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Sunspot motion in a recurrent region as a sub-photospheric circulation tracer

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RESUMEN

El movimiento propio de un grupo de manchas recurrente, expresado en una regresión polinomial de segundo grado, muestra un desplazamiento suave de la fuente sub-fotosférica del campo. Este desplazamiento se aprecia en el movimiento “regular” de las manchas de larga vida del grupo. Las observaciones de un grupo recurrente muestran un movimiento meridional de las manchas hacia el polo, contrario a resultados previos. El acuerdo cualitativo entre los resultados observacionales y la estructura solar sub-fotosférica sugiere que la circulación fotosférica puede ser descrita por el movimiento propio de las manchas solares.

PALABRAS CLAVE: Estructura del Sol, fuentes del campo magnético, movimiento propio.

ABSTRACT

A second order polynomial regression of the sunspot motion in a recurrent group shows a smooth displacement of the sub-photospheric field source. This displacement is seen in the regular motion of the longer-lived spots of the group. The observations of a recurrent group show a sunspot meridian movement toward the pole, contrary to previous results. The qualitative agreement between observational results and the proposed sub-photospheric solar structure suggest that photospheric circulation may be described by sunspot motion.

KEY WORDS: Solar structure, magnetic field sources, proper motion.

INTRODUCTION

A complete description of the solar dynamo mechanism includes the angular momentum transport mechanism in the photospheric and sub-photospheric layers. Gilman (1980) proposed a circulation towards the equator at photospheric levels and towards the pole at deeper layers of the solar fluid. Kambry *et al.* (1991) found no good agreement between measurements made by spectroscopic techniques and by tracer techniques, particularly for sunspots. Using the spot motion method, they proposed a flux toward the equator in the -20 to +15 degrees range of latitude, in disagreement with Gilman (1980). The depth for which sunspots are optimal tracers is still unknown. However, there is a strong 1ink between sunspot magnetic fields, group development, and the solar cycle stage (Bumba, 1994).

Analysis of groups with long life times might provide some clues of solar fluid circulation, especially if the magnetic field intensity of the tracer is taken into account.

This paper discusses the motion of the main spot of a recurrent group with a complex evolution. We identify the spot during two successive solar rotations, and the kinematic treatment of its motion allows us to disclose a regular pattern.

OBSERVATIONS AND METHODS

Sunspot observations were made at the Institute of Geophysics and Astronomy, Havana, from March to May, 1976. The photoheliograms were obtained with a 25 cm objective refractor with a bypass band of 100 Angstroms. The image of the sun has a diameter of 25 mm. Accurate determination of the sunspot solar coordinates (Table 1) was done with a KIM-2 coordinate measurement machine, following the method of Doval (1983). The motion parameter estimation was done with the MOVPROP program, developed by Yu. Nagovitzin, from the Main Astronomical Observatory in Russia. The program uses a spline process to obtain equally spaced values of latitude and longitude at one day intervals. A second-degree polynomial is fitted to 5 splined points describing the sunspot trajectory. Considering independent movements in latitude (lat) and longitude (lon), the process is done independently for each coordinate.

$$lon = lon_0 + V_{lon} * t + A_{lon} * t^2 \qquad (1)$$

$$lat = lat_0 + V_{lat} * t + A_{lat} * t^2 \ , \qquad (2)$$

where V is the velocity, A is acceleration, t is time and lon_0 and lat_0 are the constant components for the 5-point interval.

Table 1

Data for a recurrent sunspot during its second and third rotations. DAY, time of observation (referred to March 1976); LON and LAT, longitude and latitude; Spm, main spot area, and Sg, total group area, both in mvh

DAY	LON	LAT	Sg	Spar
26.62	43.67	-7.48	876	516
27.81	43.50	-7.58	707	275
28.59	43.42	-7.67	797	<414
29.64	43.30	-8.09	840	723
30.81	42.82	-8.49	840	793
31.84	42.77	-8.78	651	639
32.80	42.73	-8.90	626	592
33.61	42.84	-9.00	597	585
34.80	43.07	-9.03	615	607
52.60	41.30	-9.19	253	253
53.76	41.26	-9.32	251	238
54.75	41.00	-9.30	246	246
55.78	40.82	-9.52	240	228
56.56	41.04	-9.62	241	241
57.75	40.88	9.88	245	140
58.76	40.97	-10.12	214	200
59.75	40.80	-10.20	196	179
60.59	40.64	-10.26	301	176
61.58	40.39	-10.44	535	163
62.59	40.54	-10.50	561	169
63.62	40.21	-10.29	215	139

