January 18th, 1952
212 W. Seminary Ave.
Wheaton, Illinois

Dr. Newbern Smith, Chief
Radio Division
National Bureau of Standards
Washington 25, D.C.

Dear Dr. Smith:

I am enclosing herewith a description of the work on solar radio waves conducted at NBS during my stay there. The feature of most interest is the discovery of a very simple relation between the length of a solar radio transient and the wavelength of its observation.

Please turn this material over to Joe Feinstein. He may have some ideas on the theoretical explanation of the results secured. If you deem it worthwhile, it may be possible to have him work this part of the description into a short paper for Science magazine.

The high speed record charts upon which most of the above is based are, or were, in the cabinets and filing cases in Industrial. Also a considerable number of slides should be in the custody of Miss McRae which illustrate the various circumstances.

Because I have had so much difficulty with McNish when I worked at NBS and because I have so little confidence in the man, I prefer that he be left out of this matter.

Sincerely yours,

Grote Reber

S O L A R   R A D I O   W A V E S

by

Grote Reber

Introduction

During 1949 and 1950 an investigation was made into the variability of the intensity of radio waves from the sun at frequencies of 51, 160 and 480 megacycles.

At any given frequency there is a minimum background intensity, below which, the energy level never falls. This level is dependent upon the radio frequency of observation and is related to the distribution of the electron temperature and electron density in the solar atmosphere. The base level is rarely, if ever, observed except during the minimum of the eleven year solar cycle.

Superimposed on the base level are two distinct types of disturbances. One appears as a slowly varying base which may change over a period of several hours, or a few days, by a factor of three or less. The other is a rapid series of transients lasting on the order of seconds and having amplitudes of perhaps hundreds of times that of the base level. These two types of disturbances may or may not occur simultaneously. They are both results and indicators of general solar activity.

The material of the solar atmosphere is completely ionized and, in common with all other celestial bodies, the density decreases rapidly at increasing heights above the photosphere which may be used as a reference. Immediately above the photosphere the electron temperature of the ionized gas goes thru a minimum known to optical people as the reversing layer. Above this minimum the electron temperature rises steadily thru the chromosphere, the inner and outer corona. Thus the quiet sun, when viewed at progressively longer wavelengths will appear larger in diameter and of higher temperature.

Thermal Enhancement

The first of the two disturbances is associated with the magnetic field of spots. This field interacts with the electron gas in such a way that a gyrofrequency is produced. At the gyrofrequency the electron gas has high opacity which is another way of saying it may be a good absorber or emitter. This high opacity may occur at a level substantially above that where the solar atmosphere is opaque due to its electron density alone. Thus a new opaque region may be created where the electron temperature is far above the normal radiative level of the quiet sun for the wavelength in question. The matter has been gone into at some length by Denisse[1], who considers each sunspot to have a little bright bulb over it. The best wavelength to observe the phenomenon appears to be about 10 cm. At shorter wavelengths very strong fields are needed so the bulb is limited to relatively few spots or conversely the bright bulb contracts and goes down the throat of the sunspot. The effect can be observed at times at 3cm and perhaps shorter wavelengths, especially when an eclipse provides a moving shutter to pass across the sun[2].

At longer wavelengths weaker magnetic fields are needed but apparently the field of an average spot decreases more rapidly with height than the electron density of the solar atmosphere. Consequently the bulb may be down below the normal opaque level of the general atmosphere and thus not be seen or only faintly so. On a few occasions of very large spots such as the spring of 1947 the bright bulb becomes large enough to be easily observed at 60cm wavelength. In the above[3] case it may be noticed that the spot was mainly effective at meridian passage. This is because the negative index of refraction of the solar atmosphere above the spot aided in focusing the radiation into a relatively narrow cone which rapidly swept across the line of sight to the observer. Quite weak bulbs may be observed in this region of wavelengths by means of an eclipse[2,4].

It should be repeated that this kind of apparently enhanced background is a stable thermal type of phenomenon which may run along hour after hour with only a few percent change in intensity. The increase over the quiet sun intensity level may be only 50 percent or so. However since the radiating area of the bulb is probably less than one percent of the solar disk, it is evident the bulb must have a brightness of several hundred times its surroundings. These bright spots may be readily inferred from the nature of the interference pattern at sunrise and sunset. The 480mc apparatus usually showed a good clear set of maxima and minima when the background was high, indicating a small radiating source. When no sources (low background) or several sources were present the interference pattern was less conspicuous. The phenomenon of a high steady background was practically unknown at 160mc as the magnetic fields of spots are much too small to be effective far out into the solar atmosphere.

