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# THE ELEVEN YEAR CYCLE OF SOLAR ACTIVITY

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MANY observations of the solar activity and its influence on the earth's atmosphere have been accumulated as a result of completion of the programs of the International Geophysical Year, the International Geophysical Collaboration, and the Year of the Quiet Sun.

The new data have shown that the phenomena on the sun as well as their influence on earth are much more varied than has been assumed until recently. It has turned out, in particular, that the energy range of the particles emitted during the time of active processes on the sun is so wide that it includes also cosmic-ray particles. Evidence is increasing that the solar corpuscles not only act on the magnetosphere and the ionosphere of the earth, but lead to large-scale changes in the troposphere and cause changes in certain colloids, and thus interfere also in chemical and biological processes.

As a result, problems involving solar activity have attracted not only astrophysicists, geomagnetologists, and radiophysicists, but also those specializing in plasma physics, cosmic rays, upper and lower layers of the earth's atmosphere, and certain branches in physics, biology, and medicine.

The better knowledge of the interplanetary space has greatly increased the urgency of research on solar radiation and its causes, the active processes on the sun.

In this article we summarize certain results of observations of the most grandiose phenomenon in the solar system, namely the eleven-year cycle of solar activity, the manifestations of which are represented in all the aforementioned branches of science. It is our aim to systematize the important empirical laws observed recently, principally as a result of observations of the corona outside the eclipsed sun.

These laws should serve, on the one hand, as a basis for a model of solar phenomena, and on the other as the starting points for more detailed research on interactions between the sun and the earth and their practical applications.

The fact that the number of spots on the sun varies with an average period of eleven years was established in the middle of the last century first by Schwake and then by Wolf. It became subsequently known that the same changes occur also in the average values of the areas of the spots and the flares, and also all the characteristics of chromospheric formations (flocculas and chromospheric flares), prominences, active formations in the corona, and all kinds of active radiation (radio corpuscular, and ultraviolet emission). Thus, all the layers of the sun that are accessible to observation change during the eleven-year cycle. It was established soon afterwards that similar changes occur in the number of magnetic storms, auroras, intensity of terrestrial currents, and also the state of the ionosphere and the associated radio-wave propagation conditions. The presence of eleven-year oscillations in various phenomena on earth came to be regarded as evidence that these phenomena are caused by solar activity.

At the same time, attempts were made to explain the eleven-year cycle. The application of periodogramic analysis to the sunspot curve, to check the hypothesis of the occurrence of periodic processes on the sun under the influence of planets, is by now only of historical interest. The failure of this attempt led Waldmaier to a consideration of an eleven-year cycle that has a rapid rise and a gradual decrease, like an explosive process. The discovery of magnetic fields in the spots and of regularities in the distribution of the polarity over the hemispheres, and the variation of this distribution with the alternation of the cycle, have contributed to the formulation of the Bjerknes hypothesis. Subsequently, circulating as well as other processes in a highly ionized medium were taken into consideration (the hypotheses of Alfven, Babcock, and others).

Since any theory aimed at explaining the physical nature of the eleven-year cycle should be based on empirically established properties of the cycle, explain them, and under no circumstance contradict them, it is necessary first to verify again and to refine these properties, with allowance for the new extensive material.

Until recently our information on the properties of the eleven-year cycle were quite skimpy, and was all obtained either in the last century or at the beginning of the current century. The main properties were as follows:

Each new cycle is observed after the appearance of high-latitude formations (near 40°). Subsequently, as the cycle develops, new formations appear closer and closer to the equator (Spoerer's law). An exception is observed in high-latitude regions, where the maximum activity of the protuberances and of the corona shifts to the poles at the instant of the maximum of the cycle. However, the high-latitutde pro-

