FILAMENTS DIFFERENTIAL ROTATION BEHAVIOR WITHIN THE SOLAR CYCLE

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Abstract. A study of filaments observed during 1957–1989 reveals that the differential rotation velocity changes within the solar cycle. We propose that these variations are the manifestation of the torsional oscillations of the coronal magnetic field.

Key words: Sun – filaments – differential rotation.

1. INTRODUCTION

Helioseismology has transformed our understanding of the Sun's rotation. Earlier studies revealed the Sun's surface rotation, but now a detailed observational picture has been built up of the internal rotation of our nearest star. We know less about the large scale flows in the corona and about the filaments motions.

The solar differential rotation has been determined observationally from different classes of tracers: spots, magnetic features, CaK images, supergranulation, coronal brightness. The laws obtained are specific from tracer to tracer. D'Azambuja obtained the most used differential rotation law for filaments in 1948. The filaments are well-known good tracers of the solar magnetic field, they are magnetic arcades which bring together different layers of the atmosphere, from the convective zone to the corona. Glackin (1974) investigated the latitudinal component of solar differential rotation and the existence of a radial component, for filaments. He concluded that the difference of the rate of rotation between spots and filaments is too large to be accounted to the poleward migration. He showed that filaments located far from the active region rotate faster than those located nearby active regions. The filaments are faster than the photosphere by 40 m/s.

In this paper we focus on the study of the filaments rotation during the period 1957–1989. An investigation of the differential rotation is performed in Section 3, while the meridional circulation is added in Section 4. We have fitted the laws of motion for each of the 33 years related with a standard law, in the lack of observations

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for such a long period. The difference between them reveals another motion that we found to be an oscillatory one.

2. THE BUTTERFLY DIAGRAM OF FILAMENTS

We have considered the data of the mean coordinates of filaments for three solar cycles (1957–1989), as extracted from *Solar Geophysical Data*. Fig. 1 plots the distribution in latitude of filaments on the solar disk during this period of 33 years; t_i stands for the Carrington Rotations number, ranging between 1389 and 1823. Two bands of filaments are observed: one migrating toward poles and the other toward equator.

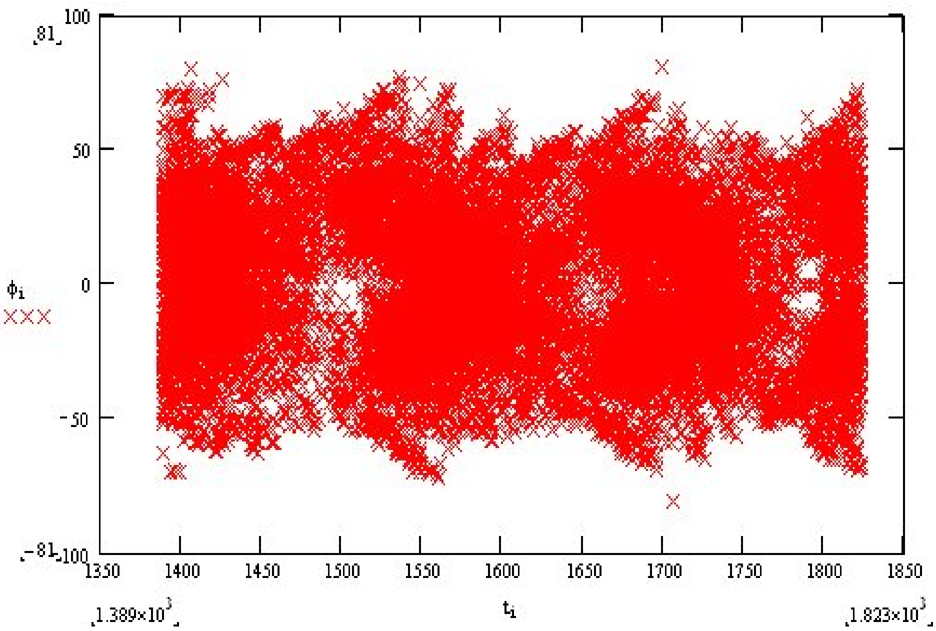


Fig. 1 – The filaments latitude distribution Carrington between rotations 1389 and 1823.

