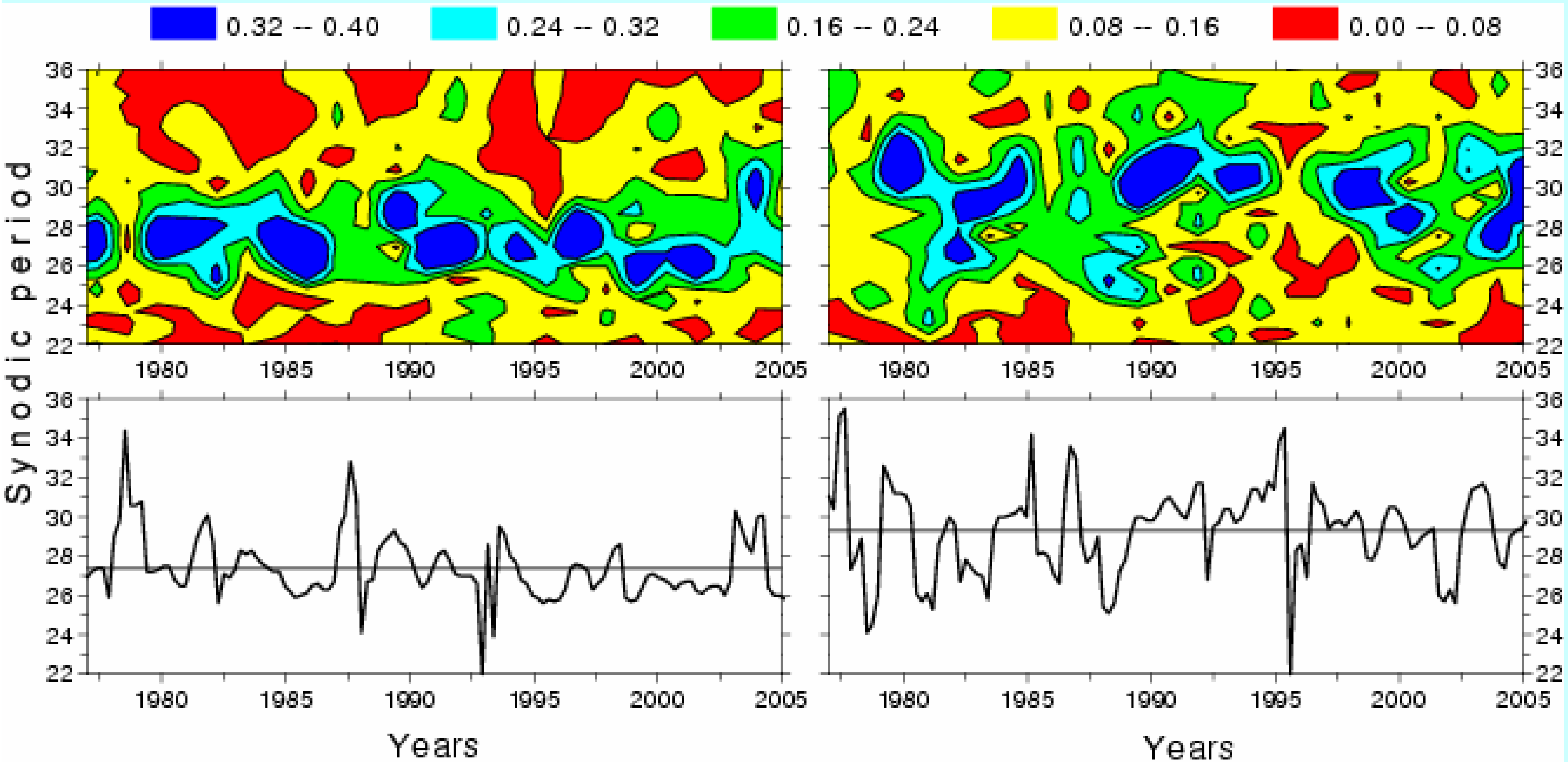


Fig.1. Two-dimensional periodograms for the latitudes of 10± *(left) and 55± North and* the distance of 1.1 *R*¯. *The lower panels show the periods with maximum amplitudes in a* mowing time window.