A polynomial is obtained for each segment of the path. The different estimations of the parameters were averaged to establish a path we call 'regular'. In this way the motion of the main spot of the recurrent group, identified as group 16 (rotation 2) and 24 (rotation 3) of 1976 by Solar Data (Solnechnye Dannye) classification, is obtained.

Table 2 shows the values of these parameters including the moduli of the velocity (VEL) and the acceleration (ACEL). DES is the distance between the regular path and the splined calculated positions.

RESULTS AND DISCUSSION

The spot, during its lifetime, shows a latitude drift towards the pole (Figure 1). In the second rotation it drifts 0.21 degrees per day, and in its third the drift reaches 0.14 degrees per day.

This result might be explained qualitatively if the subphotospheric fluid circulating toward the pole drags the sunspot magnetic field lines anchored at this depth.

The longitudinal motion is shown in Figure 2. Spot motions were calculated for the Carrington system of coordinates, where the solar rotation period is 25.38 days (14.18

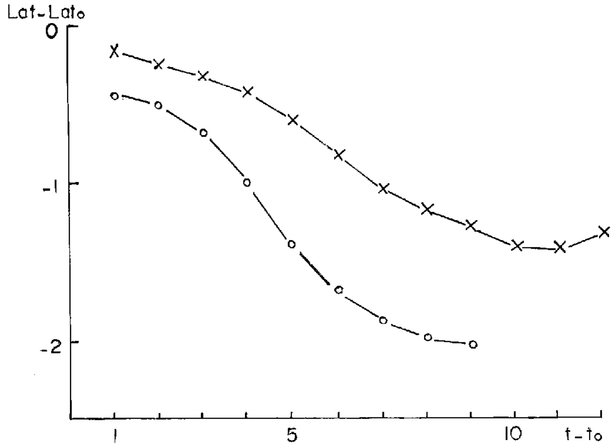

Fig. 1. Observed variation of sunspot latitude during its second (o) and third (x) rotations. Zero value refers to -7 and -9 degrees (lat$_0$) for the respective rotations. During the second rotation is drift 0.21 degrees per day (between 0.1 and 0.4 degrees per day in different sections of the path). For the third rotation the latitude variation is 0.14 degrees per day. On the X axis zero refers to March 25 and April 20, 1976 (t_0=25 and 51 day) for the second and third rotations respectively.

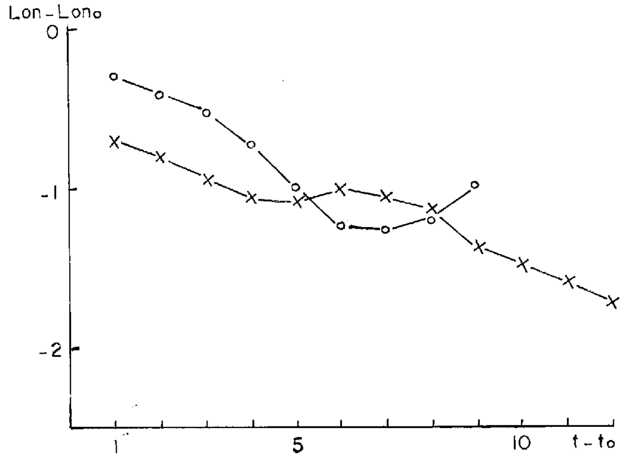

Fig. 2. Observed variation of sunspot longitude during the second (o) and third (x) rotations. Zero value refers to 44 and 42 degrees (Lon$_0$) for the respective rotations. Considering latitudinal differential rotation a 0.15 degrees per day variation was calculated; during the second rotation the estimated value varies between 0.13 and 0.21 degrees per day; in the third rotation the general drift is 0.1 degrees per day. In the X-axis the zero refers to March25 and April 20, 1976 (t_0=25 and 51 day) for the second and third rotations respectively.