A poleward migration of filaments could be observed in more stages, within the solar cycle. For instance, a zoom of Fig. 1, representing the cycle No. 20, is displayed in Fig. 2. The central, low-latitude part is similar to a butterfly diagram, but more wings go toward the solar poles. The low-latitude filaments follow the active regions, while the polar crown forms few times during an eleven-year cycle. The migrations toward poles or toward equator produce at the same time as distinct categories, as two distinct patterns. It is well known that the high-latitude filaments are bigger than the low-latitude ones. The long and quiet filaments migrate toward poles, displaying low differential rotation rates – this motion implies an important meridional flow, too, but also less perturbations than in active latitudes. The second pattern follows the active region and also the large-scale displayed by the torsional oscillations; the last ones are described in literature as azimuthal bands migrating toward low latitudes.

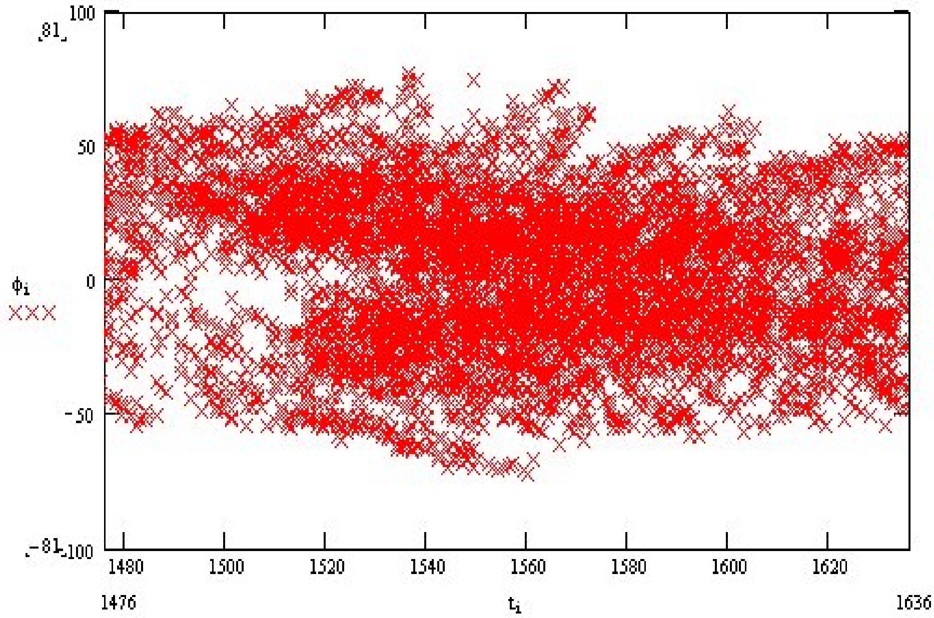


Fig. 2 – Solar cycle No. 20: the filaments distribution on the disk.

3. THE DIFFERENTIAL ROTATION WITHIN THREE SOLAR CYCLES

Our purpose is to study the filaments rotation behavior within the solar cycle. Are there variations or not, and if yes, what kind of variations they are?

D'Azambuja (1948) established the law of the differential rotation of filaments, most used in the literature, that we use as standard:

$$\omega a(\phi) = 14.42 - 1.4\sin^2\phi - 1.33\sin^4\phi\,. \tag{1}$$

Since we had no observational measurements for the differential rotation of these 19060 filaments, registered between 1957–1989, we used the values given by d'Azambuja as "observed" ones, as standard values, and we fitted the expression

$$W(k,\phi) = AA_k + BB_k \cdot \sin^2\phi + CC_k \cdot \sin^4\phi, \tag{2}$$

year by year, obtaining 33 laws ($k = \overline{1,33}$ represent the years) for the differential rotation. The results are plotted as displayed in Fig. 3. The curves obtained by these calculations are “oscillating” around the curve representing d’Azambuja law, used as standard. For latitudes higher than 40 degrees, there are maximum of variations from the d’Azambuja law, i.e., the polar filaments are especially subject to other motions. This aspect is in concordance with the measurements made by Brajsa et al. (1991), who have shown that the d’Azambuja law must be modified for the polar filaments.