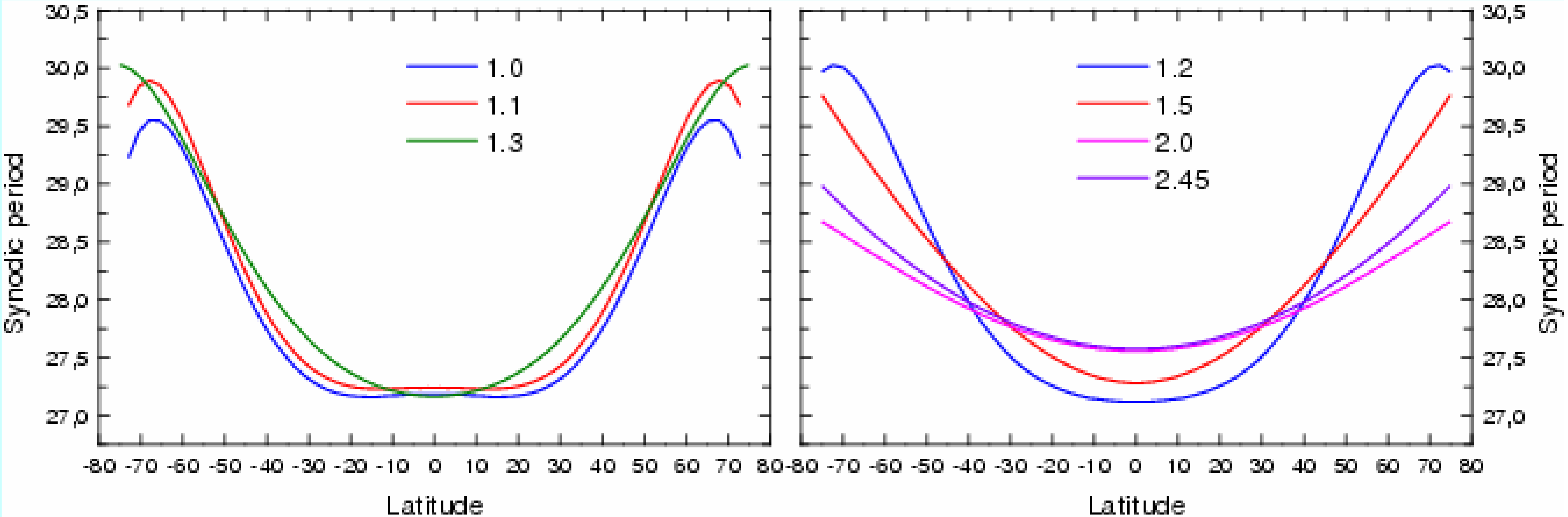
