CANADIAN SCIENTISTS REPORT

VII. SOLAR RADIO ASTRONOMY

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SYSTEMATIC studies of solar radio emission have been undertaken in several countries during the past ten years, and sufficient evidence has now been accumulated to show that these emissions may provide much needed measures of solar activity. Solar indices, such as sun-spot number and the area of sun-spots, are well established, and in the case of the Zurich numbers, extend back to 1749. In addition to their intrinsic solar interest, the Zurich numbers have been successfully used in studying solar-dependent phenomena on the earth's surface in which it is desirable to have an indication of the variable solar energy. In this case, strange as it seems, the presence of dark sun-spots was interpreted as an increase of solar emission. In the geophysical field, variation in solar activity is reflected in a variation in the number of free electrons in the ionosphere, the ozone content in the air, and the frequency of occurrence of aurorae and of magnetic storms. Present-day geophysical research has created a need for a more accurate measure of primary solar energy, and within the next few years much attention will be given to the possibilities presented by the observation of solar noise.

The Solar Spectrum

A much simplified graph of the solar energy received on a section of the earth's surface one metre square, for various wave-lengths ranging from the ultra-violet to long radio waves, is shown in figure 1. The complete range of wave-lengths shown in the abscissa of the graph cannot be observed on the earth's surface because the upper atmosphere forms natural barriers at different wave-lengths. On the earth's surface only two transmission regions are observed, one containing the light and heat waves, and the other containing the radio waves. In the graph, these two transmission bands are the clear regions between the hatched absorption bands.

The intensity of the continuous background spectrum in the optical region, after correction for the dark absorption lines, can be fitted readily

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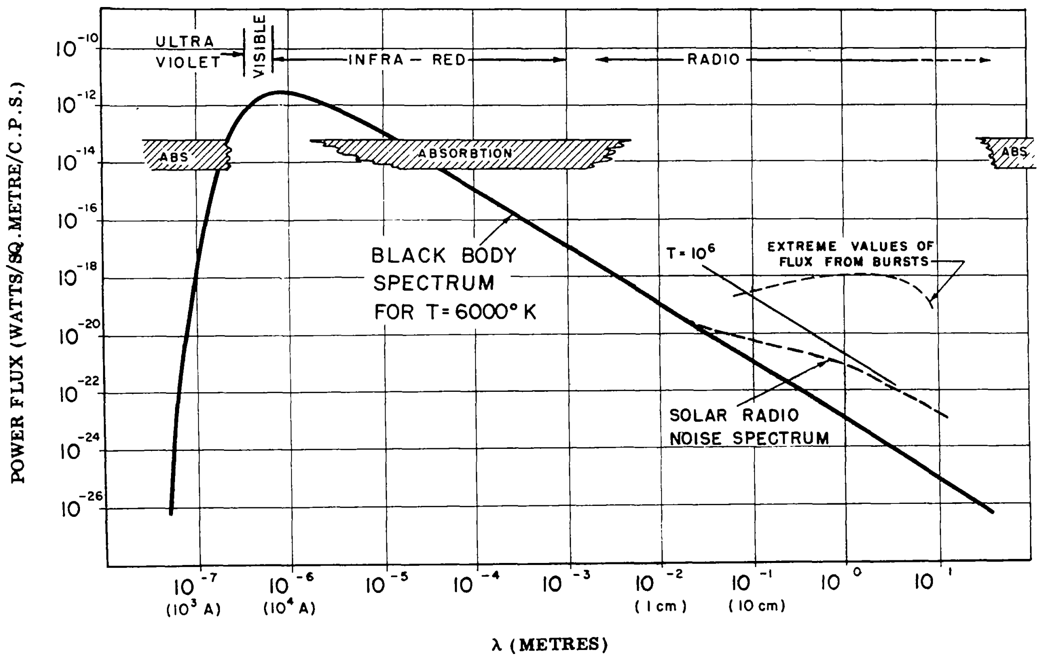

FIG. 1—Graph of the solar spectrum.

to a theoretical radiation curve of a black body at a temperature of 6000°K., as shown by a solid line on the graph (figure 1). However, in the radio spectrum, the observed curve shows a large excess over the theoretical radiation curve for 6000°, which can be explained only in terms of temperatures ranging from values of 10,000° to tens of millions of degrees. The use of a temperature to describe these deviations from the black body curve has led to the use of an equivalent temperature and is the means whereby portions of an ideal black body radiation curve may be used to measure the observed intensity over a small range of wave-lengths. Another unit for measuring the radiant solar flux, already used as the ordinate in figure 1, is the power in watts falling upon a given area within a given band of wave-lengths.