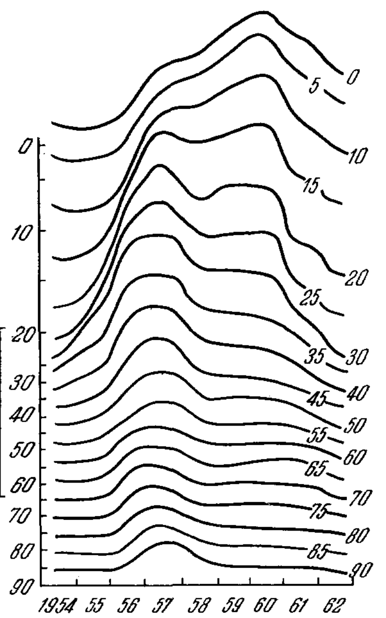


FIG. 1. Eleven-cycle of intensity of the 5303 Å coronal line at different latitudes. Abscissas – years. Ordinates – intensities, whose scale is given by the vertical bar on the left. The numbers on the right show the heliographic latitudes. The markers on the left indicate the null points of the curves. The figures at the markers are the heliographic latitudes to which the markers pertain.

tuberances and coronal regions are negligible both in size and in frequency or intensity compared with the formations at latitudes lower than 40°.

The distribution of the magnetic polarity in the groups of spots is identical for spots of one hemisphere during the entire eleven-year cycles, and is opposite to that for the spots of the other hemisphere. With start of each new cycle, the distribution of the polarity in both hemispheres is reversed (Hale's law).

An analysis of the new data, and particularly of the results of systematic observations of the corona surrounding the eclipsed sun, made it necessary to modify appreciably the foregoing regularities of the eleven-year cycle and disclosed new details[1-8].

The new possibilities were the result of the fact that by the end of the 19th cycle there have been accumulated enough observations of the corona, sufficient for comparison of data from different observatories. This has made it possible to separate the real changes in the corona from the apparent ones, which reflect the instability of the measurement system in some particular observatory[1].

The main conclusion was that the eleven-year cycle is not one but two waves of intensified activity, possessing different physical properties. This can be clearly seen in Fig. 1, where the abscissas are years and the ordinates the intensities of the coronal 5303 Å line in absolute units. Each curve corresponds to the definite latitude indicated on the right. The null points of all the curves are separated along the ordinate axis to prevent superposition of the curves. The markers on the left show the null points, and the numbers designating them show the latitudes to which the the given null points pertain. All the curves are drawn to a single intensity scale, which is indicated by the vertical bar on the left, whose length is 100 absolute intensity units. The curves are plotted from data averaged over half-year periods.

Figure 1 shows that in the 19th cycle there were two maxima: the first in 1957 and the second in 1959–1960. The first maximum is characterized by the fact that the increase and then decrease in intensity of the corona occur simultaneously in all latitudes. The second maximum appears only in low latitudes, and starting with 15° it is even larger than the first.

On the basis of the data of Fig. 1, we can plot Fig. 2, which shows the intensity of the corona (ordinates) against the latitude (abscissas) for a number of half-years. It is seen that on approaching the first maximum (1957), the intensity increases simultaneously at all latitudes. The maximum intensity remains the same at a latitude near 25°. The dashed curve pertains to the time of the second maximum (1960). At that time, the greatest intensity is observed at latitudes near 13°.

Figures 1 and 2 indicate that there is no gradual creep of the corona intensity maximum towards the equator, as would follow from Spoerer's law. Yet such a gradual decrease in latitude can be obtained by calculating the average latitude weighted for intensity. The wings of both maxima are superimposed on each other, and therefore in calculating the mean values of the latitude the influence of the first maximum will decrease, and that of the second will increase as the end of the cycle approaches. It is seen from Figs. 1 and 2, however, that the monotonic decrease in latitude obtained in this manner is only illusory, and in fact the eleven-year cycle constitutes two processes which are partially superimposed on each other in time, but whose centers occur at different fixed latitudes.

For an estimate of the reliability of the foregoing

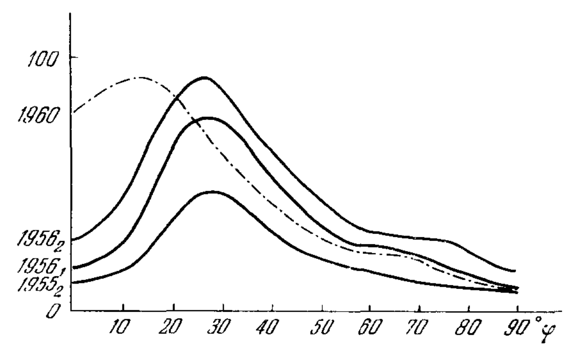


FIG. 2. Intensity of the corona (units) against the latitude (abscissas) from the number of half-years indicated on the curves on the left.

conclusions it is important that Fig. 1 agrees with the results of numerous observations of the corona during eclipses. In fact, it is known that during the years of the maximum of the cycle (i.e., during the time of the first maximum), the glowing corona can be seen clearly around the entire disc, while during the second half of the cycle (time of the second maximum) the brightness is high only near the equator.