Table 2

Kinematic data for a recurrent sunspot during its second and third rotations. DAY is the time of observation (referred to March 1976), LON and LAT is the longitude and latitude, VLON and VLAT are the corresponding velocities, and VEL the modulus. ALON, ALAT and ACEL are the accelerations in longitude, latitude, and modulus. DES is the calculated displacement between the observed and calculated positions. The values are in units of degrees and days.

DAY	LON	LAT	VLON	VLAT	VEL.	ALON	ALAT	ACEL	DES
26.50	43.69	-1.47							
27.50	43.59	-7.53	-0.101	-0.113	0.152	-0:07	-0.12	0.14	0.06
28.50	43.46	-7.10	-0.172	-0.232	0.289	-0.07	-0.12	0.14	0.06
29.50	43.26	-8.01	-0.205	-0.301	0.365	-0.06	-0.06	0.08	0.08
30.50	42.99	-8.40	-0.196	-0.311	0.368	+0.05	+0.07	0.09	0.06
31.50	42.76	-8.69	-0.123	-0.240	0.270	+0.16	+0.09	0.18	0.02
32.50	42.73	-8.88	+0.022	-0.157	0.159	+0.11	+0.08	0.14	0.01
33.50.	42.82	-8:99	+0.140	-0.075	0.159	+0.12	+0.08	0.14	0.01
34.50	43.01	-9.03							
52.50	41.30	-9.17							
53.50	41.18	-9.25	-0.161	-0.072	0.176	+0.06	-0.03	0.06	0.14
54.50	41.05	-9.33	-0.105	-0.104	0.148	+0.06	-0.03	0.06	0.05
55.50	40.93	-9.44	-0.085	-0.135	0.160	+0.10	-0.06	0.12	0.11
56.60	40.92	-9.62	-0.014	-0.191	0.192	+0:04	-0.03	0.05	0.11
57.50	40.98	-9.83	+0.001	-0.192	0.192	-0.07	+0.00	0.07	0.07
58.50	40.92	-10.05	-0.079	-0.165	0.183	-0.04	+0.06	0.07	0.04
59.50	40.85	-10.18	-0.132	-0.140	0.192	-0.10	+0.03	0.11	0.01
60.50	40.62	-10.28	-0.129	-0.111	0.170	+0.06	-0.01	0.06	0.05
61.50	40.51	-10.42	-0.131	-0.052	0.141	+0.04	+0.08	0.09	0.11
62.50	40.40	-10.43	-0.094	+0.031	0.099	+0.04	+0.08	0.09	0.16
63.50	40.2	-10.32							

degrees by day, 456 nHz). The longitudinal motion is influenced by the differential rotation, which for the latitudes under consideration is estimated at 0.14 degrees by day in the photosphere (1.0 solar radius).

During the second rotation the longitudinal drift varies between 0.13 and 0.21 degrees per day. During the third rotation the drift diminished to 0.1 degrees per day. On April 2 (point 8 in Figure 2) the drift changed sign. This behavior cannot be clearly related to the activity or evolution of the group, but the magnetic field diminished from 3200 to 2800 Oe.

We suggest that this tendency of the longitudinal drift might be related to the magnetic field intensity of the sunspot, because the more intense magnetic fields of the second rotation correspond to a higher path drift rate.

The regular longitudinal velocities for the path range from 449 to 457 nHz. These values do not agree with those reported by Vorontsov (1992) for spots of 462 nHz or for supergranules of 473 nHz. They would correspond to a layer at R=0.7 solar radii. The inversion of the drift process observed on April 2nd can be explained by a displacement of the magnetic field source of the spot toward the faster rotating layers at a depth of 0.1 solar radii (R=0.9) (Vorontsov, 1992).

A possible qualitative interpretation of the sensitivity of the sunspot longitudinal motion to magnetic field intensity is that velocity variation in the radial direction is much more intense for the longitudinal than for the latitudinal component. In this way, the ascending magnetic tubes from sources located closer to the Sun surface show a more intense drag in the East-West direction.

