A POSSIBLE CONTRIBUTION OF THE SOLAR WIND TO ANNUAL FLUCTUATION IN THE LENGTH OF DAY

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Abstract. Applying Vondrák narrow-band filters on high precision Length of Day (LOD) measurements provided by space observation techniques as well as Atmosphere Angular Momentum (AAM) computed by U.S. National Meteorological Center (NMC), we show variation in amplitude of the annual components. From filter series of LOD and AAM, we find that annual variation of the LOD induced by AAM is about 20% higher than observed one. The aim of this work is to investigate how far the torque applied by the solar wind on the Earth's magnetosphere could contribute to explain this excess. The advocated dynamical mechanism could counterbalance annual discrepancies between AAM and LOD by an amount of 20%. Therefore, the torque produced by the solar wind on the earth might be considered as one of the most possible contributions to annual fluctuation in LOD.

1. Introduction

Earth's rotation fluctuation is the witness of various dynamical processes in which the atmosphere is a major contributor from short to mean time scales, i.e., few days to few years. On time scale longer than or close to 10–year, it includes the secular variation and decade fluctuations which are attributed to the tidal energy dissipation and core-mantle coupling, respectively. All variations with interannual fluctuation, the dominant annual and semi-annual and higher frequencies components are known to be caused by exchange of angular momentum between solid earth, atmosphere and ocean, likewise solar-lunar tidal effects are to be considered. On this subject, Munk and MacDonald (1960) drew conclusion that the seasonal changes in LOD are to be attributed to a periodic exchange of angular momentum between zonal wind circulation and earth mantle.

Seasonal variation of the earth rotation rate, first detected in 1936, was determined by Stoyko (1936). The amplitude variation is about 0.5 m s. Research of small variation was largely impeded by clock instabilities until atomic clocks became available in 1955.

The high quality earth rotation and atmospheric circulation data available since 1976 make it possible to reexamine seasonal or short periodic unbalances in LOD and AAM budget as well as attempt to isolate any non-atmospheric LOD excitations can be initiated.

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The modern atmospheric and geodetic data related to earth rotation include the information with a large spectrum of frequencies and fine structure. They conduct to consider new mechanism in order to explain some of the differences shown in earth-atmosphere budget. For example, Rosen *et al.* (1985) have earlier given an up to date discussion taking into account the stratospheric wind. The discrepancy between LOD and AAM on the annual time scale may be largely eliminated if the wind is taken into account to the 10∼1 mb layer. The other investigations, in particular. Naito *et al.* (1990), speculated that redistribution of air mass and surface water storage are a possible cause of unbalance in seasonal budget. There are different views in this field and in this paper we introduce another contribution to the seasonal variation.

With this respect the principal goal of this paper is to describe the contributions of forces and torques applied on the earth by magnetospheric currents; we shall estimate this possible contribution to the annual discrepancy in earth-atmosphere budget.

2. Data Used

The earth rotation determined by only optical observations was available till two decades ago. Since the 1970s space geodetic technique has gradually to become major means of determining the earth's orientation parameters as determined by the International Earth Rotation Service (IERS). The techniques of Satellite Laser Ranging (SLR) and Very-Long Baseline Interferometry (VLBI) have been developed and progressively improved to the current accuracy of about 1 milli-arcsecond for sub-daily earth orientation determinations. A number of observation data with high accuracy have been already accumulated, which can be used as basic material for earth rotation spectrum, especially the length of day (LOD) measurements. For our study, three series have been chosen:

1. LOD series provided by the International Radio-Interferometry Service (IRIS)
The data are covering different periods which began in late 1980s; they consist of a series of Very Long Base Interferometry (VLBI) sessions designed to monitor the Universal Time (UT1) and the polar motion whose position is given by the set of coordinates (X, Y). Since January 1984, the coverage is essentially complete at 5-day intervals in UT1. Since April 1985, there is also a nearly complete coverage of UT1 at daily intervals. This system has been routinely determining UT1 with accuracy close to few tens milli-seconds of time. This series are represented by LOD_{IRIS}.