Figure 1 was constructed from data averaged over both hemispheres. Similar curves, obtained separately for the northern and southern hemispheres,[3] do not modify the foregoing conclusions.

This, naturally, raises two questions: 1) Do the described properties of cycle No. 19 pertain only to the solar corona or do they characterize phenomena both in the chromosphere and in the photosphere? 2) Is it possible to extend the conclusions drawn from the data on cycle No. 19 to all the remaining cycles?

The answer to the first question was given already in [1]. It is shown there that the spots and the protuberances exhibit the same two maxima if the characteristics of these phenomena are plotted on curves similar to Fig. 1 for the corona. This investigation was repeated in [3] with much more extensive material. Data were used on the areas of the sunspots from 1874 through 1962 as given in the Greenwich and Pulkovo catalogues. For the eight cycles covered by this period, curves similar to Fig. 1 were plotted and were then superimposed on one another for individual cycles. An effort was made in this case to obtain best alignment of all curves of one cycle pertaining to different latitudes with the corresponding curves of the other cycles. Obviously, such an alignment method is much more accurate than that customarily employed, in which the cycles are aligned at the instants of their maximum values, which are highly accidental and affected by the observational errors. In the alignment method used by us, errors or random deviations of the individual quantities cannot influence the final result, since care was taken during the alignment to obtain coincidence of many curves pertaining to different latitudes.

The result of averaging over all the cycles is shown in Fig. 3. This figure, just as Fig. 1, shows clearly that in the eleven-year cycle there is developed first one maximum, which is simultaneous at all latitudes, and later a second maximum only at low latitudes.

Figure 3, just as Fig. 1, contradicts Spoerer's law. Indeed, the curves pertaining to latitudes 15—20° shows the influence of both the first and second maxima. This indicates that the low-latitude second maximum at the end of the cycle (which is seen on the curves for 5° and 10°) is an independent process, and is not the result of shifting of the activity from higher latitudes (curves for 35°, 30°, and 25°) at the beginning of the cycle towards lower ones at the end, as would follow from Spoerer's law.

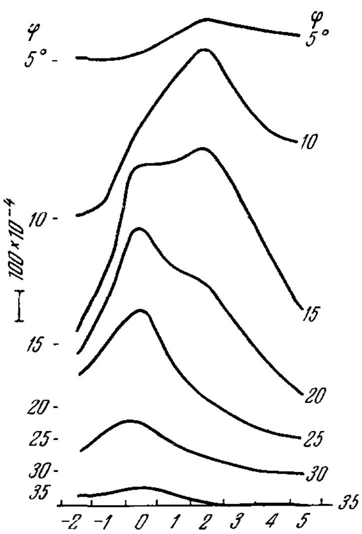


FIG. 3. Changes of spot areas in five-degree intervals of latitudes during the eleven-year cycle. Abscissas – years measured from the instant of the first maximum. Numbers on the right – latitudes to which the corresponding curves pertain. Markers on the left and the figures next to them indicate the null points of the curves. The ordinates are the areas of the spots, whose scale is shown by the vertical bar on the left.

Figure 4 shows the dependence of the area of the spots on the latitude for the instants of the first and second maxima of cycles 12 through 19.

The absolute measurements of the corona during the 18 cycles were carried out at the Pic du Midi Observatory. These data indicate that there were two activity maxima in this cycle [3].