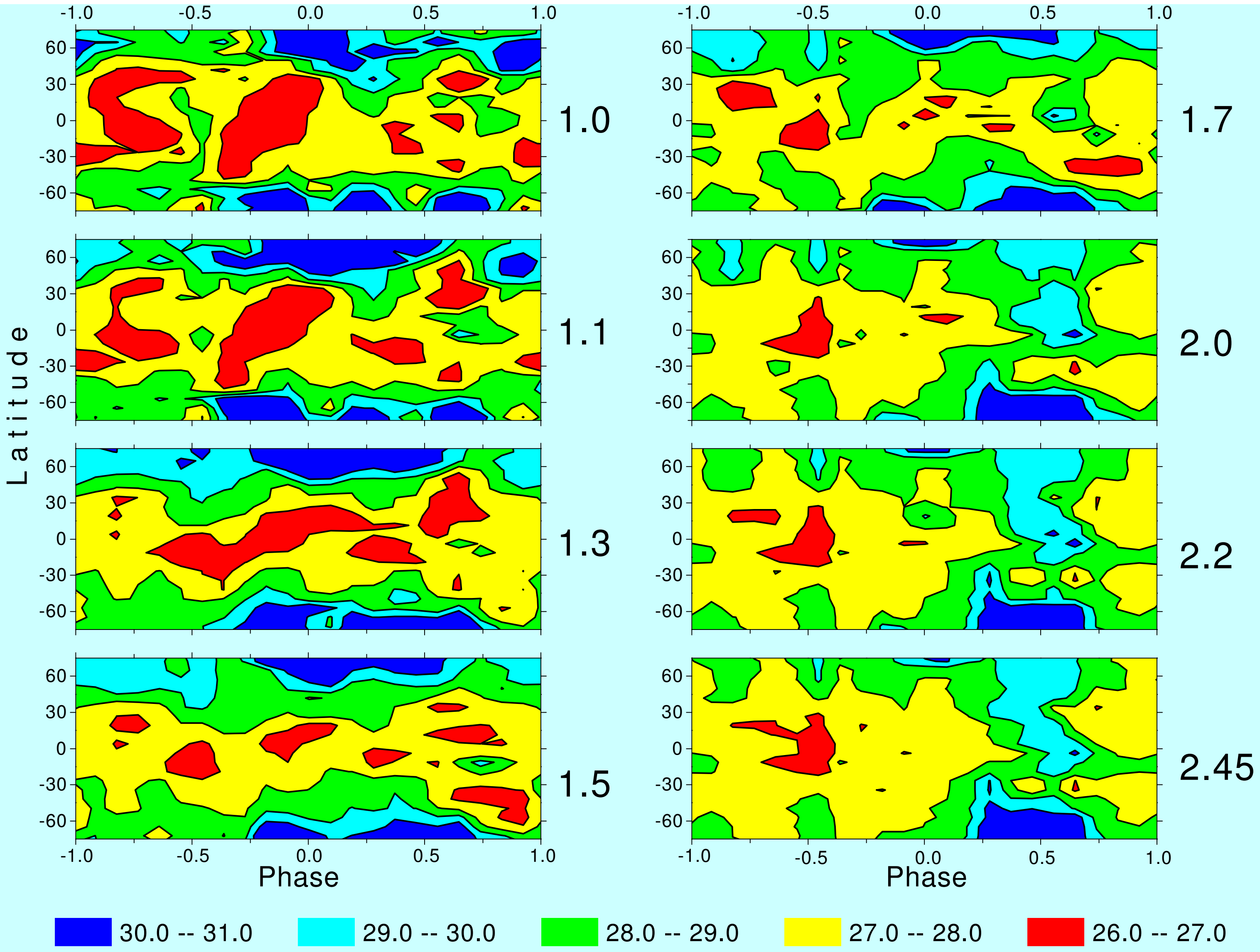