2. LOD series of the Bureau International de l'Heure (BIH)
This was a pure optical solution of earth orientation parameter (EOP) computed by BIH for the period January 1962 to January 1972. EOP results, from January 1972 until 1988, are combined by various techniques. In 1988 IERS replaced BIH

and Earth rotation parameters were provided by the new techniques only (VLBI, SLR, LLR). LOD series was obtained from the difference (UT1 − TAI) at 5-day intervals with formula (1) which have already been corrected for annual and semi-annual tides and diurnal nutation.

$$\mathrm{LOD}^* = -\mathrm{LOD}_0 \frac{(\mathrm{UT1}^* - \mathrm{TAI})(t) - (\mathrm{UT1}^* - \mathrm{TAI})(t - \Delta t)}{\Delta t}, \tag{1}$$

where Δt is the time in seconds between the epochs of the successive estimates of $(\mathrm{UT1}^* - \mathrm{TAI})\cdot(\mathrm{LOD}_0 = 86\,400$ sec.). This series are represented by $\mathrm{LOD}_{\mathrm{BIH}}$

3. AAM series

The longest series of AAM was supplied by U.S. National Meteorological Center (NMC) for weather forecasting and analysis of meteorological data. Starting in July 1976, the NMC data have been used to provide AAM twice daily: the NMC wind estimates were only integrated to the level pressure of 100 mbar. The angular momentum of the atmosphere around the polar axis relative to an earth-fixed frame is approximated by Rosen and Saltein (1983) by the expression:

$$\Delta M = \frac{2\pi a^3}{g} \int\int [u] \cos^2 \phi \, \mathrm{d}\phi \, \mathrm{d}p \,, \tag{2}$$

where a, g, p, and u are the mean radius of the earth, gravitational acceleration, the air measure and eastward component of the wind, respectively. The relation between variation ΔM of AAM and variation of rotation rate of the earth can be represented by the formula

$$\Delta\omega = -\Delta M / I_{\mathrm{shell}} \,, \tag{3}$$

where I_{shell} is the principal (axial) moment of inertia of the earth's crust and mantle, i.e., shell is included only and core is excluded.

If ω is $7.29 \times 10^{-5}\ \mathrm{s}^{-1}$, $\mathrm{LOD}_0 = 86400$ s, ΔLOD from atmospheric origin can be obtained by:

$$\Delta\mathrm{LOD}_{\mathrm{atm}} = 1.68 \times 10^{-29} \Delta M \,. \tag{4}$$

Using expression (4), $\Delta\mathrm{LOD}_{\mathrm{atm}}$ has been deduced from ΔM series; it will compose the third series analysed in this work.

3. Annual Amplitude Variations of LOD

In this paper variations of annual amplitude are presented for the three time series above: (1) LOD-BIH as provided by BIH and IERS, (2) $\mathrm{LOD}_{\mathrm{IRIS}}$ as provided by

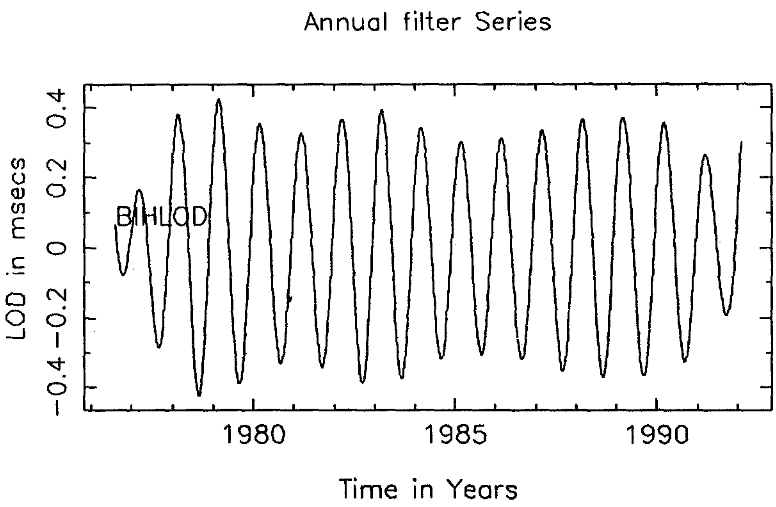

Fig. 1a.

