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LONG-TERM VARIATIONS OF THE INTEGRAL RADIATION FLUX AND POSSIBLE TEMPERATURE CHANGES IN THE SOLAR CORE

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We show that the cyclic 11-year variations observed in the solar integral radiation flux are due to some fundamental global processes which occur deeply in the Sun and which cause the corresponding changes in the radius and effective temperature of the photosphere. The 11-year variations of the "solar constant" are determined almost entirely by the changes of the area of the radiating photosphere surface at a constant effective temperature. So, an 11-year heliocycle is a simultaneous phase- and amplitude-correlated oscillation of the solar activity, radius, and radiation flux. The secular variations of the "solar constant" were detected directly for the first time. We suppose that the observed identical long-term variations of the activity, radius, and radiation flux are caused by some common processes which occur deeply in the Sun. They correlate with the global oscillations of the whole Sun. Such oscillations are caused by cyclic changes of the temperature in the solar core, and they can trigger the generation of the solar cycles. We expect that the next relatively deep minimum of the solar activity, radius, and radiation flux in the 200-year quasi-cycle will be close to the Maunder minimum level and will occur in the year 2040 ±10.

Studying the causes of the 11-year and secular variations in the solar integral radiation flux (the so-called solar constant) and of the resulting climatic changes on the Earth in the past and at present is of particular importance in view of the global warming. Correct understanding of these processes will allow forthcoming climatic changes to be predicted. Long-term space measurements of the radiation flux indicate that the 11-year heliocycles represent correlated identical oscillations of both the activity and the radiation flux. We suggested earlier that variations in the activity level amplitude should be accompanied by some changes in the amplitude of radiation flux variations [2,8]. Indeed, recent radiation flux measurements [14] entirely confirmed our conjecture and demonstrated that the 11-year variations of the activity level and "solar constant" are cross-correlated and quasi-parallel in both phase and amplitude (Fig. 1). Variations in the solar activity level, terrestrial climate, and solar radiation flux were also correlated in phase and amplitude on longer time scales (about one century and more) over the last thousand years [5,6,12,13]. Moreover, each of 18 known deep Maunder-type minima of the solar activity over the last 7500 years was accompanied by a fall of the temperature on the Earth, and high maxima of the solar activity were accompanied by climate warming [6]. Such profound changes in the terrestrial climate could be caused only by the corresponding long-term variations of the incident solar radiation flux. Therefore, the radiation flux appreciably increased when the solar activity level was at its highest maxima, and it considerably decreased in the deep solar activity minima. In other words, the secular variations of the solar activity and radiation flux were correlated (quasi-parallel) in both phase and amplitude on any observation interval [2].

The considerable decrease of the radiation flux in the cycle **22** minimum with respect to the cycle 21 minimum (Fig. 1) is a direct proof of the existence of correlation in the secular "solar constant" and activity variations.

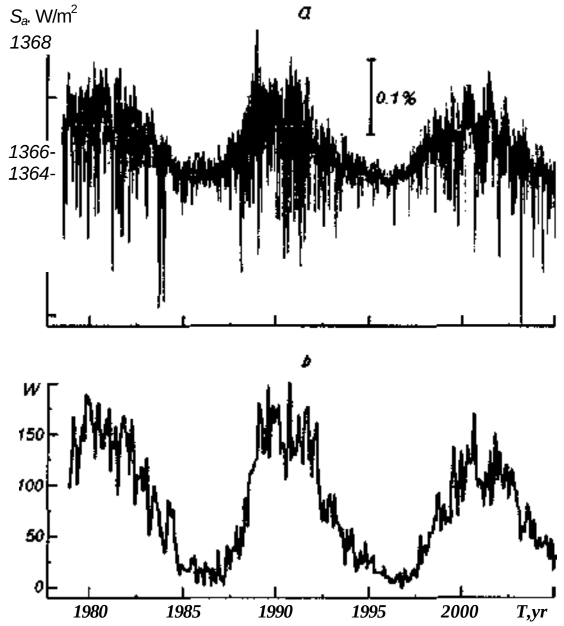

Fig. 1. Variations of the "solar constant" since 1978 [14] *(a)* and variations of the monthly average Wolf number *W(b).*