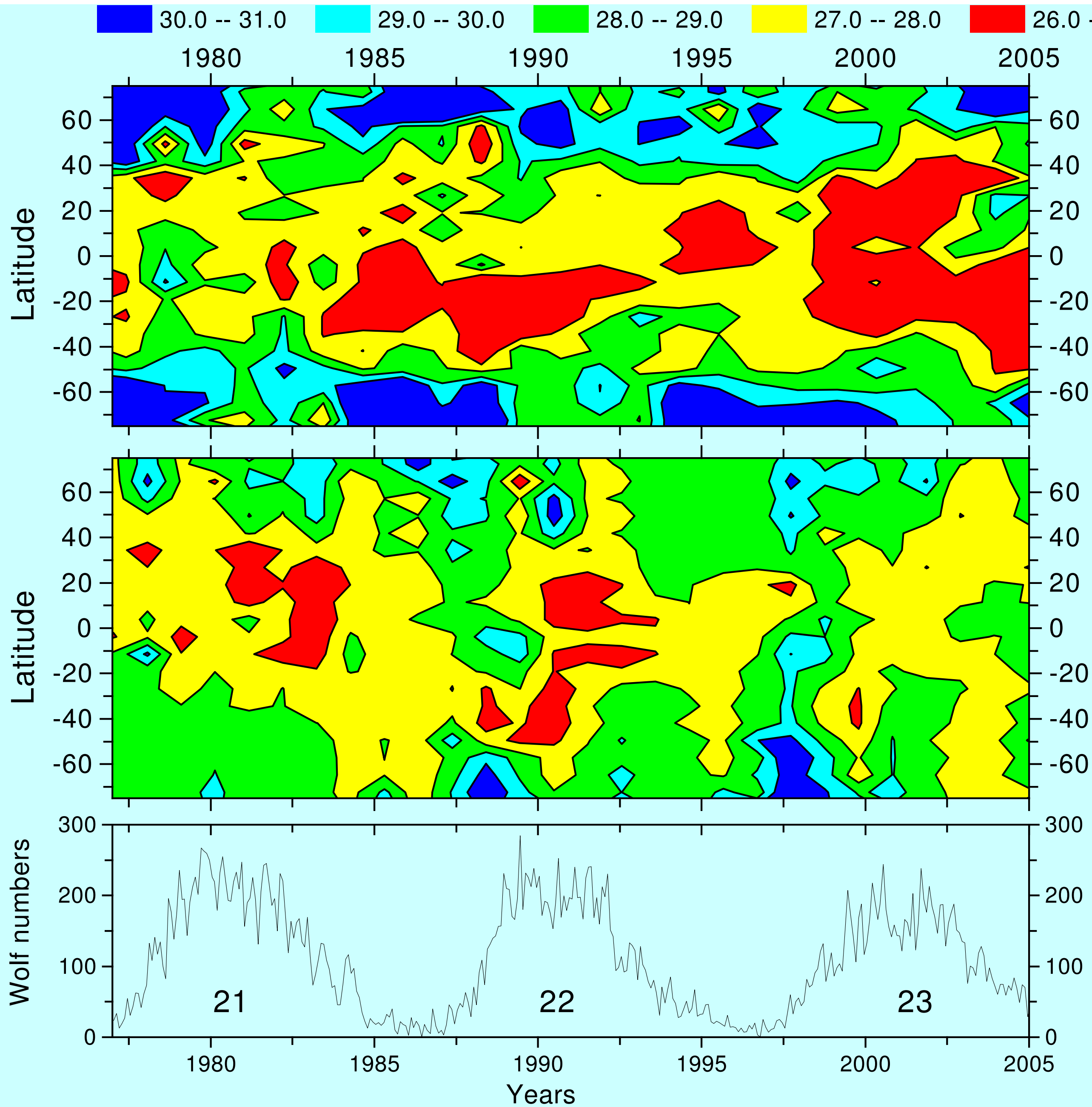