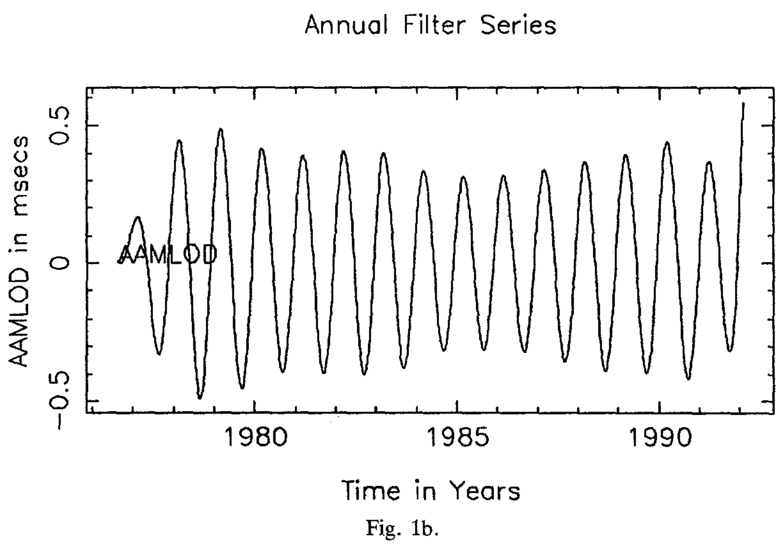

Fig. 1b.

IRIS and (3) LOD_{atm}; results given in Figure 1 are obtained by means of multistage based filter (Zheng *et al.*, 1986); the amplitude is expressed by:

$$R = c[I - A(f, \epsilon)^N]^M , \tag{5}$$

where c is real constant, N and M are positive integers, I is the unit filter, ϵ, f are smoothness and frequency, respectively. The frequency response is shown in Figure 2 for annual filter series. As it is seen in Figure 1, amplitude of annual term in LOD series changes according to the high and low solar activities (Gu,

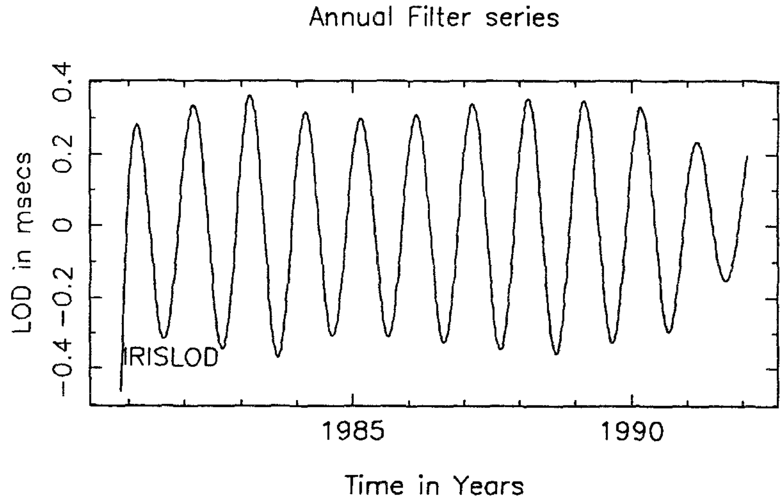

Fig. 1a–c. Three series obtained through 350–380 day band-pass filter.

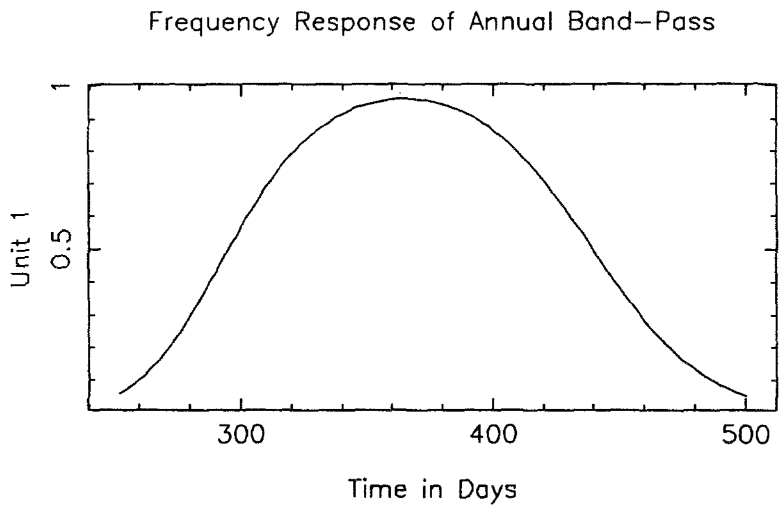

Fig. 2. The frequency response curves for 350–380 day band-pass filter.

