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CHROMOSPHERIC ROTATION DURING 1972–73, YEARS OF DECLINING ACTIVITY

E. ANTONUCCI
Istituto di Fisica Generale, Università di Torino, Italy
and
L. AZZARELLI, P. CASALINI, and S. CERRI
Istituto di Elaborazione della Informazione del CNR, Pisa, Italy

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Abstract. The rotational behaviour of the chromosphere, observed in the Ca II K_3 line, is studied during 1972–1973, years of decreasing solar activity. Daily chromospheric filtergrams, detected at the Anacapri Observatory, are digitized by means of a flying-spot photometer, controlled by computer. The time series of the daily chromospheric data detected at central meridian, relative to 30 consecutive latitude zones, are analyzed to determine the recurrence tendency due to the rotation of long-lived chromospheric features. The computed rotation rate is independent of latitude, in agreement with the results obtained for the green corona during the years before sunspot minimum. Namely both chromospheric and coronal features, with lifetime exceeding one solar rotation, are almost not affected by differential rotation before sunspot minimum.

1. Introduction

A systematic variation of the degree of differential rotation of the solar corona through the solar cycle has been found by studying the coronal behaviour through almost three solar cycles (Antonucci and Svalgaard, 1974; Antonucci and Dodero, 1977). In this study we investigate on a possible dependence on the solar cycle of the rotation rate of the chromosphere, by determining the chromospheric rotation period as a function of heliolatitude during the years of declining activity of the last sunspot cycle (No. 20). This phase of the solar cycle is characterized by a tendency of the solar atmosphere to rotate almost rigidly, at least at coronal height. In fact, in such a period, the degree of coronal differential rotation is reduced, while at the equator the rotation rate remains nearly constant through the whole solar cycle. We think that this rotation behaviour is characteristic of the quiet sun, since differential rotation occurs as soon as activity shows up at a given heliolatitude.

During solar cycle 20 coronal rigid rotation occurs in 1972–73, years preceding the last solar minimum (Antonucci and Dodero, 1977; Wagner, 1975). Therefore this period has been chosen to verify the occurrence of rigid rotation also at chromospheric level.

2. Method

The chromospheric rotation rate as function of heliolatitude is determined by studying the recurrence at central meridian of long-lived chromospheric features at

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various latitudes. Daily chromospheric filtergrams in the Ca II K_3 line are used in this analysis. The photograms are digitized and chromospheric emission data at central meridian are selected. Then the synodic rotation period is computed by performing a frequency analysis of the temporal evolution of the central meridian chromospheric emission at different latitudes. In fact, if the chromospheric pattern as a whole (or an individual feature) persists more than one solar rotation, a periodicity with period equal to the synodic rotation period of such a pattern (or feature) will be present in the chromospheric emission time series (provided proper motions are negligible). The predominant recurrence tendency in the emission time series at a given latitude (associated with the rotation rate of the predominant features) will determine the synodic rotation period at such latitude. Thus the degree of differential rotation can be estimated.

3. Data Analysis

The daily chromospheric filtergrams in the Ca II K_3 line, covering the years 1972–73, have been provided by the Fraunhofer Institut of Freiburg. They are registered at the Anacapri Observatory. These filtergrams are first digitized and corrected for orientation.

The digitization of the chromospheric photograms has been performed at the Istituto di Elaborazione della Informazione di Pisa, using the SADAF flying-spot photometer, controlled by a PDP/8/I (Antonucci *et al.*, 1976). For a photogram of dimensions (24×36) mm^2, the area scanned by the photometer is (24×24) mm^2, and 1024×1024 points are measured. Then each digitized photogram consists of an array of 1024×1024 optical density values. The densitometric resolution is of 64 grey levels in the density range 0.05–2.2. Figure 1 shows the digitization matrix of the chromospheric filtergram of July 7, 1972, as appears on the computer displayer. The scanning is performed perpendicularly to the film reference direction (vertical in Figure 1), which corresponds to the North–South terrestrial axis. Hence an horizontal scanning, as in Figure 1, would yield to digitized filtergrams with an orientation varying day by day in a solar frame. In order to avoid this, on each photogram the N–S solar axis, passing through the solar disk center, is determined by taking into account the daily value of P_0, inclination angle between the solar and terrestrial axes. Then the scanning of each filtergram is performed perpendicularly to the N–S solar axis by means of a suitable computer program, which drives the photometer flying spot along the desired scanning direction.