Both from Fig. 3, on which the areas of the spots are averaged for all eight cycles, and from the analogous curve for each of these cycles, it follows that the two maxima with the described properties are possessed by all cycles. The time interval between the first and second maximum differs in different cycles, and consequently the degree of superposition of their wings also differs. In those cases when this time interval is sufficiently large, the two maxima in the eleven-year cycles can be seen even when the spot areas are summed over the entire disc. This was

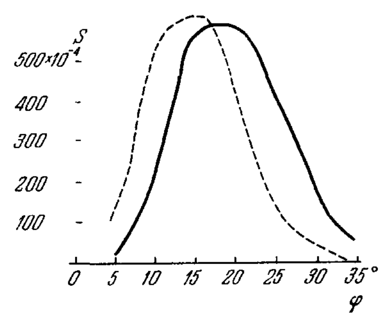


FIG. 4. Areas of the spots (ordinates) against the lattitude (abscissas) during the time of the first and second maxima. The values of the area are averaged over eight cycles.

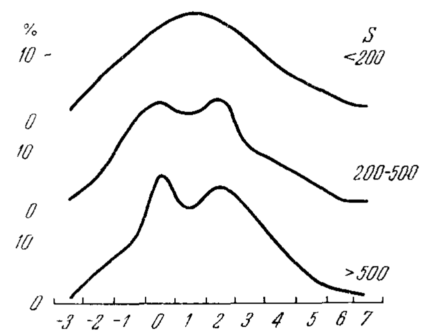


FIG. 5. Variation of the number of spot groups in the eleven-year cycle. Upper curve – number of spots with area smaller than 200 units, middle curve – with area from 200 to 500 units, lower curve – with area larger than 500 units. Ordinates – numbers of spot groups as percentage of the total number of groups of a given size in the cycle. Abscissas – time in years, reckoned in analogy with Fig. 3.

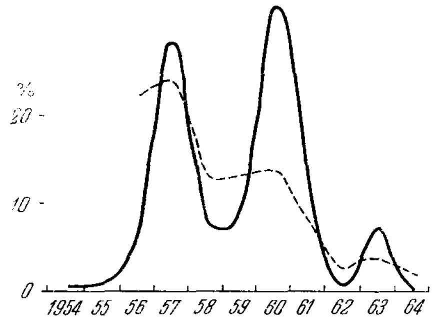


FIG. 6. Change in the number of chromospheric flares (dashed curve) and in the number of the proton flares (solid curve). Ordinates – number of flares per year as percentage of the total number per cycle. Abscissas – years.

the case, for example, in 1905 and 1908, in 1926 and 1928, and in 1947 and 1949.

If two maxima are close in time, then their mutual overlap is large and they cannot be resolved on the indices of the solar activity which are summed over the entire disc, so that we see a single-peak eleven-year curve. In these cases one can separate the maxima by using the fact that their centers are at different latitudes (see Fig. 4). To this end it is necessary to construct eleven-year curves separately for narrow latitude intervals (of 5° width), as was done in Figs. 1 and 3.

Thus, the presence of two activity maxima is an essential property of all the eleven-year cycles. The time interval between the maxima, and consequently also the degree of their overlap, other, determines the form of the summary eleven-year curve. This pertains to all the phenomena in the corona, chromosphere, and photosphere.

It is essential that two maxima can be better separated in the more active formations. Figure 5 (upper curve) shows how the number of spots with area smaller than 200 units (millionths of the solar hemisphere) vary over eight cycles; the middle curve is the same with area from 200 to 500 units, and the lower curve, with area more than 500 units. All the numbers of cases per year (ordinates) are expressed in percentages of the total number in the cycle. The abscissas represent the time in years, reckoned in the same manner as in Fig. 3. We see that the small spots give a smoothed curve of the eleven-year cycle, and this was the basis for the previously developed notions concerning the laws of its development. The numbers of large and very large spots show clearly that the eleven-year cycle consists in fact of two superimposed processes.

Of special interest is an investigation of the two-peak nature of eleven-year cycles in chromospheric flares [8] and in the radio emission from the sun [4].

Figure 6 shows how the number of chromospheric flares (dashed curve) and the number of proton flares varied during the years of the 19th cycle. The number of chromospheric flares was taken from observations of the Swedish solar station in Anacapri, which are distinguished for their completeness and uniformity. The number of proton flares was calculated from the catalog published in [8]. It is seen from Fig. 6 that both maxima are clearly pronounced in the number of the proton flares having a large value for phenomena on earth. If we separate from the number of the proton flares the cosmic flares, which emit the most energetic particles, then we note that the number of the latter is particularly large during the time of the second maximum.