1990). Application of the same analysis for the period 1956–1992 appears to have similar regularity as it can be seen in Figure 3.

Using Householder transformation (Tong *et al.*, 1980), amplitude A and phase θ were estimated and are shown in Table I. Amplitude of seasonal components clearly changes with time: in particular, the annual variations are not stable and change from year to year.

In the next paragraph we determine discrepancies between the annual components of the three series above. Let us define LOD′ to be

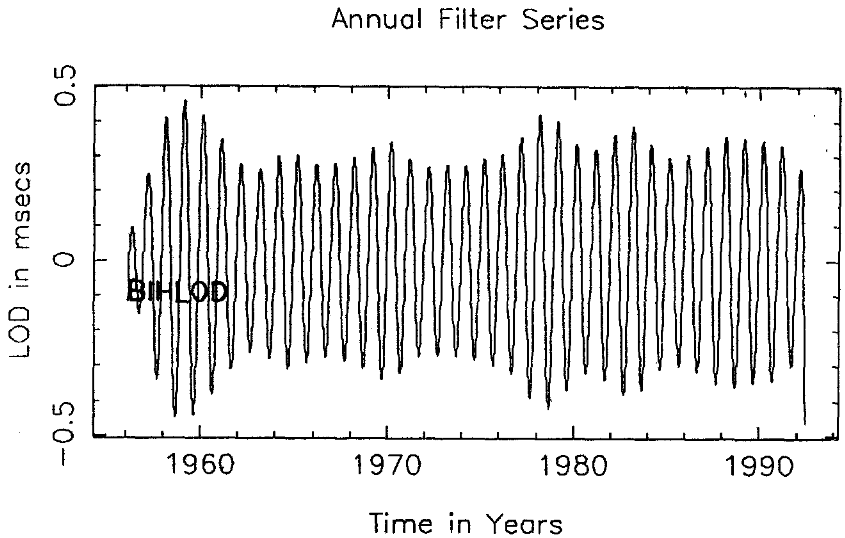

Fig. 3. LOD series in 1956–1992.4 obtained through 350–380 day band-pass filter.

$$LOD' = LOD_{atm} - LOD^* , \tag{6}$$

where LOD′ represents the difference between the LOD_{atm} and one of the two other series; LOD* is set both for LOD_{IRIS} and LOD_{BIH}; in Figure 4 the differences between LOD_{atm}, and LOD_{BIH} are presented. Variations of annual amplitude of the two LOD′ series are shown in Figure 5; they are obtained by means of multiple-band filter with periods between 350 and 380 days and the corresponding coefficients in the pass band filter are $\epsilon = 0.3195 \times 10^{-9}$, $\epsilon = 0.1738 \times 10^{-10}$, respectively. The central period is 365 days. The precise periods of the spectral peaks, amplitudes and phases by using above harmonic analysis method are listed in Table II. We would conclude from Table II that the amplitudes of the annual term of LOD′ is about 0.06 m s, which means that annual component of LOD_{atm} during 1976–1991 is 20% larger than that one of LOD_{BIH} or LOD_{IRIS}.

4. Effects of the Solar Wind to Earth's Rotation

Some authors have discussed the effects of the torque produced by the solar wind to earth rotation. When solar plasma is titled to geomagnetic dipole axis. This torque tries to restore the dipole axis at right angles to the solar wind. But it is too small to have any effect on the 26000-year precession of the rotation axis of earth. Lambeck (1980) also considered this torque when analyzing decade fluctuation of earth rotation; he reached the conclusion that it is also too small to generate enough energy for decade variation of LOD.

As seen in the paper of Papagiannis (1973), due to ecliptic obliquity (±23°.5), the torque produced by solar wind on the earth should induce a substantial annual variation; we will discuss this problem from two points:

TABLE I

Periods, amplitudes, phases and standard deviations for 1956–1992 LOD series

Date			Periods in days	Amplitudes in m sec	Phases in degrees	Std. dev. in m sec.
1956	1	9	322.42	0.1659	6.90	0.0047
(+)1957	1	8	362.36	0.3461	61.44	0 0055
(+)1958	1	8	356.32	0.4429	70.52	0.0015
(+)1959	1	8	359.29	0.4393	81.35	0.0016
1960	1	8	362.23	0.3824	86.63	0.0020
1961	1	7	368.27	0.3110	90.57	0.0024
(−)1962	1	7	377.38	0.2665	86.69	0.0007
(−)1963	1	7	374.23	0.2863	72.93	0.0016
(−)1964	1	7	361.76	0.3049	65.61	0.0004
(−)1965	1	6	364.72	0.2891	68.85	0.0011
1966	1	6	370.80	0.2777	67.89	0.0001
1967	1	6	369.24	0.2892	63.18	0.0006
(+)1968	1	6	375.40	0.3114	63.30	0.0008
(+)1969	1	5	362.88	0.3395	54.35	0.0016
1970	1	5	353.86	0.3147	55.86	0.0018
1971	1	5	368.46	0.2752	64.34	0.0014
1972	1	5	365.39	0.2756	57.54	0 0009
(−)1973	1	4	362.29	0.2743	59.42	0 0005
(−)1974	1	4	365.31	0.2860	62.59	0.0010
1975	1	4	359.22	0.2987	64.32	0.0005
1976	1	4	374 04	0.3288	72.99	0.0008
(+)1977	1	3	370.87	0.3994	66.22	0.0032
(+)1978	1	3	358.51	0.4169	63.75	0.0008
(+)1979	1	3	364.48	0.3658	70.50	0.0026
1980	1	3	373.50	0.3242	69.03	0 0009
1981	1	2	379.72	0.3502	62.09	0.0016
(*)1982	1	2	364.00	0.3863	51.85	0.0023
(*)1983	1	2	348.94	0.3612	52.74	0.0018
1984	1	2	360.57	0.3099	66.35	0.0021
(−)1985	1	2	363.52	0.3018	67.07	0.0007
(−)1986	1	1	371.88	0.3193	71.12	0.0002
1987	1	1	371.88	0.3526	65.93	0.0016
1988	1	1	364.15	0.3586	61.62	0.0004
1988	12	31	367.13	0.3491	62.03	0.0004
1989	12	31	365.59	0.3392	58.70	0 0005
(+)1990	12	31	365.59	0.3584	55.21	0.0007

(+): Maximum solar activity.
(−): Minimum solar activity.
(*): El Nino.

1. How the effects of solar wind in the magnetosphere can be advocated to change the annual term of the earth rotation;

2. An estimation of the annual fluctuation in LOD, generated by the solar wind torque, has been made.

A moved rectangular coordinate system is chosen, in which Z axis is defined on the direction of earth-sun line, toward the sun, and X axis is perpendicular to the ecliptic. The third axis Y defines a right hand system of coordinates. The

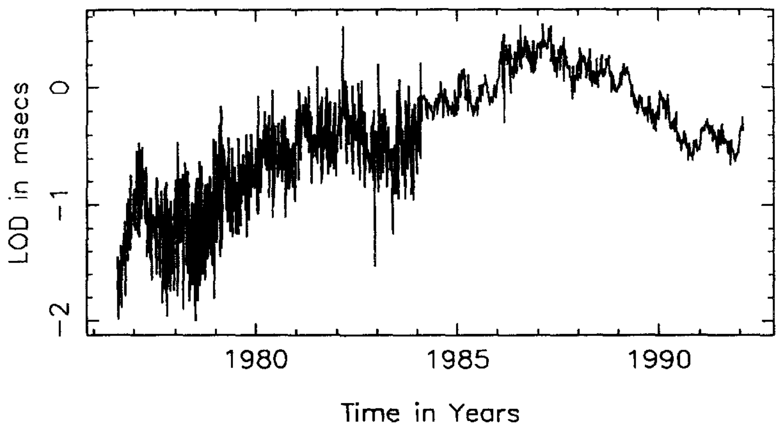

Fig. 4. Variation of differences between LOD_{atm} and LOD_{BIH}.