The intense radio emission is explained in terms of an electro-magnetic radiation from the electrons in the highly ionized outer solar atmosphere. This region of the sun extends from the visible disk—the photosphere—to a distance of several solar radii and separates into at least two layers: the chromosphere lying just above the photosphere, and the corona, again lying outside the chromosphere. The minimum equivalent temperature observed over a range of metre wave-lengths is about 1,000,000°K. and has been directly related to the kinetic energy of the free electrons. This radio evidence is one of several indications that the electrons are moving as though immersed in a medium of this high temperature. The basic radio emission associated with the minimum temperature of the corona is produced by collisions of electrons with ionized hydrogen atoms in the continual jostling arising from their heat motions. The resultant intensity, as the sum of many individual waves occurring in a random manner, changes from moment to moment. This variability, when converted into sound waves by a radio receiver and loud-speaker is evident to our senses as a hissing sound, and has resulted in the name "solar radio noise". The strength of the emission is related partly to the kinetic energy of the electrons and partly to the number of electrons per cubic metre, or the electron density. Other modifying solar features—in some cases acting as natural radio amplifiers—are the magnetic fields and jets of moving gases in the vicinity of sun-spots. These give rise to an ordering effect of the individual electrons and consequently produce greatly enhanced radiation. In contrast to the thermal emission, these latter radiations are referred to as non-thermal emission.

The total energy received on a unit section of the earth's surface is exceedingly important and has been named the solar constant. It is represented by the area under the spectrum-curve shown in figure 1. In the optical region of the spectrum, the energy originating from the outer solar atmosphere and falling upon the earth is very small, even though the kinetic temperature is very high. These outer gases are very thin and radiate efficiently only in the radio region of the spectrum. Most of the energy in the optical region arises from the cooler and denser photosphere, and a value of about 1.5 kilowatts for every square metre of the earth's surface has been measured. In the radio region, the estimated energy amounts to about one part in 10^{11} of that contained within the optical spectrum. The extension of the solar spectrum from the optical to the radio region has not led to a revision in the accepted magnitude of the solar constant. In relation to the quantity of heat received at the earth, radio emissions are insignificant, but may be very important to our understanding of how this energy is released by the sun. In this sense, the relation of the solar radio emission to the total solar energy output is similar to the ratio of the radio power of the ignition noise from an automobile to the mechanical power produced by the engine.

Radio Observations

The simplest, and hence most frequently used method of observation is the collection of the radio emission in a restricted band of wave-lengths from the whole solar disk by an antenna or "radio telescope" having a cone of acceptance of several degrees. This band of wave-lengths is restricted further when the emission is amplified by a sensitive radio receiver or "radiometer", and finally the amplified solar emission is converted into a direct current for operation of a paper-strip recording meter. Early investigators employed equipment of this type, the choice of an operating wave-length being determined principally by the availability of components from existing radar equipment. Commencing in 1942, observations have been made on various occasions at about a dozen discrete wave-lengths throughout the radio spectrum, and the resulting curves of solar flux as a function of time have provided basic information for testing hypotheses on the generation and escape of radio waves from the quiescent sun. The records, in addition to indicating the daily level of emission, may display complex variations of amplitude for short periods of time. These have become known as bursts of solar noise; sometimes they take the form of a single rise and fall of intensity and are called single bursts, but more frequently they occur in great profusion, one superimposed upon the other, with various strengths and durations. In general, metre wave-length observations show much more burst activity than those of the shorter centimetre waves. Records at the various observatories are examined to give a numerical description of the solar flux, and the results are expressed in at least three categories: (1) the mean value of the minimum flux observed for the day; (2) the variability of the emission above this mean, and (3) any burst activity of outstanding nature.