For each filtergram both the center and the contour of the solar disk image are determined. The background density of the photograms is defined as an average of the values measured at the four corners (corner spots of about 1 mm^2, visible in Figure 2) out of the solar image. Density is measured inside a spot of small area ($\sim 3\times 10^{-2}$ mm^2) moving along the horizontal direction, at the middle of the photogram, and is compared with the background value. We assume that the solar

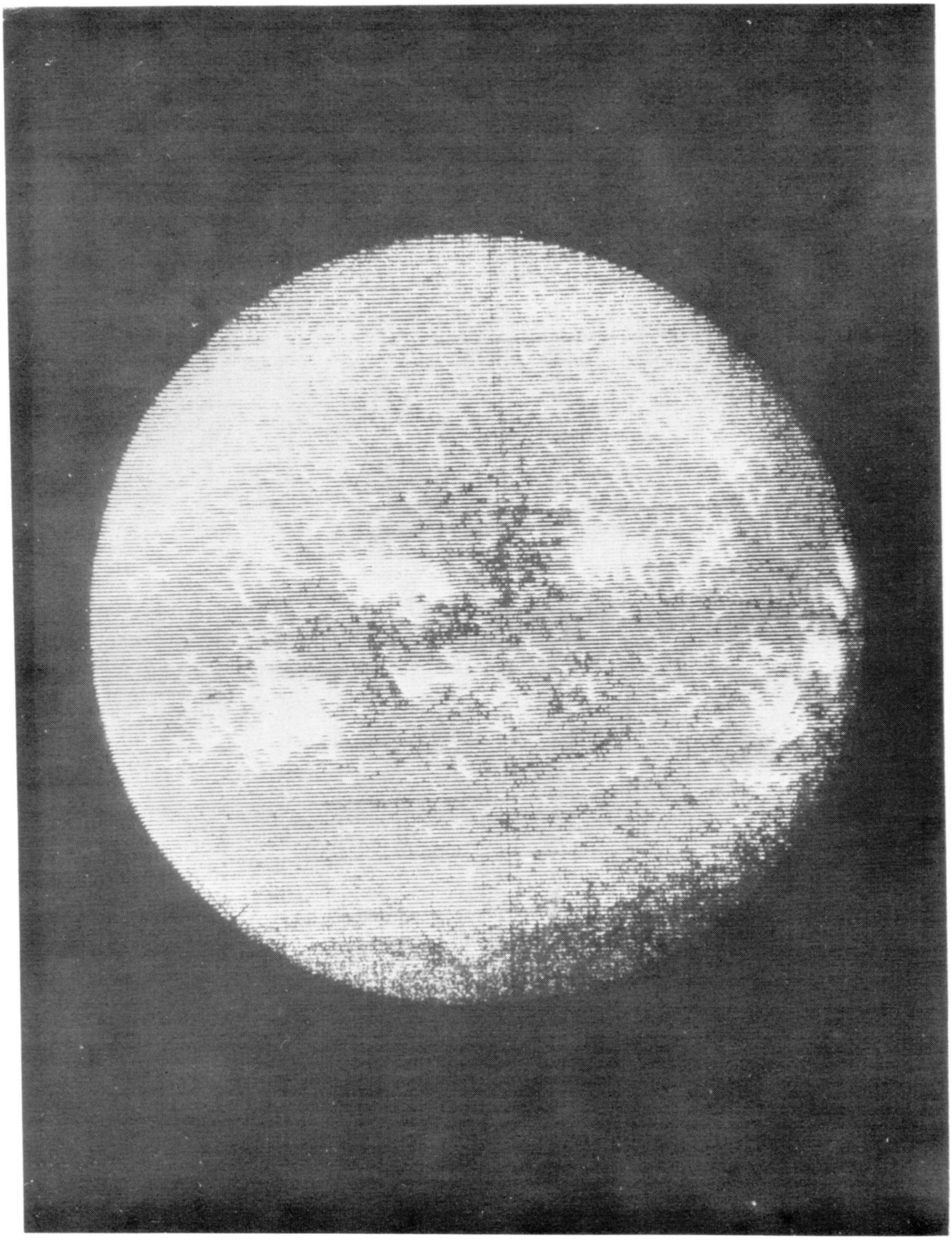

Fig. 1. Chromospheric filtergram, observed in the Ca II K_3 line at the Anacapri Observatory on July 7, 1972, when solar and terrestrial axes are inclined of $P_0 = 0°$, displayed on the computer monitor after digitization. The scanning is performed perpendicularly to the photogram reference direction (terrestrial axis direction); which coincides with the vertical.