Fig. 2. Synodic rotation period of the corona vs. latitude for some heliocentric Distances indicated on the panels.

1. The differential gradient of the coronal rotation decreases with distance from the center of the Sun { as the distance increases, the curves become flatter.
2. The synodic period at the equator ($\theta = 0$) *increases gradually (the rotation* rate decreases) with the increase of the distance.
3. The synodic period at the high latitudes *decreases gradually (the rotation* rate increase) with the increase of the distance
4. Even in the vicinity of the source surface (2.45 *R0), the rotation of the corona* remains differential.

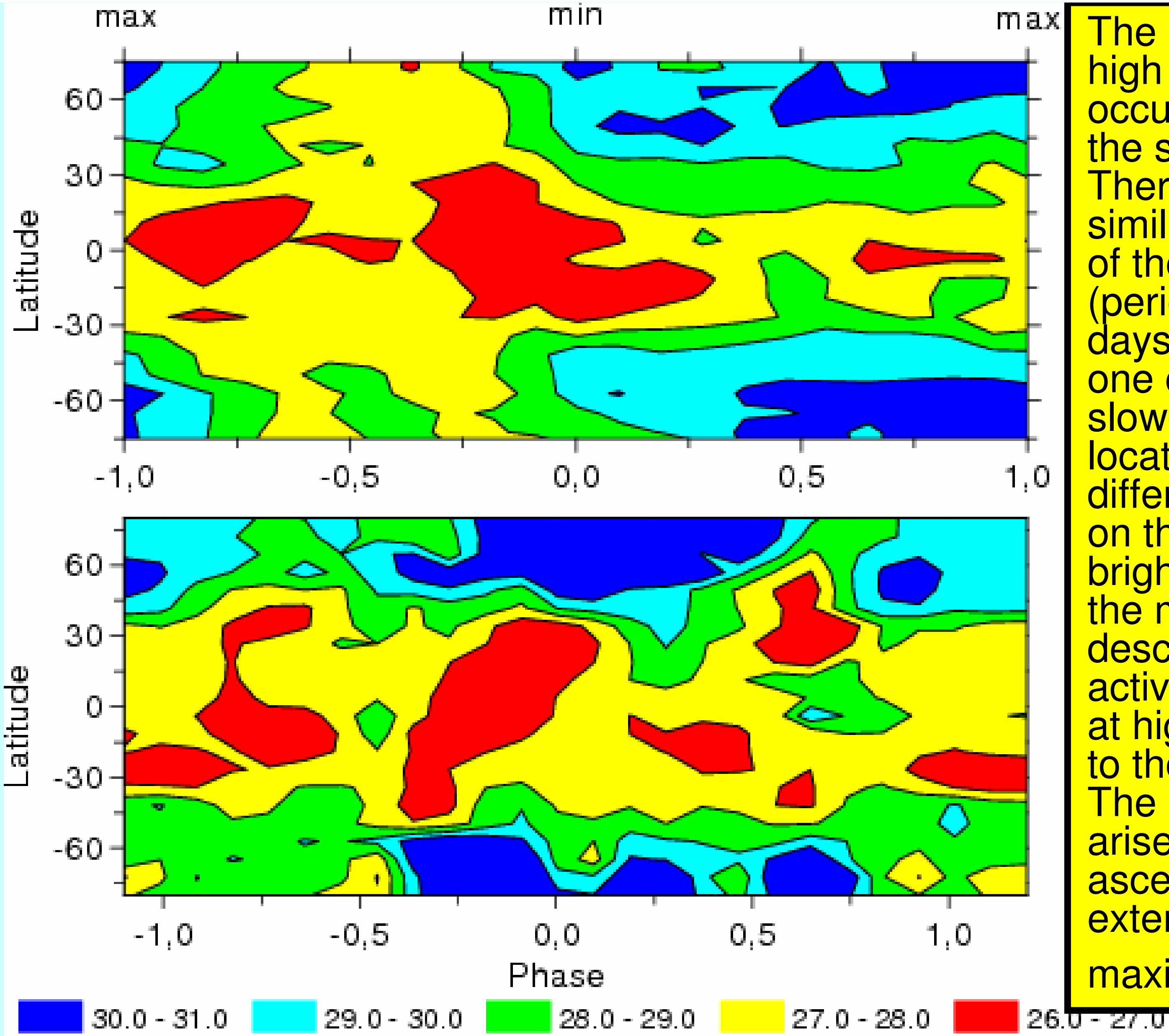


Distribution of the rotation periods of the solar corona on the phase-latitude maps.
The phase is 0 at the minimum of each cycle and ~1 at the maximum.
The heliocentric distances in the range of 1.0 *R – 2.45 R* are shown *.*
The scale of the synodic rotation periods of the corona are given at the bottom.



Time-latitude maps of the rotation periods or the distances 1.1 *R0 (top) and 2.0 R0 (middle).*

- At low latitudes, the periods on both maps do not exceed 28 days.
- At distance 2.0 R_0 the rapidly rotating regions are usually observed after the cycle maximum, at the beginning of the decline phase.
- At high latitudes, the maps do not display any visible periodicity in the appearance of slowly rotating regions (rotation periods more than 30 days, blue color), though there is a hint that they rather tend to form near the minimum of the cycle.



The low--latitude band of high rotation rates occupies approximately the same latitude range. There is also some similarity in the distribution of the fastest rotation rates (periods less than 27 days). At higher latitudes, one can see the zones of slower rotation, but their location on the maps is different. The map based on the green--line brightness shows that, in the middle of the descending branch of activity, the rotation rates at high latitudes are close to those at low latitudes The zones of slow rotation arise at the middle of the ascending branch and extend partly to the maximum. .

Cycle distribution of the rotation periods based on the green--line (top) and magnetic--field (bottom) data.