The Radio and Electrical Engineering Division of the National Research Council, Ottawa, has placed particular emphasis upon solar observations at 10-centimetre wave-length. Various surveys of the solar emission on this, as well as other discrete wave-lengths throughout the radio spectrum, have been conducted at other observatories (Pawsey and Bracewell, 1955), and have revealed complex intensity variations as a function of time, as previously noted. Fortunately, the essential variations may be observed by examining the solar radio emission in two widely different wave-length bands which, on the basis of past and present observations, may be designated by the specific wave-lengths, 10 cm. and 150 cm. The appearance of bursts on these two wave-lengths is generally different; the shorter wave-length bursts occur occasionally and change smoothly, while the longer wave-length bursts are very numerous and show many rapid changes of intensity (Covington and Medd, 1949). Such an arbitrary division hardly does justice to the vast amount of detailed information available, and is undertaken only as a convenience to provide two groups of observations with entirely different characteristics. The desirability of obtaining complete world coverage on these two wave-lengths has been recognized by the International Scientific Radio Union.

Analysis shows that the solar atmosphere may be regarded as a series of layers, and at a given wave-length of observation only certain layers contribute to the resultant intensity. The controlling factor is the electron density which, at a height depending on the wave-length, creates a reflecting layer in the same manner as a reflecting layer is formed in the earth's ionosphere. Radio waves of the specified wave-length originating below this solar reflecting layer are quickly attenuated in the dense atmosphere of electrons, while waves originating in layers above, travel freely outwards through the thin atmosphere. It is further found that waves of the critical wave-length are very efficiently radiated from the vicinity of the reflecting layer. If the observing wave-length is made shorter, the reflecting layer is situated at a lower level so that emission from a lower region of the ionized gas will be observed. Thus observations at a given wave-length provide information about certain regions of the solar atmosphere—the longer wave-lengths for the outer layers, and the shorter wave-lengths for the inner layers. In certain regions of the solar atmosphere the physical characteristics of density and temperature of the gas change rapidly, so that the overlying layer will be semi-transparent, partly absorbing the emitted radiation from below, and at the same time emitting a radiation of its own.

Radio emission from the quiet sun in the metre band (150 cm.) may be regarded as originating from the outer corona at levels given by radii of about 1.4 units expressed in terms of unit radius for the photosphere. The ten-centimetre radiation originates partly from a deeper layer, at the base of the corona, with $r = 1.05$, and partly from the outer corona. This radiation, originating as it does in two layers, will consequently be very sensitive to the physical difference of the two layers. One-centimetre emission is mainly from a still deeper layer, the chromosphere, with negligible contribution from the corona; and finally, the short optical wave-length emissions originate almost completely in the photosphere, the bottom of the solar atmosphere.

In the optical region of the spectrum emission from the outer corona is so weak that it can be measured only under the special conditions of a total eclipse, while emission from the inner corona and chromosphere, although seen during an eclipse, may now be isolated at any time by special instruments called, respectively, the coronagraph and the spectroheliograph. The importance of the radio observations perhaps lies in the ease with which emission from the outer rarified gases of the sun may be measured. In addition, radio observations can be made throughout the day regardless of the presence of clouds or rain, and, with international co-operation, a very small number of participating stations provide a continuous watch on the sun.

Radio Observations at N.R.C., Ottawa

Daily observation of 10.7-cm. emission from the sun, taken in Ottawa, has now entered the tenth year. A typical record with a four-foot parabolic reflector, for the afternoon of January 20, 1957, is shown in figure 2.

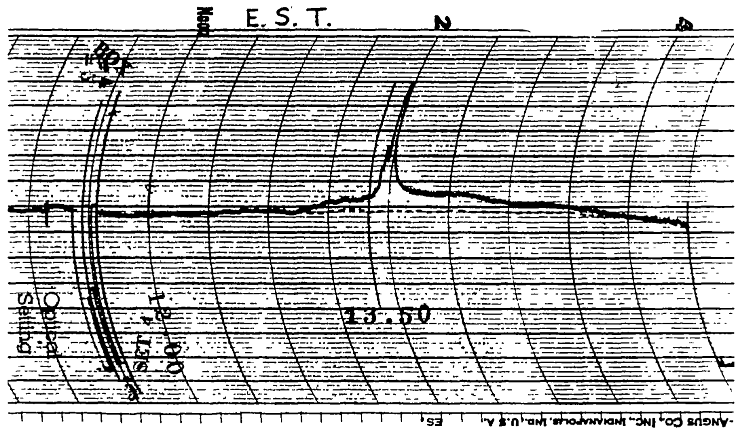

FIG. 2—Recording of 10.7-cm. solar radio flux for afternoon of Jan. 20, 1957.