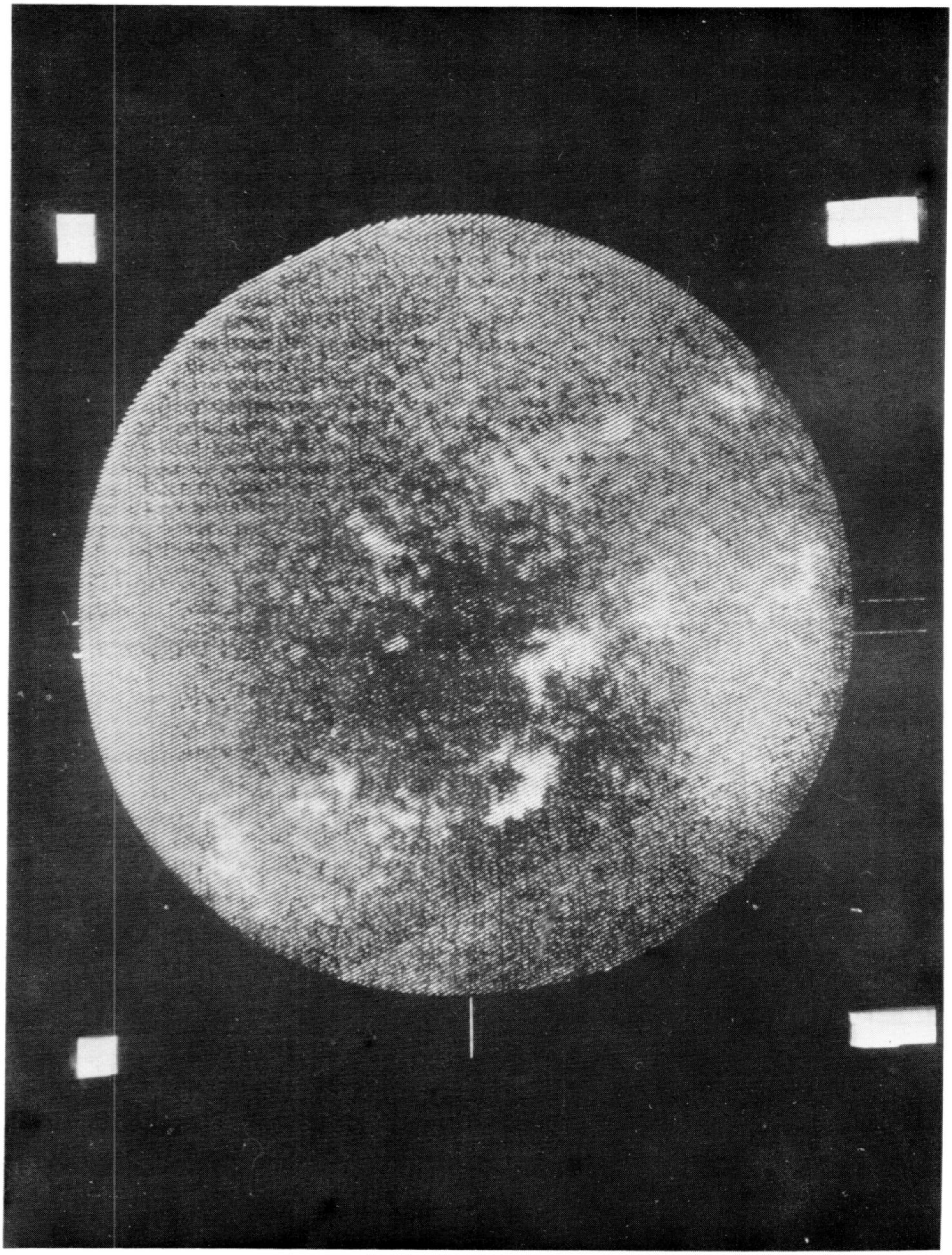

Fig. 2. Chromospheric filtergram in the Ca II K_3 line, observed on October 7, 1972 ($P_0 = +26.^\circ3$). The scanning on the photogram is performed perpendicularly to the solar axis, inclined counterclockwise of $26.^\circ3$ with respect to the vertical. The scanning is performed inside the contour circumference, determined by computer program.