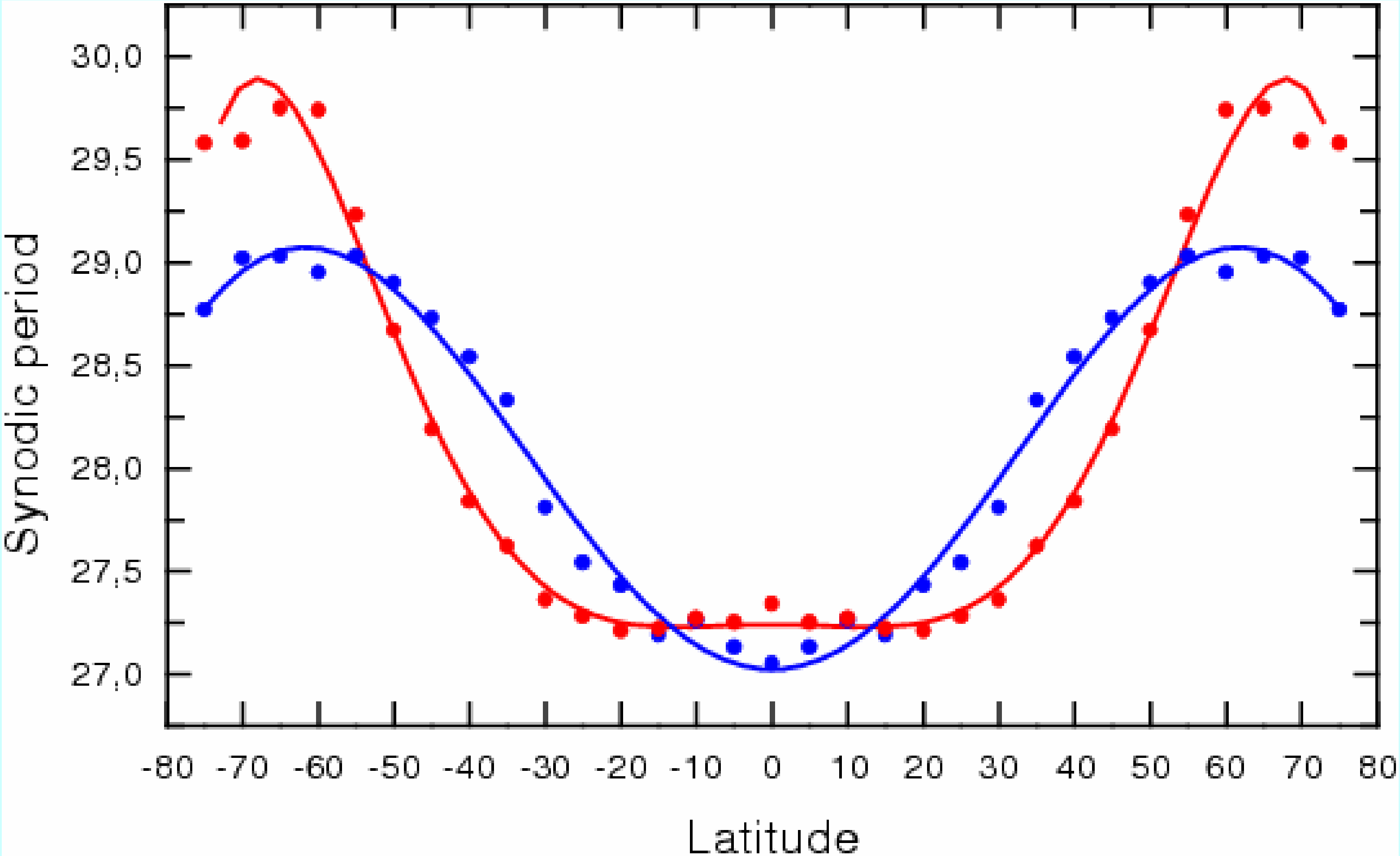


Fig. 9. Synodic periods of the differential rotation of the solar corona as determined from the green--line brightness (blue curve) and magnetic--field data at the distance 1.1 R_0 (red curve).

A decrease of the rotation period is observed at high latitudes This particularity was noted by Stenflo (1989). It is also revealed when determining the rotation of the corona