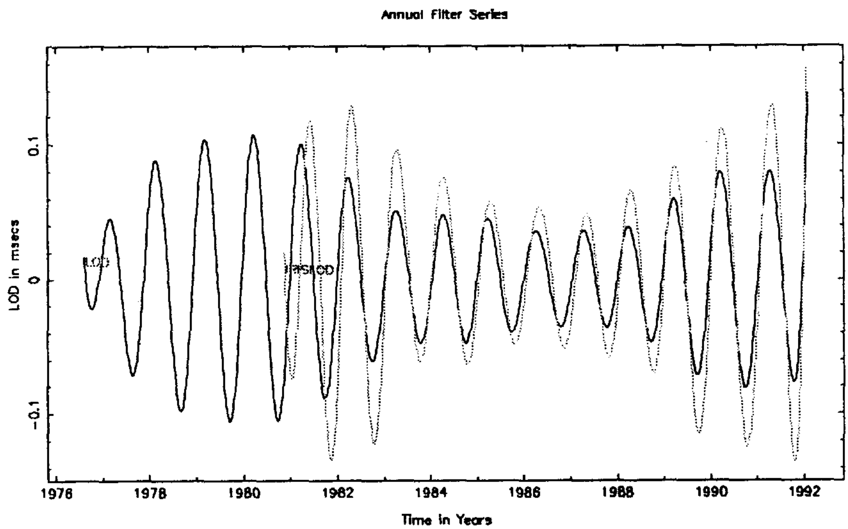

Fig. 5. Differences ($LOD_{atm} - LOD_{BIH}$) and ($LOD_{atm} - LOD_{IRIS}$) obtained through 350–380 day band-pass filter.

origin of the system is chosen at geocentre. For the next developments we refer to the Figure 1 of Papagiannis's paper (1973); the original position is taken such that the dipole axis lies in the X-Z plane and is titled to X axis to an angle of about $\chi = 30°$; due to revolution of the earth around the sun, the dipole axis periodically will be out of the X-Z plane. Thus, the dipole moment ($\vec{M}$) projected to the axis of the reference system is given by

TABLE IIa

Periods, amplitudes, phases and standard deviation for the series ($LOD_{atm} - LOD_{BIH}$) data

Date			Period in days	Amplitudes in m sec.	Phases in degrees	Std. dev. in m. sec.
1976	7	2	373.75	0.04083	135.18	0.01009
1977	7	2	355.87	0.08221	245.40	0.00382
1978	7	2	376.44	0 10124	253.02	0 00095
1979	7	2	376.44	0.10657	238.08	0.00034
1980	7	1	373.25	0.10228	227.12	0.00137
1981	7	1	379.47	0.08141	230.26	0.00262
1982	7	1	385.79	0.05591	228.52	0.00145
1983	7	1	357.07	0.04796	192.34	0.00060
1984	6	30	357.07	0.04627	204.36	0.00117
1985	6	30	390.05	0.03749	236.29	0.00061
1986	6	30	361.01	0.03614	193.11	0 00054
1987	6	30	342.96	0.03792	187.41	0.00086
1988	6	30	342.96	0.05423	200.70	0.00270
1989	6	29	365.53	0.07608	226.47	0.00052
1990	6	29	390.22	0.08076	235.02	0.00032

TABLE IIb

Periods, amplitudes, phases and standard deviations for series ($LOD_{atm} - LOD_{IRIS}$) data

Date			Period in days	Amplitudes in m sec.	Phases in degrees	Std. dev. in m. sec.
1980	10	14	341.64	0.11018	169.56	0.00235
1981	10	14	336.82	0.12948	257.36	0.00173
1982	10	14	387.35	0.10084	339.99	0 00153
1983	10	14	374.43	0.07053	318.71	0.00021
1984	10	13	383.85	0.05883	326.92	0.00062
1985	10	13	387.05	0.05202	310.93	0.00016
1986	10	13	348.34	0.05198	258.69	0.00053
1987	10	13	345.39	0.06487	273.27	0.00049
1988	10	12	342.51	0.08619	284.98	0.00079
1989	10	12	379.90	0.11658	333.76	0.00024
1990	10	12	370.46	0.12717	300.72	0.00257

$$M_x = -M_0 \cos\lambda$$
$$M_y = -M_0 \sin\lambda \sin\beta \qquad (7)$$
$$M_z = -M_0 \sin\lambda \sin\beta\,,$$

where M_0 is the dipole moment of the earth's magnetic field ($M_0 = 8 \times 10^{25}\,\mathrm{G\,cm^3}$), χ, the angle between the dipole moment and X axis, β the ecliptic longitude of the sun.

According to Olson (1974): "The interaction of the solar wind with the geomagnetic field produces currents that flow on the magnetopause. The current system in turn produces a magnetic field $\vec{B}$ that interact with the geomagnetic field. It is this interaction that transmits the solar wind forces and torques to the earth".