limb is intersected when both the density exceeds the background value and its derivative, along the scanning direction, exceeds a fixed number, to account for the largest deviation of the background density as measured in the four corners. The left and right limb points on the horizontal line are determined by repeating this measure, starting from both left and right sides of the photogram. Using this definition of limb points the center coordinates and the radius of the solar disk are computed and the circumference corresponding to the solar contour is traced. Now the scanning will be performed inside this circumference, with the proper inclination to correct for the tilt P_0 between solar and terrestrial axes, namely perpendicularly to the solar axis (which is varying day by day with respect to the reference direction of the photogram). While outside the solar contour the density is leveled to its lowest value. Thus the digitization matrix is reduced to contain exclusively points inside a square centered on the sun center, with dimension of a solar diameter. Figures 1 and 2 show respectively the digitized filtergrams of the chromosphere observed in the Ca II K_3 line on the 7 July 1972, when $P_0 = 0$ and the scanning is horizontal, and on the 7 October 1972, when $P_0 = +26\overset{\circ}{.}3$ and the scanning is performed with an inclination of $26\overset{\circ}{.}3$ counterclockwise. Hence equally oriented digitized filtergrams are memorized on magnetic tape.

As discussed earlier, in case of existence of long-lived chromospheric features, periodicities related to their rotation, show up in the chromospheric data detected at central meridian as a function of time, which yield to the evaluation of their synodic rotation period. Therefore the solar disk is divided in 30 latitudinal zones and for each zone the daily chromospheric data are ordered as temporal sequences two-year long.

For each digitized filtergram a longitudinal sector, centered on the central meridian and 10° wide, is taken into account. Then this central longitudinal sector is divided in 30 latitudinal zones with the same amplitude in $\sin \lambda$ (λ latitude). Near the equator the zones are $\sim 4°$ wide, and their amplitude in degrees, increases toward the poles. When the equator is tilted, corrections, taking into account the equatorial inclination, are performed to maintain the same latitude belts. Density is averaged over each latitude zone, 10° wide in longitude. Then the data are transformed by subtracting the density averaged over the whole solar disk, in order to reduce the influence of variations from a filtergram to another, due to the daily changes in the observation and detection conditions. And, for each latitude belt, such daily data are ordered in time sequences covering the years 1972–73. Possible gaps are covered by linear interpolation.

A frequency analysis of each time series will allow to determine the periodicities which are present in the chromospheric emission temporal evolution at central meridian. In particular we want to test the existence of the recurrence tendency introduced by solar rotation and, if this is the case, to estimate the degree of differential rotation of the chromosphere as seen in the Ca II K_3 line.

Power spectra of the temporal sequences of chromospheric data are computed separately for the years 1972 and 1973, for each latitude belt. The data of the time series are transformed to have a zero mean value, and the time records are multiplied by the Hanning window function $(\frac{1}{2}-\frac{1}{2}\cos(2\pi t/T))$, where T is the record length. Then the discrete finite fast Fourier transform is performed on each data record, and power spectra are computed. Power spectra, normalized to unit area, are averaged over the two years 1972 and 1973 and then over three consecutive latitude zones, in the assumption that the frequency composition of the chromospheric data changes weakly during the consecutive years 1972–73 and in adjacent latitude zones. Each computed spectrum is then an average of six estimates. Hence the variance on the expected value of each spectral line $\sigma=(G(f)/\sqrt{n})$. 100% ($G(f)$ power of the spectral line at frequency f and n number of estimates of the spectrum) is reduced by a factor 0.4.

4. Results

In Figure 3 power spectra relative to latitude belts of the northern hemisphere are shown; frequencies higher than half a solar rotation frequency f are plotted. Each spectrum displays a dominant peak associated with the rotation frequency f, which corresponds to a 28 day periodicity. Not every power spectrum relative to the equatorial zones and to the southern hemisphere does show a significant peak at the frequency f. The significance of a peak of the spectrum is determined on the basis of the resolution of nearly spectral lines. The peak is assumed to be significant when the separation between two spectral lines, whose powers differ more than two standard deviations, is less than or equal to twice the frequency resolution of the spectrum. Correspondently the uncertainty of the synodic rotation period, estimated from a significant rotation peak, is assumed to be the time interval corresponding to the frequency gap between two resolved spectral lines.

The first consequence of these results is that in the northern hemisphere, within the latitude range 90°–23° N, a persistent chromospheric pattern, living more than one solar rotation, exists. While only in certain belts of the equatorial zone and of the southern hemisphere this is verified, namely transient features or data noise predominate. The power associated with the rotation peaks of the spectra increases with latitude at North. There is almost an increase of a factor 10 from $\sim 30°$ to $\sim 60°$ N; the peak power increases respectively from 5×10^{-3} to 4×10^{-2}. Therefore there is an indication for a less disturbed long-lived chromospheric pattern at high latitudes. On the contrary towards low latitudes, where persistent features can also be associated with activity, the frequency signal due to rotation decreases and sometimes is not significant. Hence the chromospheric pattern is less persistent or various features with different rotation rates and a higher noise level coexist.