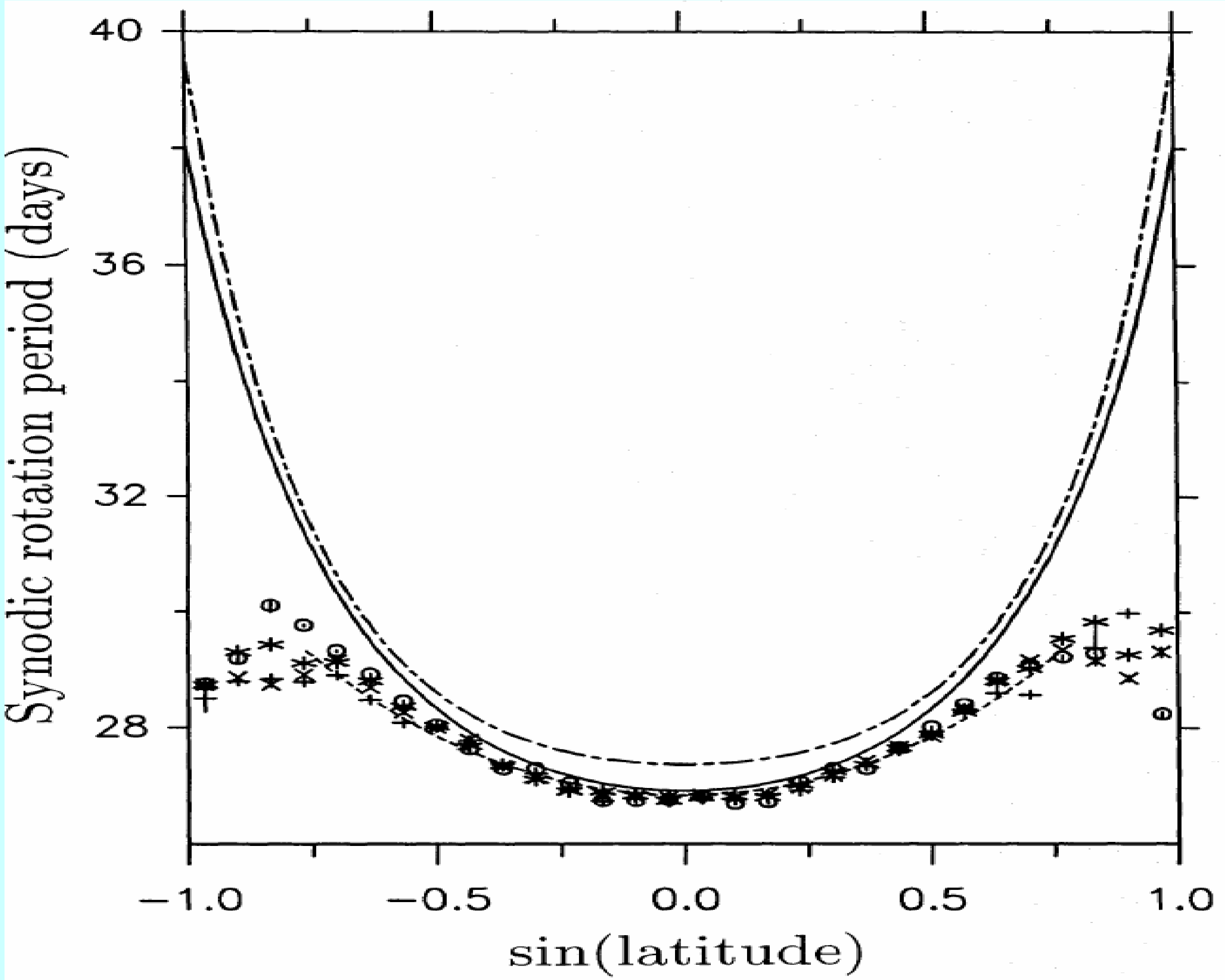


Fig. 2. Synodic period of rotation vs. sine of the latitude. The four different symbols with error bars give the rotation period determined from the first four autocorrelation peaks. Open circles: 1st peak. Stars: 2nd peak. Pluses: 3rd peak. Crosses: 4th peak. The dashed curve was determined in 1974 using the same type of approach, but with a smaller data set (Stenflo, 1974). The solid curve is the magnetic-field rotation law of Snodgrass (1983), the dashed-dotted curve the law obtained from observed Doppler shifts (Howard et al., 1983)

