PLANETARY TIDAL EFFECTS ON SOLAR ACTIVITY

Georgieva K.[1], Semi P.A.[2], Kirov B[1], Obridko V.N.[3], Shelting B.D.[3]
1 – STIL-BAS, Sofia, Bulgaria
2 - private programmer, Prague, Czech Republic
3 – IZMIRAN, Troitsk, Russian Federation

ПЛАНЕТАРНЫЕ ПРИЛИВНЫЕ ВЛИЯНИЯ НА СОЛНЕЧНУЮ АКТИВНОСТ

Георгиева К.[1], Семи П.А.[2], Киров Б.[1], Обридко В.Н.[3], Шелтинг Б.Д.[3]
1 – ИСЗВ-БАН, София, Болгария
2 – независимый программист, Прага, Чешская Республика
3 – ИЗМИРАН, Троицк, Россия

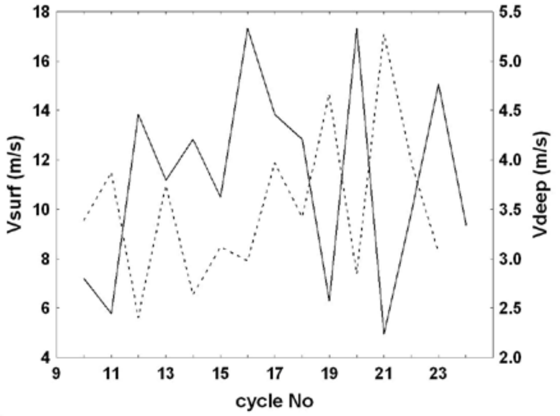
Абстракт

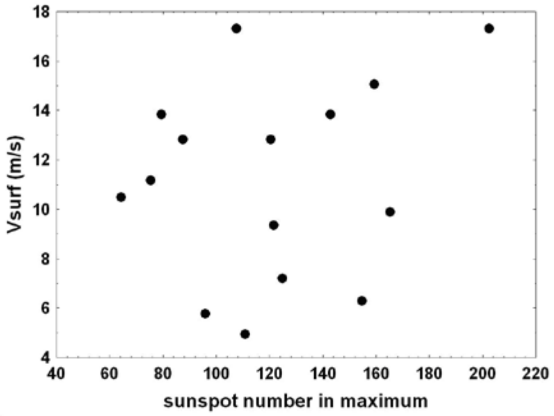
Долгосрочные вариации солнечной активности могут модулировать геомагнитную активность и климат Земли. Чтобы понять эти влияния, сначала нужно понять что вызывает изменения солнечной активности. Основание солнечной активности – солнечное динамо, которое трансформирует солнечное полоидальное поле в тороидальное поле, и это тороидальное поле в полоидальное поле следующего солнечного цикла с противоположной магнитной полярностью. Важную роль в этом процессе играет солнечная меридиональная циркуляция, направленная к полюсу на поверхности и к экватору в основании солнечной конвективной зоны. Скорость поверхностной циркуляции существенна для регенерации полоидального поля из тороидального поля предыдущего цисла солнечных пятен, а скорость глубокой циркуляции определяет генерацию тороидального поля следующего цикла. Наши предыдущие исследования демонстрировали, что скорость поверхностной направленной к полюсу циркуляции является определяющей для всей цепочки корреляций. Здесь мы показываем, что скорость поверхностной направленной к полюсу циркуляции модулируется приливными силами больших планет, и оцениваем значение этой поверхностной меридиональной циркуляции для геомагнитной активности и климата.

The most prominent solar variability is the ~11-year cycle of the number of sunspots. Neither the amplitude nor the period of the sunspot cycle are constant. Some solar dynamo models mimic this variability by introducing stochastic fluctuation (e.g. Charbonneau and Dikpati, 2000; Bushby and Tobias, 2007). However, the parameters of the sunspot cycle seem to vary in a quasi-periodic way implying that this cycle may be modulated by a longer-term phenomenon.

The existence of magnetic activity of the Sun and Sun-like stars is believed to be due to the presence of a convective envelope where the turbulent motions of conducting matter generate a dipolar magnetic field [1]. The mechanism responsible for the solar activity is the solar dynamo transforming this poloidal field into toroidal field and again into poloidal field with the opposite polarity. Recently, substantial progress has been achieved in solar dynamo theory, and especially in the so-called “flux-transport” dynamo mechanism which includes a large-scale meridional circulation in the solar convection zone. This circulation carries the remnants of sunspot pairs poleward at the surface to form the poloidal field of the next solar cycle, and carries the poloidal field equatorward at the base of the convection zone to transform it into toroidal field which emerges as the sunspots of the next cycle [2]. Our previous studies [3] have demonstrated that the speeds of the surface and the deep circulation determine the amplitude and period of the sunspot cycle which is a confirmation of the flux-transport dynamo theory.