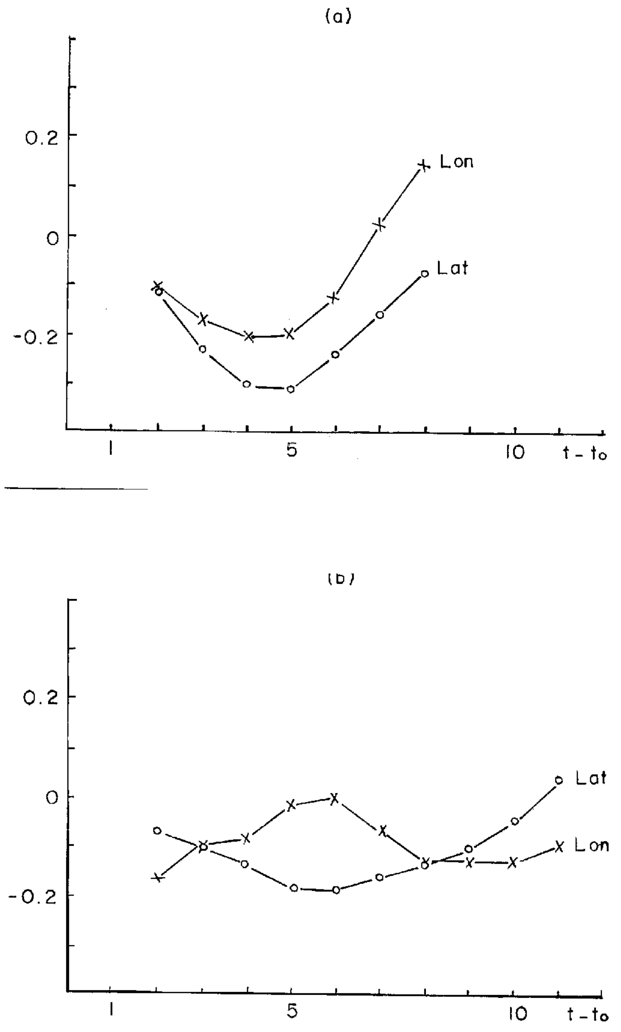

Fig. 3. Velocity variation in latitude (o) and longitude (x) for the second (a) and third (b) sunspot rotations.

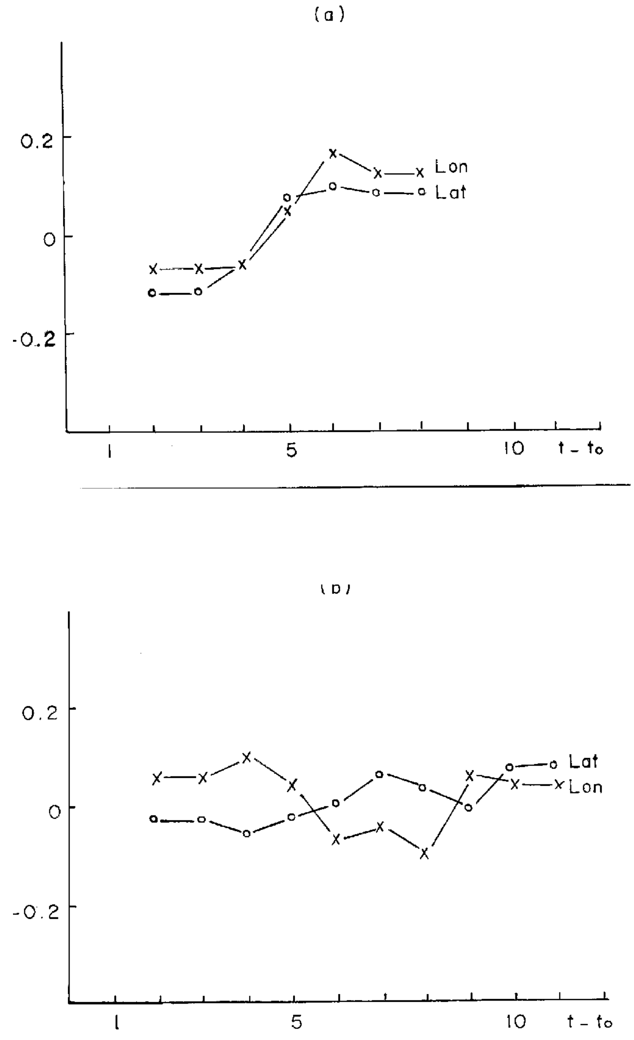

Fig. 4. Acceleration variation in latitude (o) and longitude (x) for the second (a) and third (b) sunspot rotations.