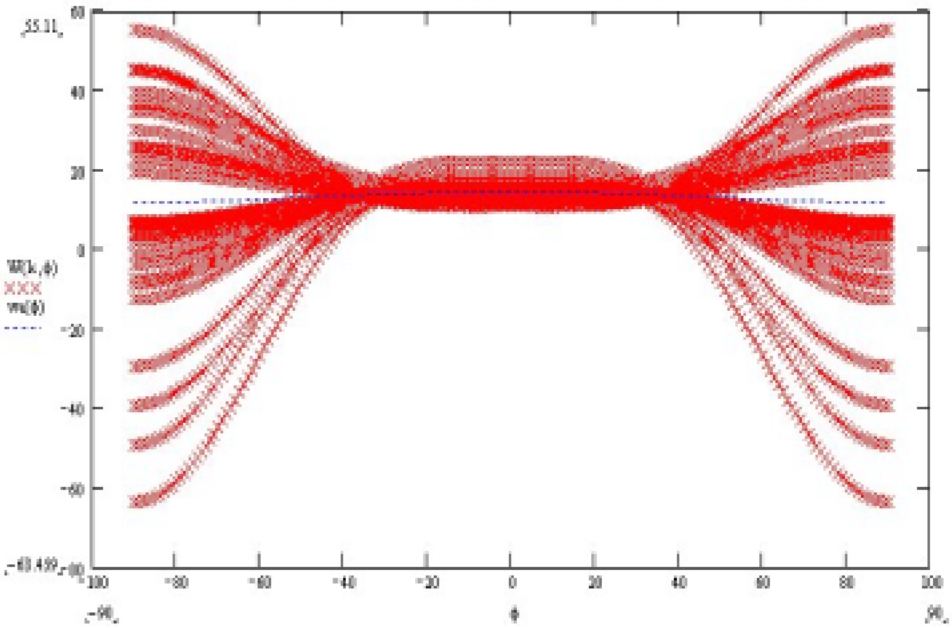
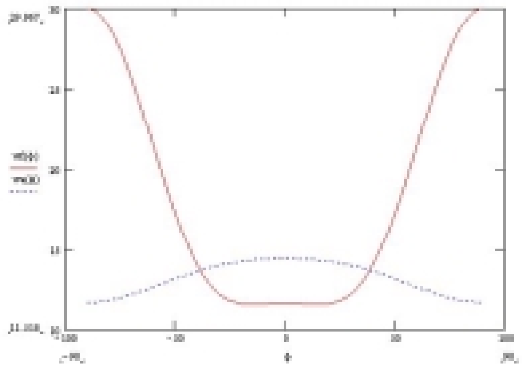
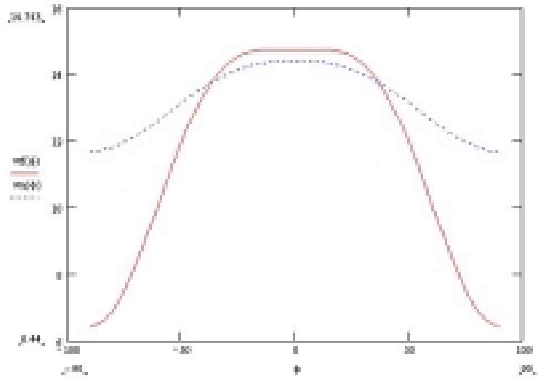


Fig. 3 – The fitted laws of the differential rotation of filaments during 1957–1989 compared with d'Azambuja law (dotted line).

A normal question is about how these laws are at the solar maximum and how there are at the minimum of solar activity. The answer could be found in Fig. 4. One of the most interesting results is the fact that the curves of type (a) are found near the sunspot minimum year of solar activity, while during the rest of the cycle, especially near the solar maximum, the fitted curves are of type (b). Curves of type (a) are found for the years: 1963–1965, 1974–1977, and 1986–1987. This result implies polar velocities of filaments greater at the solar minimum related to the maximum.



(a)



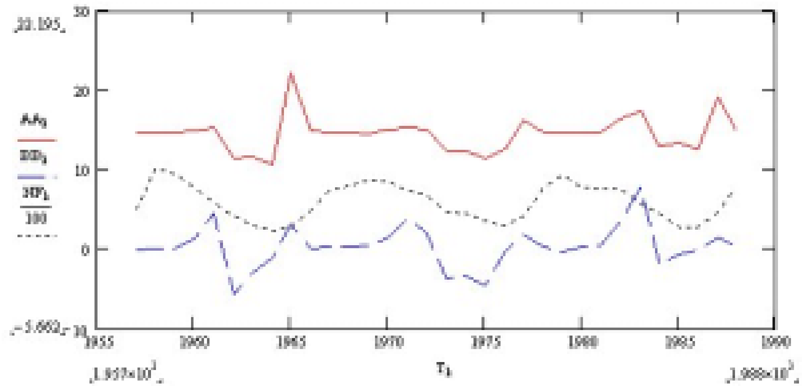
(b)

Fig. 4 – Different forms of the differential velocity law for filaments:
(a) at the solar minimum and (b) at the solar maximum.