The expression (Olson, 1974; Jackson, 1962) for the force $\vec{F}$ exerted on the geomagnetic field is:

$$\vec{F} = (M\cdot\nabla)\vec{B}\,; \tag{8}$$

We now obtain the components for $\vec{F}$ as:

$$\begin{aligned}
F_x &= -M_0\left(\cos\chi\frac{\partial B_x}{\partial x} + \sin\chi\sin\beta\frac{\partial B_x}{\partial y} + \sin\chi\cos\beta\frac{\partial B_x}{\partial z}\right),\\
F_y &= -M_0\left(\cos\chi\frac{\partial B_y}{\partial x} + \sin\chi\sin\beta\frac{\partial B_y}{\partial y} + \sin\chi\cos\beta\frac{\partial B_y}{\partial z}\right),\\
F_z &= -M_0\left(\cos\chi\frac{\partial B_z}{\partial x} + \sin\chi\sin\beta\frac{\partial B_z}{\partial y} + \sin\chi\cos\beta\frac{\partial B_z}{\partial z}\right),
\end{aligned} \tag{9}$$

where the magnetic field $\vec{B}$ is a function of the radial distance r, so $\vec{F}$ are dependent on β only which causes the annual term. The force $\vec{F}$ produced by solar wind on the geomagnetic field is related to configuration of the magnetosphere; it makes the calculation very complex, so some simplifications have to be done to obtain the order of magnitude of the effect on Earth rotation.

With this respect it is worth to point out that up to now, papers devoted to this field, have not yet considered effects of the unsymmetry in the distribution of magnetic lines with respect to Z plane: as the satellite data show that due to the discontinuity of the magnetic field in the magnetopause, there is a surface current in the magnetopause. From the direction of the sun, the surface currents around magnetic cavity is anti-clockwise in upper part and clockwise in lower part of the geomagnetic tail: upper parts magnetic lines of the cavity are towards the earth and those in the lower part are away from the earth. In consequence a torque in Y component, produced by interaction between surface currents with geomagnetic field, may be derived.

In such a case, the interaction between surface currents and magnetic field produces the force, whose X component of the magnetopause is positive. This force is acted on the magnetopause by the magnetic field in the cavity. As we know, the configuration of the magnetopause is determined by the balance of the solar wind pressure with the magnetic pressure in the cavity, i.e., the magnetic cavity has the pressure from the solar wind. If the magnetic lines are symmetric with respect to the X-Z plane, the resulting torque on Y-axis is zero. However, when the Earth rotation and obliquity of the rotation axis are taken into account, the most crowding of the magnetic lines will happen near the magnetopause in the plane with positive X and positive Y and the sparseness of the magnetic lines will occur in the other parts when rotation axis is inclined to position Y-axis. The crowding of magnetic lines implies more magnetic flux, and vice versa. This induces the dissymmetry of the magnitude of forces along X-axis, which contributes the net torque on Y-axis and induces the variation of the Earth rotation. The net torque on Y-axis is directed to the negative Y-axis, which component in rotation axis is opposite to the rotation axis, i.e., this torque will decelerate the rotation of the Earth. It is a qualitative analysis. Unfortunately, there is no quantitative observation data in this dissymmetry. In the following, we will see what amount of this kind of dissymmetry can explain the gap between the observed annual variation of LOD and the annual variation of LOD caused by AAM.

We have calculated the torque along the Y axis exerted by solar wind on the magnetotail. In the reference system defined above be $\vec{j}(0, \sigma, 0)$ *the induced current*, $\vec{B}(0, 0, \mu_0\sigma)$ the magnetic field produced by the current which flows on the magnetopause: μ_0 is the permeability ($4\pi \times 10^{-7}$ Wb/mA, 10^{-4} Wb/m^2 = 10^{-4} N/Am). The component of the force $\vec{F} = \vec{j} \times \vec{B}$ along X-axis is needed for the derivation of the torque.