Figure 3 shows the behavior of velocity in longitude and latitude. During the second rotation the variations of the latitudinal and longitudinal velocities were mainly on phase. During the third rotation they were mainly out of phase.

The longitude and latitude components of acceleration were also in phase during the second rotation and out of phase during the third rotation (Figure 4).

Note that the variation in phase of the latitude and longitude velocities shows that the modular value of the vector is really increasing or decreasing. The out-of-phase variation points to a probable change in the direction or the vector, but not to a clear change of modulus. In Table 2 in the column VEL, for the third rotation of the group, the velocity has a nearly constant value.

The occurrence of strong flares during the second (March 26) and third (April 30) rotations coincided with changes in the sunspot movement parameters. The latitude drift during the second rotation had been stable around 0.14 degrees/day but changed on March 28. This change is clearly seen on the acceleration components (Figure 4a). The latitude and longitude velocity components, which during the third rotation had moved out of phase, start to move in phase (Figure 3b).

Figure 5 shows the path of the group. At the end of the second rotation, the sunspot deviates to the west from the direction it was following. This third rotation starts from a position distant from the one expected, according to the path followed during its second rotation, and the sunspot gradually returns to its previous path as the reorganization of the group takes place.

This behavior suggests that the reorganization of the group implies the appearance of new deeply-anchored magnetic field lines, which would account for the displacement

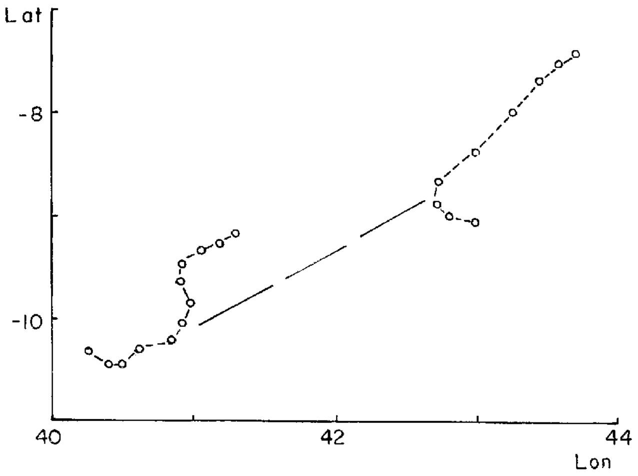

Fig. 5. Path of the sunspot movement on the solar surface.

Table 3

Mean values of velocity, acceleration and displacement in units of degrees and days, of the main sunspot during its lifetime as group 16 and 24 in 1976

Group	Velocity	Acceleration	Displacement
16	0.2561 +/- 0.045	0.1741 +/-0.033	0.0471+/-0.009
24	0.1701+/-0.021	0.1281+/-0.026	0.0811 +/-0.010

of the sunspot towards the original regular path. The displacement at the beginning of the third rotation could be the distance to which the magnetic field lines from a deeply anchored source could be stretched by sub-photospheric fluid motion.

Velocities and accelerations for the second rotation are greater than those calculated for the third rotation (Table 3). The deviations of the calculated positions, on the other hand, are smaller during the second than during the third rotation. Considering the active region path as a whole, the greater deviations appear when the group is decaying, thus reaching values much greater than those characterizing the developed group.

CONCLUSIONS

The approach in this paper enables us to determine a regular path whose longitude and latitude velocities give a better description of the overall motion of the sunspot.

The longitude velocities calculated for the regular path of the group were in the 449-457 nHz range. According to Vorontsov, these values correspond either to the photospheric level, or to Sun layers at R=0.7 solar radii, below the maximum rotational velocity level (R=0,9 solar radii).

The observed poleward latitude drift points to a non-photospheric sunspot source. In addition to the deep rotational drift values, this is a reliable indication of sunspot magnetic field sources anchored deep in the Sun. Our findings are in agreement with the Gilman sub-photospheric fluid circulation model and disagree with previously reported observational results.

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