Cyclic long-term variations of the "solar constant", which is expressed by the formula

$$S_⊙ = \sigma R_⊙^2 T_{eff}^4/A^2,$$

where A is the astronomical unit, are determined by the corresponding variations of the radius $R_⊙$ and the effective temperature T_{eff} of the photosphere:

$$\Delta S_⊙/S_⊙ = 2\Delta R_⊙/R_⊙ + 4\Delta T_{eff}/T_{eff},$$

These variations are caused by some fundamental global processes which occur deeply in the Sun and which arise from variations of basic internal solar parameters. The radius variation at a constant effective temperature *(*$\Delta T_{eff} = 0$) is $\Delta R_⊙ \leq 350$ km/cycle and the temperature variation at a constant radius *(*$\Delta R_⊙ = 0$) is $\Delta T_{eff} \sim 1.45^o$/cycle (or less than 0.001^o/day), since $\Delta S_⊙/S_⊙ \leq 0.001$. Gradual temperature variations of about 0.001^o/day in the photosphere cause the photospheric pressure to change, and this leads to an unbalance between the internal pressure forces and the gravitational force. As a result, the photosphere radius gradually changes until the hydrostatic equilibrium is restored, and the temperature virtually returns to its original value [3,8]. Therefore, we suppose that the cyclic long-term variations of the "solar constant" are determined almost entirely by the corresponding changes of the area of the radiating photosphere surface at an almost constant effective temperature, i.e.,

$$\Delta S_⊙/S_⊙ \approx 2\Delta R_⊙/R_⊙.$$

So, the variations of the "solar constant" are determined by the photosphere radius oscillations with an amplitude up to 350 km *(*$\Delta R_⊙ < 0.5''$) per 11-year cycle [8]. Thus, an 11-year heliocycle is a simultaneous phase- and amplitude-correlated oscillation of the solar activity, radius, and radiation flux.

The existence of the 11-year variations of the radius and their correlation with the variations of the activity level and radiation flux were confirmed by direct long-term ground-based observations, even though such observations are considerably distorted by the atmosphere and the observation series are quite irregular. The larger radius is related to the higher activity level and the smaller radius is related to the lower activity level, as it was found by comparing the visual measurements of the radius and the variations of the activity level over the last 300 years [9]. Recent photometric ground-based measurements of the radius [7,17,18] also confirmed that the activity level and radiation flux variations in 11-year cycles are in close relation to the radius variations. The amplitude of the radius variations was larger in the cycles with higher activity level, and it was smaller in the cycles with lower activity level [7], i.e., the curves of the 11-year variations of the radius and activity level and the curves of the "solar constant" variations are cross-correlated and quasi-parallel in both phase and amplitude. The existence of a 80-year cycle in the radius variations [7,15,19] along with the secular climatic changes is an additional proof for the existence of the previously found secular variations of the solar radiation flux.

Thus, the 11-year and secular variations of the solar activity which have easily been observed on the Earth for a rather long period of time also point at the quasi-proportional variations of the solar radius and radiation flux. Therefore, strictly speaking, the Sun as a whole is not in the state of mechanical and energy equilibrium. The Sun is a variable star which demonstrates the correlated quasi-periodic variations of activity, radius, and radiation flux with at least three periods (11, 80, and 200 years). Such correlated long-term variations require enormous energy resources. So, these variations are likely to be caused by some common processes which occur deeply in the Sun, and they correlate with the global oscillations of the whole Sun. These global oscillations are due to cyclic temperature variations in the solar core. The energy released from the core disturbs the solar equilibrium [1].