By means of automatic equipment, monitoring of the emission now commences at sunrise and continues until sunset. Near local noon each day the sensitivity of the radiometer is determined by an operator, so that the steady flux for the whole day may be calculated. The significance of day-to-day variations of this quantity has been discussed in detail, and it has been shown that the changes may be related to radio emission from hot spots in the solar corona. During the ten-year period, a plot of the monthly average solar flux shows a threefold variation (see figure 3). The minimum value of 70 flux units was observed for the year 1954 (a period of sun-spot minimum), and may be taken to represent the intensity of emission from the undisturbed solar atmosphere. The increased intensity, both before and after this period, coincides in the first case with the declining sun-spot activity from the previous peak in 1947, and in the second case it corresponds to the growth of the present sun-spot activity.

The question of the variability of solar emission is important. Solar emission in the visible and infra-red regions certainly shows no such large variation during the sun-spot cycle, while the intensity of the solar ultraviolet radiation, as measured by the ionization density produced in the

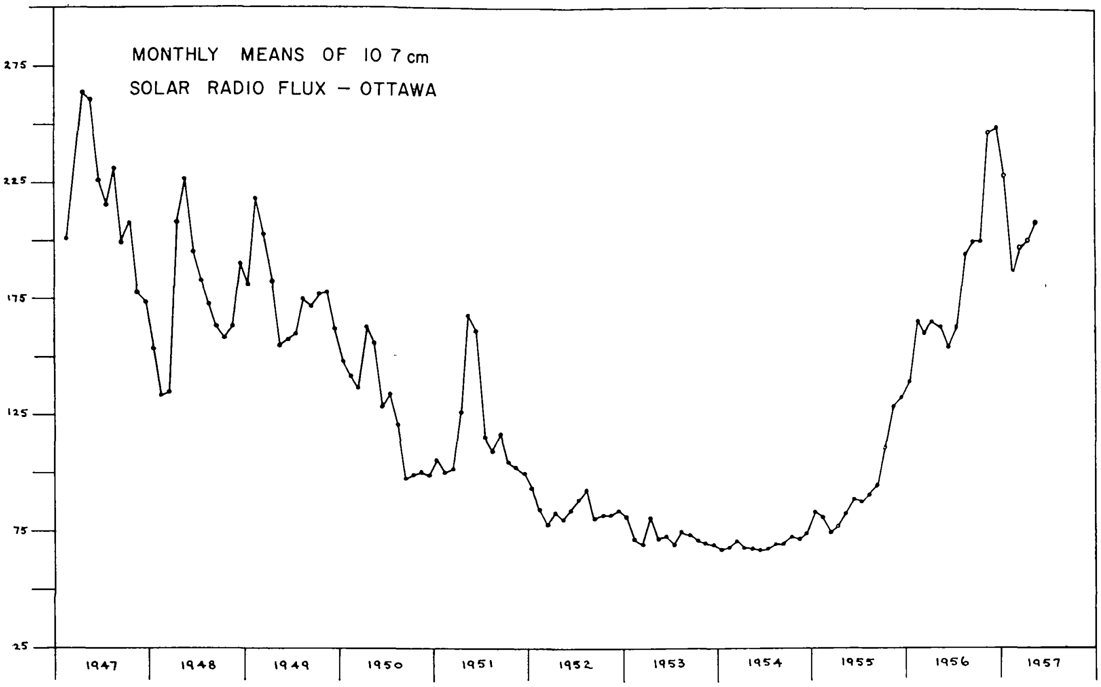

FIG. 3—Monthly averages of 10.7-cm. solar flux, 1947 to 1957.

earth's upper atmosphere, has been found in the cycle previous to the past one to vary by a factor of two. The change in magnitude of both the ultra-violet and the slowly varying ten-centimetre radio emission is comparable, and may have significance in relation to the variable source of solar energy. It is important that both emissions are associated with the same bright solar region seen in hydrogen and ionized calcium spectroheliograms (Covington and Broten, 1954; Dodson, 1954), and this suggests that the ten-centimetre flux could be considered, at least, as an index of ultra-violet radiation. This solar radio index is a direct measure of a solar quantity, and unlike the ionospheric electron densities, needs no correction for particle emission. Any possible particle emission, together with the associated temporary increase in ultra-violet emission, has already been included in the ten-centimetre burst phenomena.