The second remark is that the spectra, plotted in Figure 3, peak at exactly the same frequency f at all latitudes, namely the synodic rotation period is invariant within the latitude range 90°–23° N. The value of the chromospheric synodic

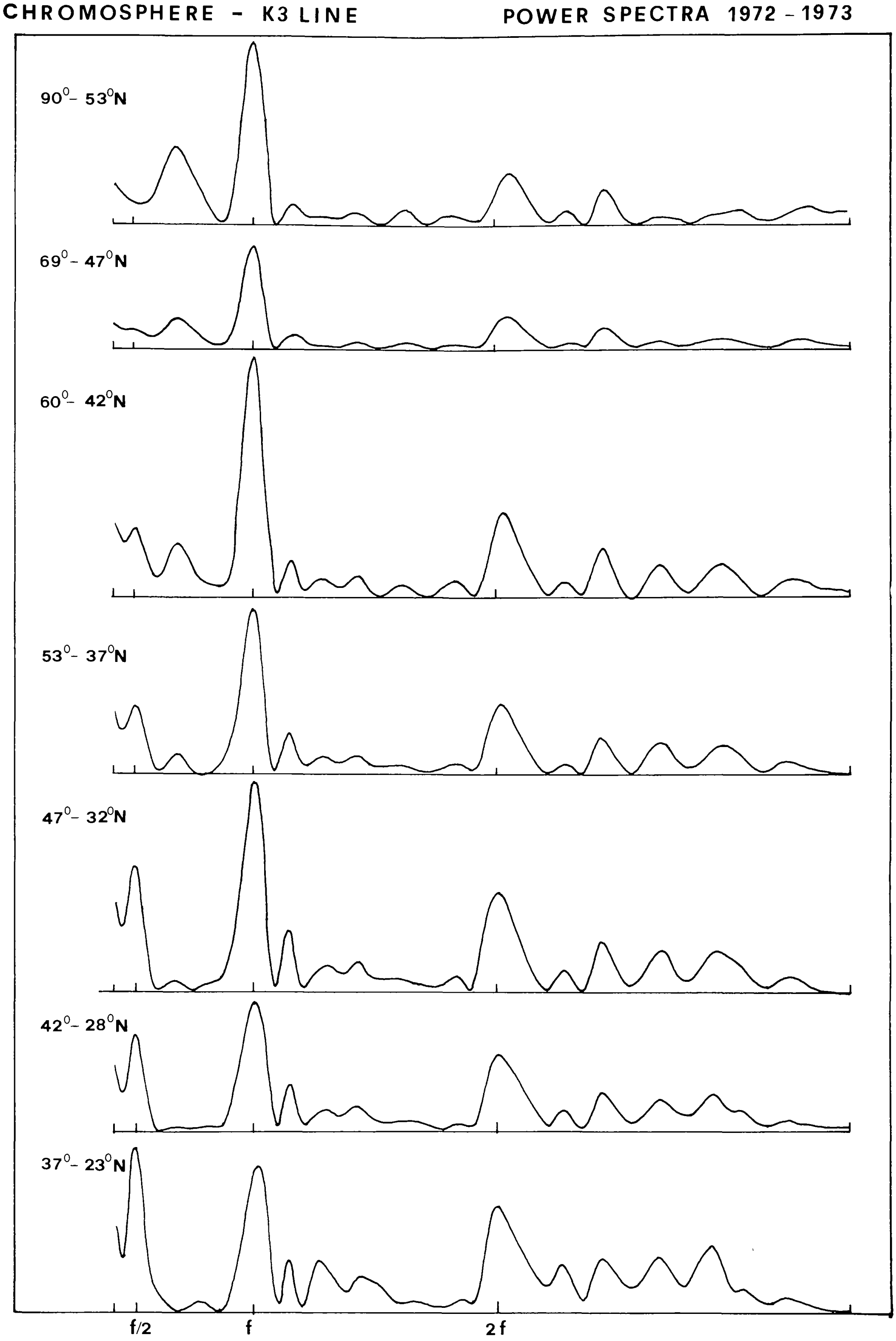

Fig. 3. Power spectra relative to the chromospheric Ca II K_3 line intensity observed near central meridian, at northern heliolatitudes, during 1972–73. Power spectra are normalized to unit area and are not all plotted in the same scale. The frequency f corresponds to the solar rotation frequency.

rotation period for each latitude belt is plotted in Figure 4 with the appropriate error bar. Gaps appear in the chromospheric rotation curve, if the power spectrum does not show a significant rotation peak. The rotation rate can be estimated from 90° N to 28° S approximately, with our method of analysis. Below 28° S the signal-to-noise ratio decreases and unambiguous peaks are not identified in the power spectra.