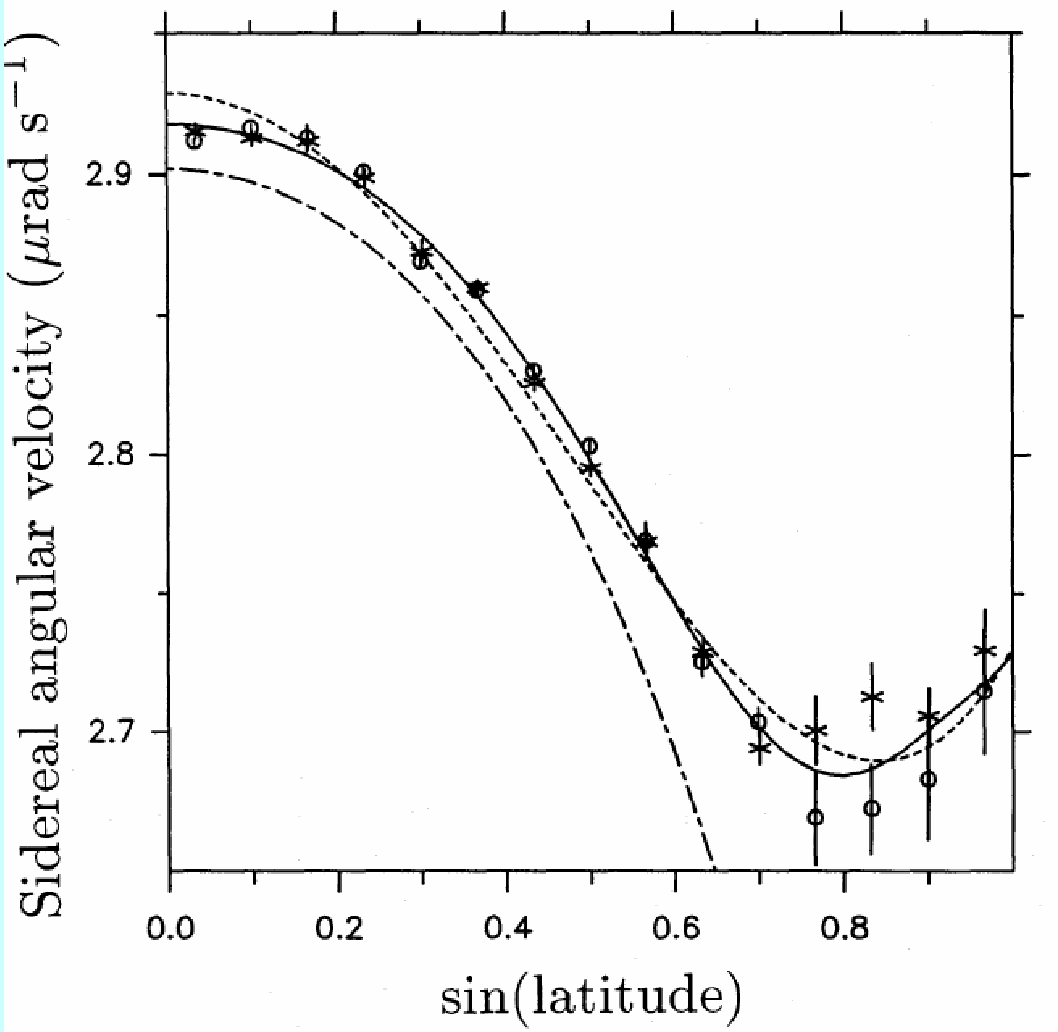


Fig. 3. Sidereal angular velocity of rotation vs. sine of the latitude. Open circles: North hemisphere (average results of the first four autocorrelation peaks). Stars: South hemisphere. Solid curve: Polynomial fit using Eq. (1) with $N = 7$. Dashed curve: Polynomial fit with $N = 2$. Dashed-dotted curve: Rotation law of Snodgrass (1983)

Conclusions

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- 1) the differential gradient of the coronal rotation decreases with distance – as the distance increases, the curves become flatter;
- 2) the synodic period at the equator increases gradually with the increase of the distance;
- 3) The synodic period at the high latitudes decreases gradually (the rotation rate increase) with the increase of the distance
- 5) even in the vicinity of the source surface (2.45 R_0), the rotation of the corona remains differential;
- 6) a decrease of the rotation period is observed at high latitudes **a short distances from the Sun**.

Variations in the differential rotation of the corona with the phase of an activity cycle have been considered in detail. In the time interval under consideration, the largest differential gradient is detected at short heliocentric distances (no more than 1.4 R_0) in the equatorial zone. Both at the ascending and at the descending branch of activity, the rotation of the corona is the less differential the closer we are to the maximum of activity.

Our results show that when going to higher coronal levels, the essentially differential rotation is becoming increasingly rigid. As follows from the calculation procedure itself, this is accompanied by disappearance of high-order harmonics. Thus, at high altitudes, we encounter objects of increasingly large scales.

This reminds us of the change in the rotation characteristics with depth in the subphotospheric layers. Generally speaking, this is not surprising. The coronal rotation reflects the rotation of the subphotospheric layers . The higher layers of the corona reflect the rotation of the deeper layers of the Sun. The proposed method allows us to expect that the study of the corona rotation at different heliocentric distances will make it possible to ‘‘look’’ into the subphotospheric layers and calculate the rotation parameters therein..

- *Thank you for the attention!*