The solar neutrino flux exhibits considerable (up to 40 percent) temporal variations with various periods. Although these variations have not rigorously been proved to correlate with the cycle phase, they point at some appreciable changes of the thermonuclear processes in the solar core [16]. Similar variations of the solar disk oblateness are also evidence of certain changes in the dynamic processes in the core [10,20,22]. The long-term quasi-periodic growth of the temperature and pressure in the core inevitably causes the whole Sun to heat up, the size of the Sun and the "solar constant" increasing proportionally to the squared radius. The resulting global cyclic changes in the Sun can trigger the generation of the activity and radiation flux cycles at the expense of the additional energy released by the core [3]. We believe that cyclic disturbances of the tachocline and its position as well as probable changes of its width can stimulate the generation and drop of activity cycles. The long-term quasi-periodic growth of the core temperature and the corresponding expansion of the whole Sun seem to give rise to a cycle with increased solar activity and radiation flux, whereas a decrease in the temperature and the corresponding contraction of the Sun can result in a weaker cycle. The amplitude of the core temperature variations seems to determine the cycle power. Small-amplitude temperature oscillations give rise to weak cycles with small activity level and radiation flux amplitudes, whereas more powerful cycles develop at larger temperature variations. Deep Maunder-type minima of the solar activity and radiation flux can occur when the core temperature is at its minimum and the temperature variations are very small [8]. Thus, the solar radius is a most important fundamental parameter, and it is one of the main indicators of the solar activity and radiation flux level.

Climatic changes on the Earth, which represent long-term geophysical processes, are mainly determined by the quasi-periodic correlated 11-, 80-, and 200-year variations in the solar activity and radius, and consequently in the "solar constant" ($\Delta S_{\odot}/S_{\odot} \approx 2\Delta R_{\odot}/R_{\odot}$). However, the effect of variations of the "solar constant" on climatic changes is essentially smoothed by the Earth's thermal inertia, although the amplitude of these variations over one 11-year cycle is as large as 0.1 percent. Nevertheless, this effect can lead to gradual climatic changes when the amplitude of the "solar constant" variations continuously increases or decreases over two 11-year cycles [1].

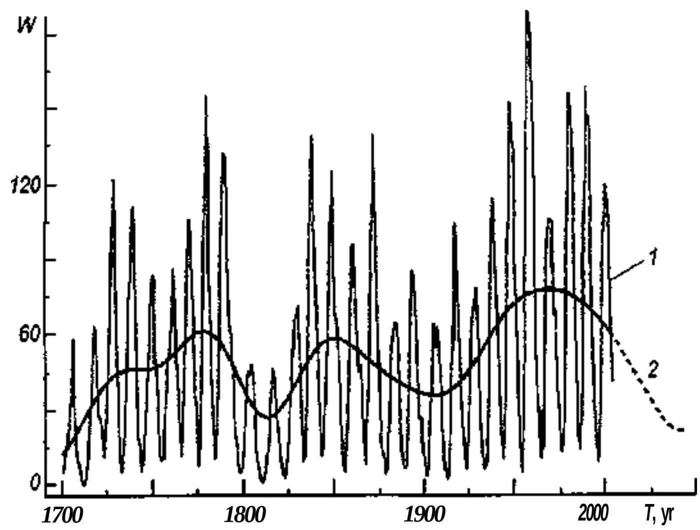

Fig. 2. Observed levels of the quasi-periodic 11-year oscillations of the Wolf number *W* over the last 300 years (curve 1) and cyclic variations of the secular component (curve *2)*.

The secular component of the activity level was dropping over almost three last decades (Fig. 2), so that the 11-year activity level should decrease over at least three solar cycles after the year 2000 [11,21]. As a result, the Gnevyshev-Ohl rule implying that the maximum activity level in any odd cycle is higher than that in the preceding even cycle should be violated in cycles 24–25 just as it was violated in cycles 22–23 [11]. Thus, the variations of the radiation flux and 11-year activity will continue to decrease in cycles 24–25.

The observed violation of the Gnevyshev-Ohl rule in cycles 22–23 and the expected violation of this rule in cycles 24–25 indicate that the current 200-year quasi-cycle starts to descend (Fig. 2). We suppose that the next relatively deep minimum of the solar activity, radiation flux, and radius will occur at the end of this quasi-cycle and will be close to the Maunder minimum level. According to our estimates, this will happen at the beginning of cycle 27 in the year 2040 ± 10 [4]. On the other hand, we infer that the cyclic oscillations of the solar activity level which develop along with the oscillations of the radius and radiation flux and which accompany the cyclic oscillations of the whole Sun do not significantly affect the radiation flux variations and climatic changes.

Thus, our conjecture about cyclic temperature variations in the solar core can generally explain the observed long-term nonstationary phenomena in identical cyclic variations of the solar activity, radius, and radiation flux.

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