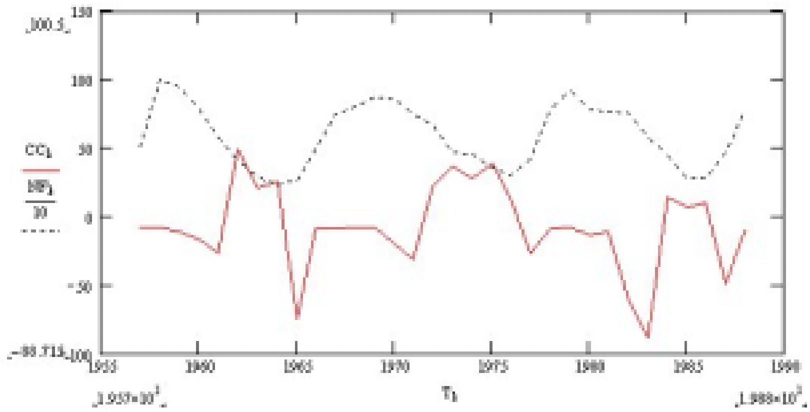
The long-term variations of the coefficients are plotted in figures 5. In equation (2), the coefficients AA_k represent the rigid body rates and BB_k, CC_k represent the shear, decomposed into modes of wave number 1/2, respectively 1 hemisphere. The series AA_k and BB_k are in phase, between them and the solar cycle, while CC_k is of opposition of phase with the others (Fig. 5), i.e., the coefficients CC_k reach their minimum at the maximum of activity for filaments within the solar cycle.

4. LARGE-SCALE MOTIONS

The surface flows are dominated by the basic rotation of the Sun, the meridional and cellular convection flows. These flows and their extensions into the interior play a significant role in the solar cycle dynamics. The differential rotation plays an essential role in generating the solar magnetic fields. Carrington established the differential rotation of the Sun's surface, in the 19th century, for sunspots first. Different laws were determinate for different tracers. The meridional circulation was more observed in the last tens years. Some authors found the meridional circulation to be equatorialward, while others suggest that, on the average, it is poleward oriented.



(a)



(b)

Fig. 5 – The coefficients AA_k, BB_k, CC_k variations during the solar cycles compared with the number of filaments *NF*.

Howard and LaBonte (1980) found the solar torsional oscillations in the analysis of Mount Wilson Doppler data. These are global periodic flows closely related to the magnetic activity. *The torsional oscillations are latitude bands of slightly faster and slower rotation propagating toward the equator during the solar cycle.* The mechanism responsible for producing the 11-year solar torsional oscillations is thought to be the non-linear interaction between the magnetic field and the solar differential rotation. The active regions tend to form in the places where the latitudinal shear is enhanced. The magnetic features seem to rotate faster than the photospheric plasma. Kichatinov (1990) considered two mechanisms by which a large-scale magnetic field affects a global zonal flow: the first one is the Lorentz force and the second is the effect of the magnetic filed on the small-scale turbulent motions, i.e., the Reynolds stress. Snodgrass an Dailey (1996) and Snodgrass and Smith (2000) consider the torsional oscillations as an artifact of the meridional motions. On the contrary, Ulrich et al. (1988) state that the torsional oscillations are much wavelike than they are cell-like.

The filaments are subjects of these motions, but we know more about the differential rotation velocity and the meridional circulation. If we consider a movement formed by these two, the rest of the total motions could contain also the torsional oscillations. The module of the motions we search for is expressed by

$$W(\phi, k) = \sqrt{Wd^2(\phi, k) + Wm^2(\phi, k)}\,, \tag{3}$$

where $k = \overline{1, 33}$ represent the years; $Wd(\phi, k)$ is the differential rotation, while $Wm(\phi, k)$ is the meridional motion expressed respectively by

$$Wd(\phi, k) = A_{0,k} + A_{1,k} \cdot \sin^2(\phi) + A_{2,k} \cdot \sin^4(\phi)\,, \tag{4}$$

$$Wm(\phi, k) = A_{3,k} \cdot \sin(\phi) + A_{4,k} \cdot \sin(2\phi) + A_{5,k} \cdot \sin(4\phi)\,. \tag{5}$$