The number of the chromospheric flares reflects also the second maximum in the form of a step on the 1960 curve.

From a comparison of the dashed and the continuous curves on Fig. 6, when account is taken of the remark made above concerning the cosmic flares, we can conclude that the more energetic the phenomenon, the greater the part it plays in the second maximum.

The described two maxima in the eleven-year cycle enable us to explain interesting properties of radio emission from the sun [4].

The data accumulated to date on solar radio emission have been obtained with apparatus having small angular resolution, and therefore the measured fluxes are the summary emission from the entire disc of the sun, and in the case of meter waves they include the radiation from the corona.

Figure 7 shows the variation of the flux of the radio emission at different wavelengths from 3 to 450 cm during the 19th eleven-year cycle. The wavelength in centimeters is indicated on the left of each curve.

The curves of Fig. 7 can be divided, depending on their shape, into three groups. The first (waves from 3 to 30 cm) is characterized by the fact that in the eleven-year cycle it duplicates the single-vertex sunspot-area curve summed over the entire disc of the sun. In the 19th cycle there was a strong super-

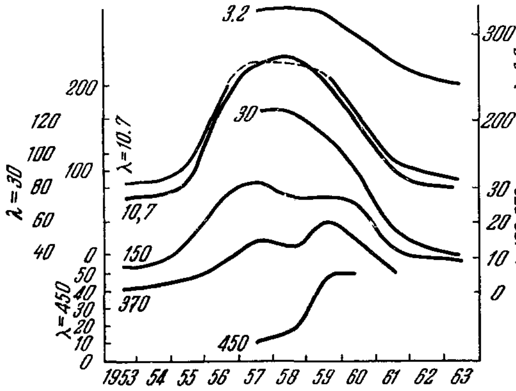


FIG. 7. Comparison of eleven-year curve of the flux F of solar radio emission at different wavelengths λ(in cm). Abscissas – years. Ordinates – flux in $10^{-22}$ W-cm$^2$. The curves are marked on the left with the values of λ in cm.

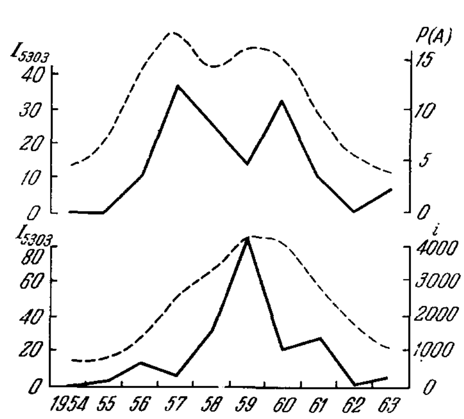


FIG. 8. Top: solid curve – number of PCA cases by years, dashed – intensity of 5303 Å coronal line, averaged over all latitudes. Bottom: solid curve – mean-annual value of the intensity (i) of the proton component of the solar radiation; dashed – intensity of the coronal line in a solid angle of 10°. Ordinates: left – line intensity, right – number of PCA cases. Ordinates: left – intensity of 5303 Å line, right – average intensity of the proton component in cm$^2$ sec-sr. Abscissas – years.

position of the first and second maxima, and therefore they are separated only on the curves constructed separately for different latitudes (such as in Fig. 3).

(In the preceding 18th cycle the time interval between the two maxima was longer, and therefore the curves of the spot areas summed over the entire disc, as well as the curves of radio emission at decimeter wavelengths, show the two maxima.)

The second group (150 and 370 cm waves) is characterized by the presence of two maxima. Finally, the third group (450 cm wave), for which unfortunately the observations were carried out only for a short time, shows only the second maximum.

Thus, only one maximum is seen at centimeter wavelengths. With increasing wavelength, one can see also the second maximum, and at sufficiently large wavelength, the first maximum disappears. This regularity can be attributed to the fact that the solid angle of the radio emission from the sun decreases with increasing wavelength.