Although the equatorial synodic rotation period appears somewhat smaller, no differential rotation gradient is appreciable. Within the error limits the chromosphere, observed in the Ca II K_3 line, is not affected by differential rotation during 1972–1973. In Figure 4 the rotation curve of the chromosphere can be compared with the curves relative to the 'quiet' (years of decreasing activity) green corona (λ5303 Å) and to the EUV coronal hole (λ284 Å). Since all these estimates of chromospheric and coronal rotation refer to the same period 1972–1973, they are comparable and are in agreement within the uncertainties. Hence we conclude that the solar atmosphere both at chromospheric and at coronal heights shows evidence of almost rigid rotation in years of declining activity, before solar

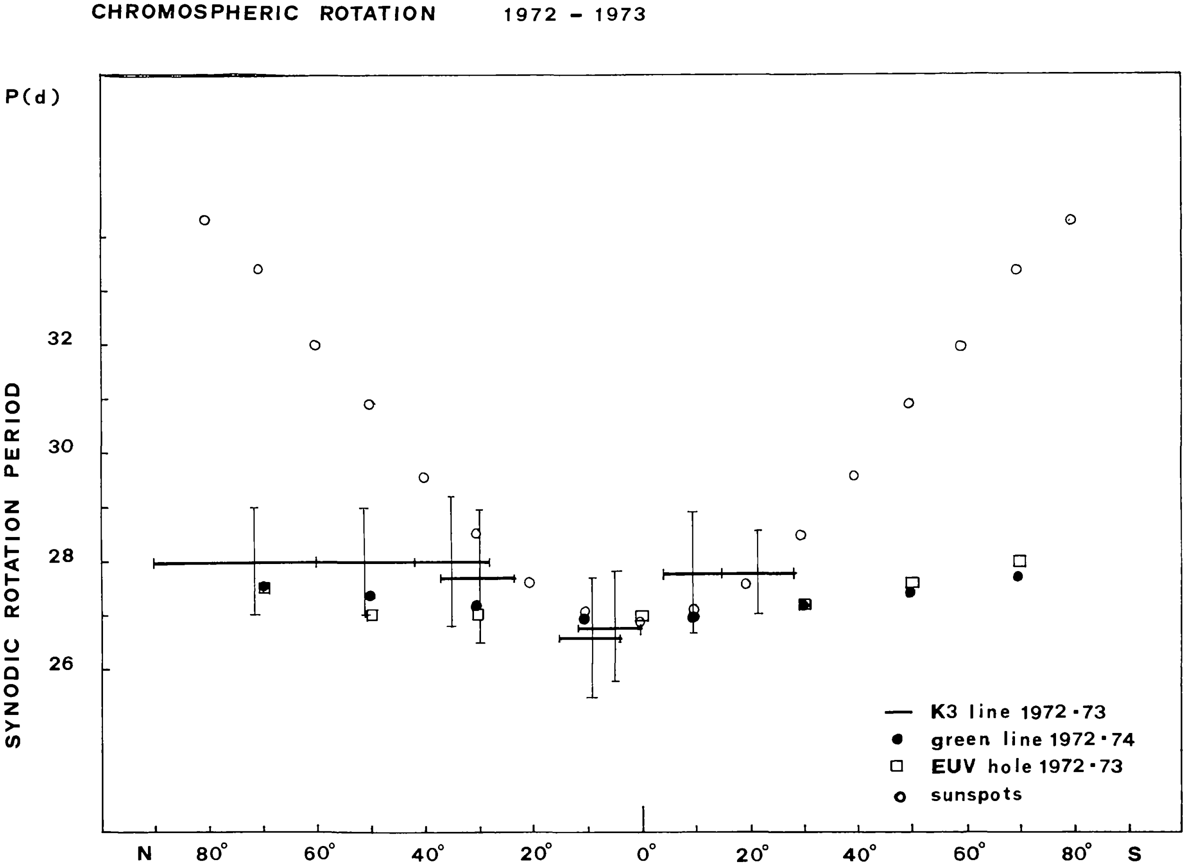

Fig. 4. The synodic rotation periods of the chromosphere, observed in the Ca II K_3 line during the years 1972–1973, are plotted versus latitude. They are relative to three consecutive latitude belts, sliding one latitude belt at a time. The green corona rotation curve, relative to the period January 1972–June 1974 and given in Table I (Antonucci and Dodero, 1977), the EUV coronal hole synodic rotation periods, estimated for the interval May, 1972–October, 1973 (Wagner, 1975), and the sunspot rotation curve (Newton and Nunn, 1951) are reported for comparison.