The sequence of correlations is the following: the higher the speed of the surface poleward circulation V_{surf}, the lower the speed of the deep equatorward circulation V_{deep} following it (Fig.1). The correlation is r=-0.79 and highly statistically (p=0.002), and is a possible manifestation of the Malkus-Proctor mechanism [4]. Further, the higher the speed of the deep equatorward circulation V_{deep}, the higher the sunspot maximum following it (Fig.2). This correlation is also highly statistically significant (r=0.79 with p=0.001) and indicates that solar dynamo operates in diffusion-dominated regime [5]. However, there is no correlation at all between the sunspot maximum and the speed of the surface poleward circulation V_{surf} following it (Fig.3). We can therefore conclude that a factor important for the amplitude of the sunspot cycle is the speed of the surface poleward meridional circulation. The question is what factor modulates V_{surf}.





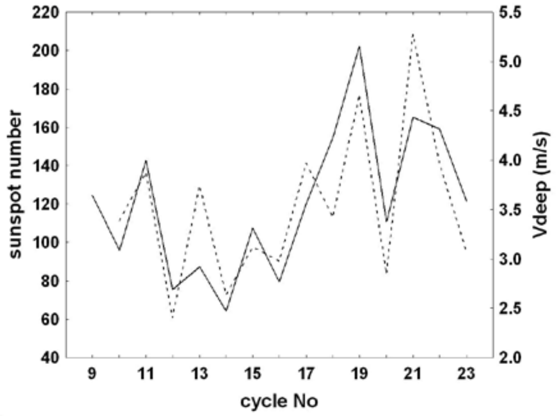


Fig.1. (upper left panel) Surface meridional circulation V_{surf} (solid line) and deep meridional circulation V_{deep} following it (dashed line).

Fig.2. (lower left panel) Deep meridional circulation V_{deep} (dashed line) and maximum sunspot number following it (solid line).

Fig.3. (upper right panel) Dependence of the surface meridional circulation V_{surf} on the maximum sunspot number preceding it.

The dynamo theory explaining solar and stellar magnetic activity works without any planets. If the star has planets, tidal effects exerted by the planets on the surface of the star can be described by the classical tidal theory. The tidal driving force is the gradient of the gravity field of the planets. In the simplest case of only one planet orbiting in the solar equatorial plane, the tide generating potential V at distance r from the center of the Sun is

$$V = -\frac{\gamma M r^2}{2R^3}(3\cos^2\varphi - 1) \tag{1}$$

where γ is the gravitational constant, M is the planet's mass, R is the distance between the centers of the Sun and the planet, and φ is the heliolatitude. The tide generating force has components perpendicular and parallel to the solar surface. The horizontal component is

$$H = -\frac{1}{r}\frac{\partial V}{\partial \varphi} = \frac{2G}{r}\sin 2\varphi \qquad (2)$$

where $G = \frac{3}{4}\gamma M\left(\frac{r^2}{R^3}\right)$, and r is the distance from the center of the star [6]. Fig.4 from [7] illustrates the distribution of the horizontal component of the tidal force on the surface of the star when the tide-generating planet is above the equator at Z.

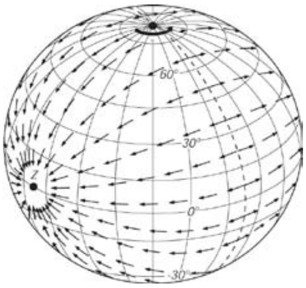


Fig.4

In the case of the Sun with a number of planets, the tidal forces depend on the distance and relative positions of the planets which change with time. Fig.5 shows the horizontal (upper panels) and the vertical (lower panels) tidal forces calculated from the positions of Mercury (M), Venus (V), the Earth-Moon system (E), Jupiter (J), Saturn (S), and the Solar system barycenter (SSB) in two periods: September 2005 (left) and September 2009 (right).