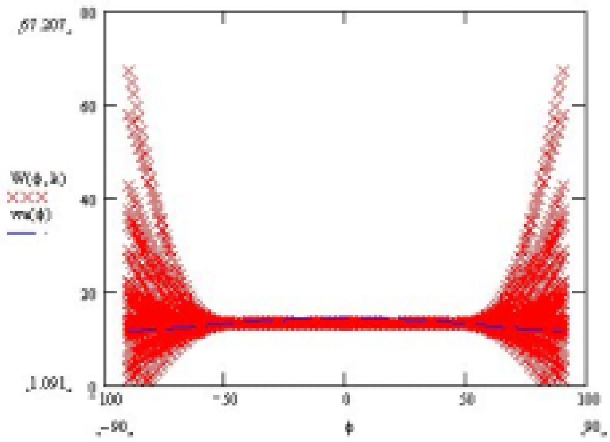
We obtain 33 laws for the years 1957–1989, plotted in Fig. 6 along with the d'Azambuja law (dashed line).

We observe the same oscillation of the curves around the classical d'Azambuja law, in the case of the total motion composed by *Wd* and *Wm* (Fig. 6a), as for as the differential rotation laws (Fig. 6b). The meridional motions (Fig. 6c) display also variations within the solar cycle, but the values obtained exceed the d'Azambuja law values only for latitudes higher than 50 degrees and for the years when we observe the poleward migration (Section 2). The 33 laws obtained for the meridional circulation do not seem to present a regular periodicity.

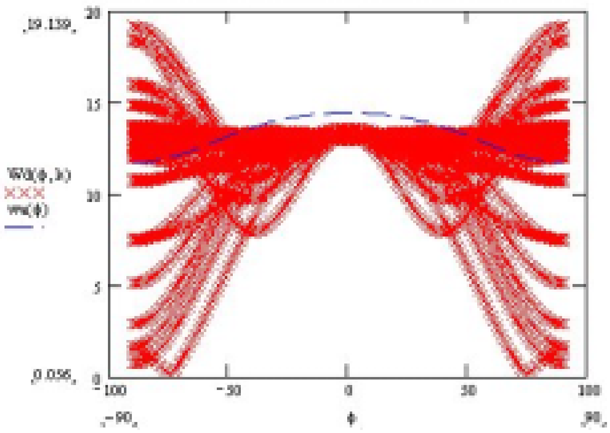
5. CONCLUSIONS

The differential rotation of magnetic features is important to be understood since, together with the meridional circulation, plays an essential role in the solar dynamo.

We have fitted the differential rotation laws (Section 3) and the movement composed by differential rotation and the meridional circulation (Section 4). In the absence of observational data, we have used the values given by d'Azambuja law as standard ones. The results of our investigations reveal in both cases oscillating curves around a mean curve. The difference between the standard law and the fitted laws contain the torsional oscillation, too, as manifestation of a vibrating star.



(a)



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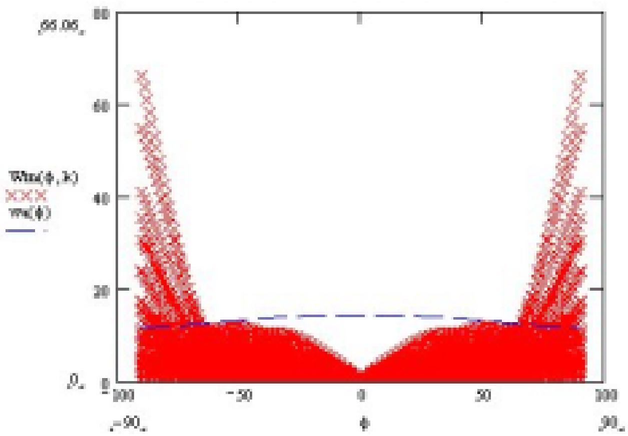

(c)

Fig. 6 – The fit of the motion of filaments over three solar cycles: (a) differential and meridional motion; (b) differential rotation; (c) meridional circulation.

The differential rotation is found to have a cyclical behavior in the 11-year cycle, while the meridional circulation seems to follow a more complicated pattern. The regular pattern of periodic oscillations of the curves is revealed, in both cases of calculations, by the differential rotation laws or by the total rotation $W(\phi, k)$ containing the differential rotation motion, too.

For these reasons we conclude that the differential rotation of the Sun causes distortions of the large-scale circulation pattern and introduce spherical harmonic waves-like. These results agree with similar research, observational or simulations, made during the last years.

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