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minimum. As a consequence of these results we suggest that the chromosphere also changes its rotation conditions through the solar cycle, as the green corona, switching from differential to rigid rotation in the last phase of the cycle.

The equatorial rotation rate of the Ca II chromosphere and of the green corona (27 days, synodic period) does agree with the rate of photospheric magnetic features, both sunspots and large-scale magnetic fields.

5. Comparison with Other Results

In the present study we have selected tracers of chromospheric rotation with lifetime exceeding one solar rotation period at least. Almost every result available

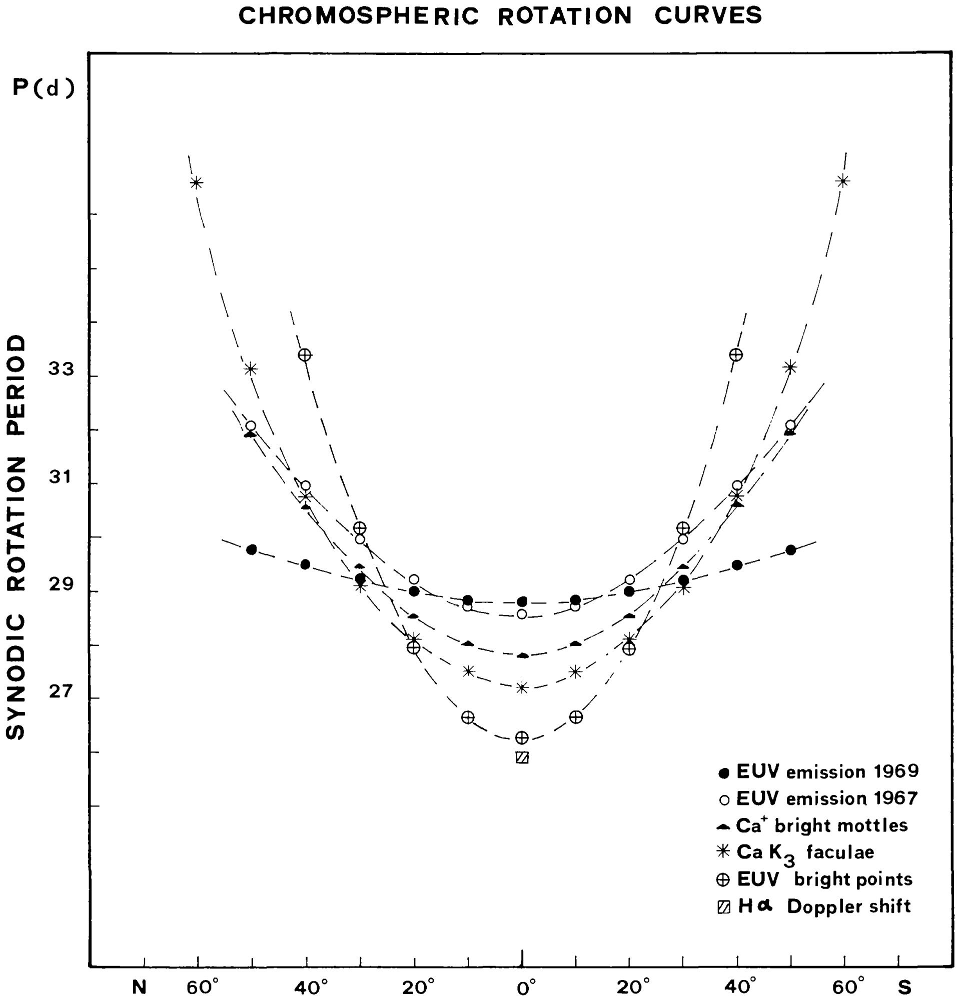

Fig. 5. Rotation curves of short-lived chromospheric features: Ca K_3 faculae, 1948–49, by Miloševič (1955b) (stars); EUV bright points by Simon and Noyes (1972) (circles and crosses), Ca$^+$ bright mottles by Schröter and Wöhl, (1976) (triangles); EUV short-lived emission during 1967 (circles) and 1969 (solid dots) by Dupree and Henze (1972, 1973); Hα Doppler shift measurement (dashed square) by Livingston, (1969b). The equatorial synodic rotation period ranges from 28.78 ± 0.45 days, for LC short-lived emission (Dupree and Henze, 1973) to 25.87 days for Hα Doppler shift measurement (Livingston, 1969b). The differential rotation degree is highly variable for various tracers and does not appear to be related to the solar cycle phase.