At centimeter wavelengths, the radiation from the sun propagates in a very wide angle and is therefore the sum of components pertaining both to the first maximum (the center of which is located father away from the direction to the earth) and to the second, low-latitude maximum. Radiation at very long waves, which are emitted in a narrow solid angle, can be received only from phenomena connected with the second maximum.

In similar fashion, the two activity maxima of the eleven-year cycle can be used to demonstrate the narrowness of the solid angle of proton radiation from the sun [4].

The solid curve in the upper part of Fig. 8 shows the change in the annual number of cases of intensification of the proton component causing absorption in the polar region (the so-called PCA), according to the Baily catalog [9]. The dashed curve shows the intensity of the 5303 Å coronal line, averaged over all the latitudes. In the lower part of Fig. 8, the solid curve characterizes the change in the average intensity over the years (i) of the proton component in the PCA, calculated from the data of the same Baily catalog. The dashed curve is the intensity of the 5303 Å coronal line in a narrow solid angle of width 10° directed towards the earth. It follows from Fig. 8 that whereas the number of PCA duplicates the variations in the activity on the entire sun, the observed intensity of the proton radiation is connected with narrow directed radiation.

Thus, the fact that the eleven-year cycle consists of two processes is essential not only for the construction of the physical model of this phenomena, but also makes it possible to reduce numerous facts from various fields to a single system.

Of particular importance, however, is allowance of these properties of the eleven-year cycle when searching for and investigating sun-earth correlations.

In this respect, mention must be made first of the connection between the solar activity and geomagnetic disturbances. As is well known, the connection between these phenomena has been established long ago, but nonetheless the forms of the eleven-year curves of the indices of solar activity and of the geomagnetic perturbations differ noticeably. This difference can be attributed to the narrowness of the beams of corpuscular radiation, but a much better agreement is obtained when the above two maxima are taken into account [7].

Figure 9 shows a plot of the planetary index $\bar{A}_p$ of geomagnetic activity, introduced by Bartels (dashed curve), and a plot (solid) of the intensity of the 5303 Å coronal line, averaged in the solid angle ± 30° to the direction to the earth. The connection between these two quantities is characterized by a correlation coefficient +0.98 ± 0.01. Thus, geomagnetic

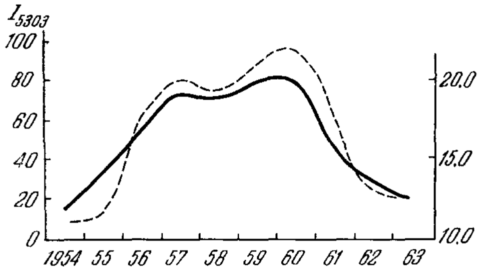


FIG. 9. Planetary index $\overline{A}_p$ of geomagnetic activity (continuous curve) and intensity of 5303 Å coronal line (solid curve) averaged in a solid angle ± 30° to the direction to the earth. Abscissas – years.

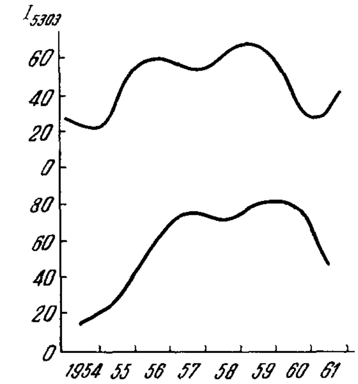


FIG. 10. Comparison of the number of cases of exceedingly large baric formations (upper curve) with the change in intensity of the 5303 Å coronal line in a solid angle ± 30° to the direction to the earth. Abscissas – years.

disturbances reflect the existence of a second maximum, whose influence to the fact that the solar formations are very close to the direction towards the earth.

When searching for eleven-year cyclicity in the tropospheric processes, notice was taken many times of the presence of a second maximum, but at that time it was the cause of misunderstandings and was regarded as proof of the absence of correlation, inasmuch as it was not noted in the solar phenomena.