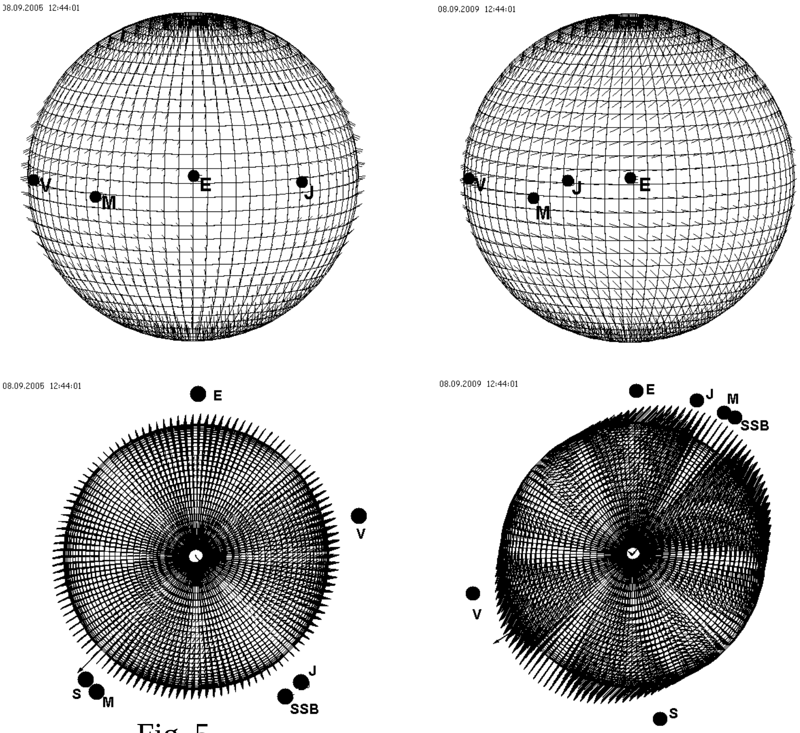


Fig. 5

To calculate tidal force of planets onto the Solar surface, we use JPL planetary and lunar ephemerides, version DE406 [8], which specify planet positions at any time covered by their time-span, in ICRS Earth-centered reference frame. We first rotate the reference frame to transfer it into Sun-centered. We use all 9 planets including Pluto (as specified in the Ephemerides, excluding only the Asteroids). Instead of Earth alone, the Earth-Moon Barycenter is used, with the combined mass of Earth and Moon. On the solar surface, the mesh of points are set up with 5° spacing and the tidal force of each planet is evaluated at each mesh point, which are then summed over the latitude to get per-latitude average of tidal force. The daily values are calculated at midnight UTC in 1 earth day steps, which are then averaged either to monthly or yearly averages.

Fig.5 shows that the tidal forces, both horizontal and vertical, vary strongly depending on the positions of the planets. The speed of the surface poleward meridional circulation is modulated by the meridional tidal force which is always directed equatorward and its effect is to slow down V_{surf}. The meridional tidal force varies periodically and its average value does not change much (Fig,6). However, what is important for the modulation of the solar cycle is its average magnitude during the period when the surface meridional circulation carries the flux from sunspot latitudes to the poles – that is, from sunspot maximum to the geomagnetic activity maximum on the sunspot decline phase. These periods, marked with thicker lines in

Fig.6 which covers the period 1750-2005, have different duration and come on different parts of the tidal force sinusoid. In Fig.7 the average meridional tidal force acting on V_{surf} during the poleward transport of the flux is compared to the maximum number of sunspots in the following solar cycle.

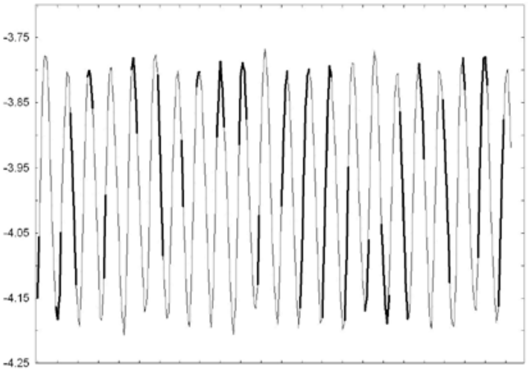


Fig.6

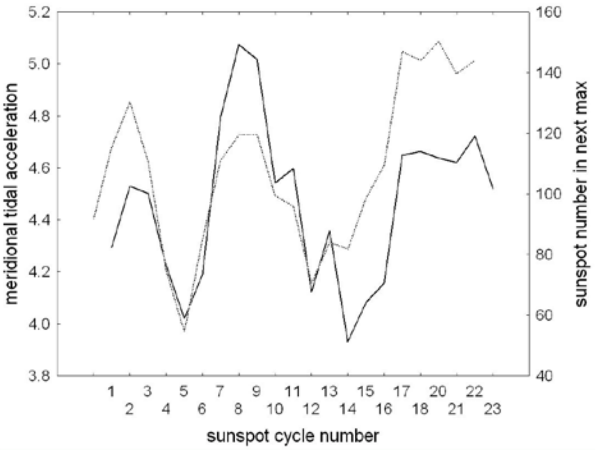


Fig.7

Fig.7 demonstrated a very good correspondence between the planetary tidal force (solid line) and the amplitude of the sunspot cycle (dash-ed line), with the Dalton minimum (the beginning of 19th century) and Gleissberg minimum (end of 19th and beginning of 20th century) coinciding with low tidal forces during the surface flux transport, and the secular solar maxima in the 18th, 19th and 20th centuries – with maxima in the tidal forces during these periods.

We can make a rough estimation of the magnitude of the effect of the planetary induced tidal forces. The calculated magnitude of the tidal force is of order $F \sim 10^{-10}$ N/kg. The acceleration caused by this force is $a = F/\rho$ where the density ρ in the surface layer of the Sun is ~ 10^{-5} gr/cm^3 = 10^{-2} kg/m^3. During the time when the flux is carried poleward (of order 10^8 sec), this acceleration can change the speed of the surface meridional circulation with a few m/s, which corresponds to the observed variations in V_{surf}.

As seen from Fig.7, the next 24 sunspot cycle is expected to be lower than cycle 23. Longer forecasts are difficult because we need to calculate the tidal force in the period between the next sunspot maximum and the geomagnetic activity maximum following it, and these times are not known. If the next sunspot maximum is in 2012, and the following geomagnetic activity maximum is in 2014, cycle 25 will be even lower than cycle 24. The result is not much different if the periods of the maxima are shifted by +/- 1 year.

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