TABLE I

Sidereal rotational velocities of solar chromosphere and corona

	a (deg day^{-1})	b	σ	Period	Latitude range
Long-lived features:					
Chromosphere, Ca II K_3 line	14.09	−0.37	0.2	1972–73	90° N–28° S
Corona, green line	14.33	−0.34	0.13	1972–74	67°.5 N–62°.5 S
EUV coronal hole	14.33	−0.39	0.04	1972–73	80° N–80° S
Short-lived features:					
LC bright points	14.7±0.2	−7.1±1.1		1967(27-X/29-XI)	50° N–50° S
LC short-lived emission	13.59	−2.34	0.4	1967(25-X/27-XI)	55° N–55° S
LC short-lived emission	13.49	−0.68	0.21	1969(27-X/28-XI)	50° N–50° S
Ca^+ bright mottles	13.93±0.08	−2.9±0.73		1974–75	40° N–40° S
Hα Doppler shift	14.9			1968(30-31/XII)	80° N–80° S
Ca, K_3 faculae	14.1	−3.23		1953–54	80° N–80° S
Ca, K_3 faculae	14.18	−3.05		1948-49	70° N–70° S

on chromospheric rotation instead refer to short-lived tracers: small chromospheric faculae, observed in the Ca II K_3 line, with life-time of 2 or 3 days (Miloševič, 1955a, b); bright points of active regions in Lyman continuum, with maximum rotation path observed over a time interval of 5 days (OSO-IV observations, Simon and Noyes, 1972); short-lived Lyman continuum emission analyzed by statistical techniques over $\leqslant 3$ days (OSO-IV and VI observations, Dupree and Henze, 1972; Henze and Dupree, 1973); bright mottles of the Ca^+ network, followed in their path for 3 to 5 hr (Schröter and Wöhl, 1975, 1976); chromospheric K faculae (Belvedere *et al.*, 1976) Rotational chromospheric velocities have also been measured directly by Doppler shift of Hα lines (Livingston, 1969a, b). Figure 5 shows the rotation curves relative to short-lived chromospheric features. Although no observation of differential rotation, reported in Figure 5, refers only to periods of decreasing activity (estimates for sunspot minimum are available: Miloševič (1955a), Schröter and Wöhl (1975, 1976), probably the differential rotation profile for short-lived chromospheric features is not related to the solar cycle phase as for the long-lived features.

Table I reports the sidereal angular velocity ω (deg day^{-1}) vs latitude λ, in the form of $\omega = a + b \sin^2 \lambda$ (only in the case of Miloševič results, $\omega = a + b\lambda^2$ is used) for short and long-lived chromospheric features, green corona and the EUV coronal hole. The rms deviation of the single data points from the fitted curves is indicated by σ in Table I.

6. Conclusion

In conclusion the long-lived chromospheric pattern, observed in the Ca II K_3 line, rotates rigidly during years of decreasing solar activity (1972–1973), as the green corona. We think this result confirms the dependence of the solar atmosphere rotation rate on the solar cycle phase, at least for persistent features; differential rotation takes place as a slow down at high latitudes, synchronized with the appearance of activity.

The existence of persistent chromospheric features, not related to activity is also confirmed. They live at least more than one solar rotation and show up more clearly at higher latitudes. On the basis of the agreement of chromospheric results with the green corona (and in particular with the coronal hole) rotation rate estimate, one suggestion is that coronal holes are dominant features during periods of low activity and affect also the chromospheric level. Hence, because of the statistical approach, they are predominant in determining the value of coronal and chromospheric synodic rotation periods. Another possible interpretation is that, in quiet conditions, the chromospheric network shows a non-uniform persistent pattern, which rotates independently of latitude. This same view has been proposed for the corona: the coronal 'quiet' pattern as a whole rotates rigidly (with coronal holes as a part of it) in 1972–1973 and is organized in a dipolar manner (Antonucci and Dodero, 1977). This last characteristic can be revealed in the chromosphere too; in Figure 3, the significant peak present in each spectrum at twice the rotation frequency suggests a dipolar structure also at chromospheric level. Hence both the large-scale organization and the rotational behaviour show the same characteristics at chromospheric and coronal heights.

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