In 1964, B. I. Sazonov [10] reported an important investigation in which, on the basis of an analysis of 12,000 high-altitude baric maps of the northern hemisphere for 1949–1962, it was shown that the regions of the greatest frequency of the maximal and minimal phenomena form ring-like zones, similar to the aurora zone. This indicates that their occurrence is connected with the penetration of solar corpuscular streams. However, the number of such tropospheric formations has exhibited a second maximum in the eleven-year cycle in 1960, a maximum not observed in the customarily employed summary indices of solar activity. This contradiction was eliminated [2] when the second maximum in the eleven-year cycle of the solar activity was observed.

The upper curve of Fig. 10 [2] shows the variation of the number of exceedingly large baric formations, while the lower curve shows the variation of the intensity of the 5303 Å coronal line, averaged in the same solid angle as for Fig. 9. It is obvious that the good agreement of the curves of Fig. 10, which is not accidental, is attained at the same value of the solid angle as in the comparison with the geomagnetic disturbances.

Thus, the second maximum is a convincing confirmation of the fact that the tropospheric processes are due to solar activity. In this connection, new significance is attached to the numerous facts connected with the presence of two peaks in the eleven-year cycle, which were observed in the runoff of the rivers Syr-Dar'ya and Amu-Dar'ya, and as a result, in the level of the Aral' Sea, in the level of Lake Victoria, and in the thicknesses of the deposits of marls, silt, and clay. According to geological data, the double wave in the eleven-year cycle, which is called the five–six year cycle, can be traced back millions of years.

In 1955, at the initiative of Dr. G. Piccardi of the Physico-chemical Institute in Florence, interesting observations on the behavior of colloids were started in a number of specially organized stations at different geographic latitudes. It turned out that certain chemical tests vary in identical fashion in the same stations and exhibit with this a dependence on the solar activity. The only "confusing" circumstance was the presence of the second maximum in the eleven-year variations of these tests [11]. As can be seen from Fig. 11, this second maximum in the chemical tests (dashed curve) occurs at the same time as the second maximum in the intensity of the 5303 Å coronal line (solid curve).

Finally, there are by now numerous indications that the solar activity causes a change in the composition of the blood. It is obvious that from the physical and chemical point of view this phenomenon is connected with G. Piccardi's discovery. If this is so, then the influence of the solar activity should be observed in many chemical and biological processes not only in the atmosphere but also in the hydrosphere of the earth.

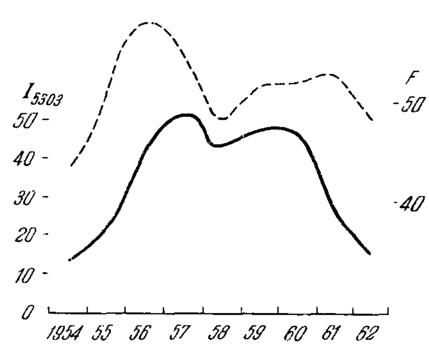


FIG. 11. Comparison of Piccardi's chemical test F (dashed curve) with the intensity of the 5303 Å coronal line (solid curve) averaged over all latitudes. Abscissas – years.

Indeed, the number of indications pointing to the presence of such connections increases continuously, and they deserve a most attentive and thorough investigation.

The manifestations of the solar activity can be found not only on earth. The brightness of comets also varies in accord with an eleven-year cycle in which a second maximum is observed. Thus, problems of solar activity touch upon a wide circle of interesting and important problems still awaiting solution. In particular, it would be very important to observe the agent capable of penetrating the earth's surface.

One of the most important trends is an investigation of the eleven-year cycle of solar activity. It is seen from the foregoing that a seemingly insignificant detail—the presence of two activity maxima in the cycle instead of one—leads to results that are very important both for the understanding of the nature of this phenomenon and for a clarification, refinement, and prediction of a number of its consequences. Indeed, numerous data on phenomena in the solar corona, chromosphere, photosphere, solar radio emission, magnetosphere, troposphere, and even in some chemical and biological phenomena on earth are unified in a single scheme. This agreement between the data obtained by different methods and even from different fields of knowledge is convincing proof of the correctness of this scheme. Of course, the regularities of the eleven-year cycle still need further refinement, detailing, and interpretation. Of great significance for this purpose are continuous and stable observations of the solar activity, especially the solar corona, which provide the main material for this research.

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Translated by J. G. Adashko