If R_E represents the earth radius, let us suppose that radius and length of a cylindrical magnetotail are taken to be equal to $20R_E$ and $40R_E$ (Lyons, 1992), respectively. In consequence of the difficulty of the measurement, larger scale surface currents at the boundary of the magnetopause are little known; from satellites observation, an accepted value for the current on the magnetotail is $\sigma = 5 \times 10^5\ A/R_E$ (Tu *et al.*, 1980). The torque oriented along Y positive is given by

$$N_y = \mu_0\sigma^2\pi \times (20R_E)^2 \times 40R_E\,, \tag{10}$$

thus

$$N_y = 1.0059 \times 10^{24}\ \text{dyn cm}. \tag{11}$$

This torque will induce a change $\Delta\omega$ of the earth rotation:

$$\Delta\omega = N_y\Delta t/I_{\text{sheet}}\,. \tag{12}$$

From

$$\Delta t = 3.1557 \times 10^7\ \text{s}, \tag{13}$$

$$\Delta\omega = 0.4484 \times 10^{-13}/\text{s}, \tag{14}$$

we deduce, successively,

$$\frac{\Delta\omega}{\omega} = 0.0615 \times 10^{-5}\,, \tag{15}$$

$$\frac{\Delta\omega}{\omega} = -\frac{\Delta\text{LOD}}{\text{LOD}}\,, \tag{16}$$

$$\Delta\text{LOD} = -0.054\ \text{m s}. \tag{17}$$

As a matter of fact, in the expression (10), we just know that if the X-force on the positive X part of the magnetopause is twice larger than that on the negative

X part, it will cause the variation of the Earth rotation and fill the gap mentioned above.

One more thing should be mentioned. From the data analysis of both observed annual term and the annual variation induced by AAM, they have same phase.

On the average, the phase of the annual variation of LOD in January is about 60 degrees. That means the peak of this variation should be at 90 degrees, i.e., in February. Let us have a look at the phase of the annual variation of LOD by the solar wind. Because of the ecliptic obliquity, the rotation vector of the Earth in Winter and Summer is in X-Z plane and that in Autumn and Spring is in the plane perpendicular to X-Z plane. And the rotation vector of the Earth in Autumn is inclined to the positive Y part and that in Spring is inclined to the negative Y part. Therefore, the unsymmetry of the magnetic lines in the cavity is the strongest one. The peak of the variation of LOD by solar wind should take place near Autumn and Spring. In Spring, the torque by the solar wind will accelerate the rotation of the Earth and in Autumn it will decelerate the rotation of the Earth. It should be pointed out that the geomagnetic dipole axis is different from the rotation axis, but not too much.

From this analysis, the difference of the phase for the observed variation of LOD and the variation of LOD by solar wind is about 7–8 months, i.e., when the observed annual variation of the Earth rotation accelerates, the annual variation of the earth rotation by solar wind decelerates.

As mentioned above, the amplitude of annual term LOD_{atm} is obvious bigger than that one measures by astronomical methods LOD; the average discrepancy of two amplitude is about 0.06 m s. Magnetopause currents produced a torque of about 1.0059×10^{24} dy cm on the earth, which tends to diminish LOD. From the estimation above, it means that the 20% unbalance, between LOD_{atm} and one of LOD_{BIH} or LOD_{IRIS} corresponds mostly to the torque originated by the solar wind.

5. Conclusion

The analysis and comparisons of the Length of Day variation measured by astronomical methods and deduced from Atmospheric Angular Momentum conducted to the following conclusions:

1. No obvious differences appear in annual variation characteristics of LOD as determined by new and classical techniques.

2 During the period 1956–1992, the maximum and minimum values of annual term of LOD correspond to strong and weak solar activity respectively. Lambeck *et al.* (1982) reached also the same conclusion. It can be attributed to the seasonal angular momentum imbalance between atmospheric circulations which are controlled some by solar activity.

3. From the three series of LOD analysed after Vondrák band filter, it is shown that annual amplitude varies with time due to a non-linear behaviour in the earth-

atmosphere angular momentum budget. The amplitude of annual term of LOD_{atm} is bigger than that measured by astronomical methods; the average discrepancy of the two amplitudes is about 0.06 m s.

4. According to the Olson (1974) magnetospheric model, in which the earth's revolution and rotation are considered, magnetic line in magnetosphere caused by the solar wind are non-symmetric. The torque created by this non-symmetric contribution decreases the LOD by 0.054 m s which amounts 20% of the annual variation of LOD derived from AAM budget. Thus, we conclude that the observed annual variation of LOD is contributed by both the AAM and the solar wind.

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