Solar Noise Bursts

As was mentioned previously, a burst of solar noise is recognized by an enhancement of emission above the daily level. In figure 2, two types of burst may be recognized from the record of January 20: a long rise-and-fall, with a more intense impulsive burst superimposed; while in figure 4 only the impulsive burst appears. The most intense bursts of solar noise are observed almost simultaneously throughout the solar

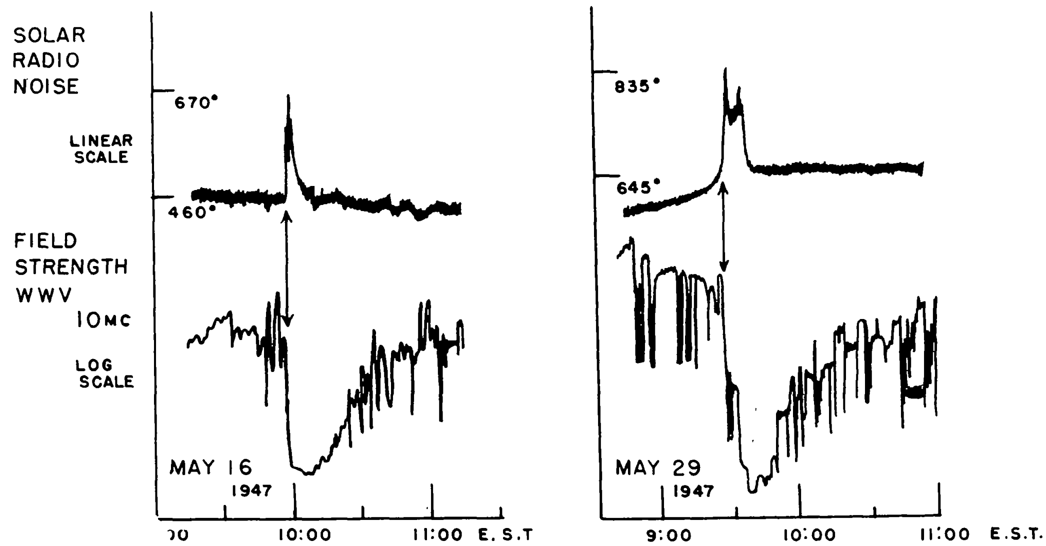

FIG. 4—*Upper Trace*: Selected 10.7-cm. solar noise bursts. *Lower Trace*: Associated interruption of WWV transmission.

spectrum and are usually associated with the appearance of solar flares. In the optical region, the solar flare is recognized as an intense brightening of the pre-existing bright regions around sun-spots seen in the monochromatic light from ionized hydrogen or calcium atoms. Nearly all of the bursts in the ten-centimetre region have been shown to be associated with solar flares—the burst and flare commencing within a few minutes of each other. In the metre wave-lengths only the more intense bursts, or outbursts, show this flare association; the other more numerous burst features present in this region are apparently not duplicated in the microwave region, but are, presumably, also related to a flare and its associated active region in some complex but as yet unknown manner.

The time of commencement of some outbursts has shown a tendency to vary with the wave-length of observation—the longer wave-length bursts arriving after the shorter wave-length bursts—with intervals of time ranging from seconds to several minutes. This time delay has been interpreted as a delay in the excitation of the various layers of the corona. At the time of the flare, large amounts of energy in all forms are suddenly released. Solar material is ejected from the photosphere, exciting first the lower levels responsible for the short-wave emission, and then the upper levels responsible for the metre wave-length emission. The large intensities observed are sometimes hundreds of times the emission from the whole solar disk, and indicate that very special non-thermal mechanisms are responsible for the generation of the radio noise.

Construction of radio equipment capable of making observations in rapid succession over a large portion of the radio spectrum from 1 metre to 10 metres has enabled part of this time delay to be studied more easily. The observations from the equipment are called "dynamic spectra" and have enabled comprehensive results to be obtained of what would be otherwise a very complicated problem in instrumentation. The difference in time of burst commencement at the different wave-lengths has enabled velocities of ejection to be found. Some velocities are a small fraction of the velocity of light and have been attributed to the ejection of cosmic ray particles; other velocities correspond to the ejection of auroral particles which take about a day to reach the earth. The existence of bursts characterized by a fundamental frequency and overtones has also been revealed and has provided an important clue for theoretical work. When these techniques are employed throughout the whole radio spectrum and the complete radio results related to the optical phenomena, a better classification of flares will be possible.

Geophysical Effects of Flares

The effects on earth of a solar flare are manifold. In the unusually intense flares which occur only a few times in the eleven-year sun-spot cycle, clearly recognized major disturbances in several fields have been observed and are attributed to the liberation of energy from the solar eruption. These are shown pictorially in figure 5. The light and radio waves both travel with a speed of approximately 3×10^5 kilometres per second; the cosmic rays with a slightly lower velocity. All are recorded directly on appropriate instruments. The ultra-violet light is measured indirectly by observing effects arising through the formation of an absorbing layer of ionization in the sunlit portions of the earth's upper atmosphere; as observed both by the interruption of short-wave radio circuits (for example, see the lower curve of figure 3), and by a small characteristic variation in the direction in which the compass needle points. Some of the solar particles ejected during the flare travel much more slowly than light, and usually strike the earth's atmosphere after a travel time of about one or two days. The earth's magnetic field guides the incoming ionized particles into many paths, some of which end on the dark side of the earth. Here, upon striking the earth's atmosphere, the ionized particles give rise to an auroral display. As in the case of the temporary ultra-violet light emission, the disturbed ionosphere interrupts radio communication and causes the compass needle to experience violent displacements. During the more numerous weaker flares, cosmic-

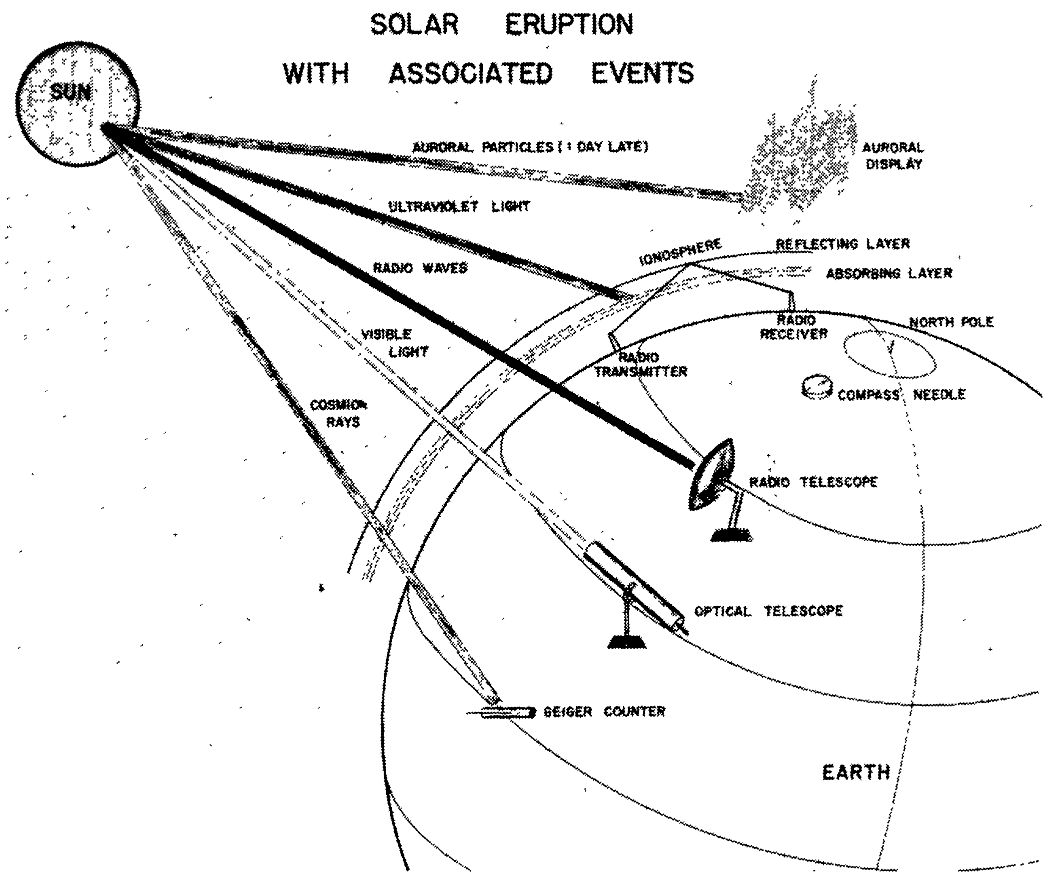

FIG. 5—Representation of solar emission during intense flare.

ray emission appears to be absent, or very weak, while the remaining effects appear in various combinations and patterns.

During the present sun-spot cycle, and particularly during the International Geophysical Year (1957–1958), extensive recording of the optical flares with the associated solar noise emission, ionospheric and geomagnetic events, will further the investigation of the important sun-earth energy relationships.

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