Bursts and Outbursts

Considerable effort was expended studying these as they are quite spectacular and very little understood. In general, an outburst is merely a burst of great magnitude. The former may last an hour or so while the latter are usually limited to a few minutes. A typical burst of the progressive type has been described[5] in some detail. After a collection of recordings of these phemonena had been secured at several frequencies it was apparent they all were vaguely similar but in detail entirely different. They were composed of a great number of transients having periods on the order of seconds. Since the transients overlapped in profusion it was evident that no single source was being observed. Also the details of this fine structure on a given burst at one frequency bore no relation to the details at any other frequency. Obviously these highly complex phenomena could not be understood until knowledge had been secured about their components. The building blocks of these bursts seemed to be the transients.

Period of Transients

These discrete impulses were named "pips" because of their similarity to the marks on a radar scope. By making high speed recordings on quiet days a considerable number of isolated or at least separated pips were secured at 51, 160 and 480mc. An individual pip has a steep but not impulsive rise, a nearly sinusoidal top, an at first rapid decay and then a small nearly exponential tail. Quite a number of these pips were monitored by ear. They all sounded like a momentary application of thermal noise. In no case were there any snapping, popping or cracking sounds. Thus it may be assumed there are no steep wavefronts associated with the phenomenon. This is in agreement with the shape of the recordings.

The duration or period of a variety of pips were measured at the above three frequencies. Special care was exercised in their selection. All pips showing any irregularity on either slope were rejected. This should eliminate pairs where a weak one overlapped a strong one. All pips having a peak amplitude less than three times the adjacent background were eliminated from consideration. Those having a peak amplitude less than ten times the background were adjusted for this circumstance. The period of a pip was then arbitrarily defined as the duration at one half intensity or 0.707 amplitude. By selecting from the smallest pips on a quiet day to the largest pips in a burst, a wide variety of amplitudes could be secured. Pip duration was then plotted versus pip amplitude. The resultant scatter diagram showed no correllation whatever between these parameters. In other words, the duration was in no way related to the amplitude. Oddly enough all the pips at a given wavelength fell within a total range of 3 to 1 in duration and about half fell within a range of plus or minus 30% of the mean. The variation in amplitude was over 100 to 1. These studies were made at 51mc(5.9meters), 160mc(1.88meters) and 480mc(.63meters). The mean duration "T" of the pips at these three wavelengths "λ" was found to be widely different and to approximate the relation

$$T \approx \lambda$$

where T is in seconds and λ is in meters. The earlier phases of this study have been reported upon[6]. Early observations in England[7] fit into the above relation satisfactorily. When these circumstances became known it was obvious why a burst appeared so different in detail at different frequencies. At 480mc nine average pips could occur in the time required for one average pip at 51mc.

While the above empirical relationship has been deduced from data at the frequencies indicated, it seems likely that it extends into the centimeter region. A few charts taken at Cornell using continuous wave techniques on frequencies of 1420 and 3200mc show a number of small but very short pips. In both cases the duration was obviously much less than the time constant of the Esterline Angus recorder so accurate information is not available. However the evidence suggest duration on the order of a couple of tenths of a second. To record these transients requires high speed equipment. The conventional chopper type of microwave receiver with a long time constant used at some laboratories merely indicates an envelope of the disturbance.

The information available at long wavelengths is quite meager. However Ruby Payne-Scott[8] shows at the bottom of her figure 4 a few groups of transients recorded at 19mc. Inspection of these data indicate a pip length of approximately one quarter of a minute. This is in close agreement with the above empirical relation. Apparently the formula holds over a range of at least one hundred to one in wavelength. For this to be so, it seems that some fundamental physical phenomenon must be at work. Undoubtedly it is related to the distribution of charge and density in the solar atmosphere.

Spectrum of Transients

Gross effects like bursts appeared nearly simultaneously at all frequencies. They are the separate results of some common cause and can in no way be considered a spectrum.

On quiet days a few pips would occur at one frequency and nothing whatever at the other frequencies. Their appearance seemed entirely random with a somewhat higher number of occurrences at 160mc. At this point it was decided to introduce two more classifications, namely groups and clusters. Individual pips were quite rare. They usually occurred in small groups of two to a dozen. Each group lasted perhaps 15 seconds to a minute. Often there would be a period of activity lasting from 10 minutes to half an hour when a number of groups would appear. These protracted periods were known as clusters.

Arrangements were then concluded with Cornell at Ithaca, N.Y. to make high speed (6 inches per minute) recordings on a frequency of 205mc at selected times. These were later compared with similar recordings taken at Sterling, Va. on a frequency of 160mc. Inspection of the records showed no time correllation whatever between pips and only a slight correllation between groups at these frequencies. However the time correllation between clusters was quite marked. Thus it was assumed that the weak primary sources acting were effective over a range of perhaps 25% in frequency when the disturbance was of this magnitude. The phenomenon was markedly different from the powerful primary sources responsible for bursts which are effective over a frequency range of 100 to 1 or more. However still nothing was learned about the spectra of the pips.

Next, two receivers, each having band widths of about one half megacycle were setup at Sterling, Va. on frequencies of 160mc and 156mc. Simultaneous high speed recordings were made as before. Now correllation between individual pips could be secured altho it was far from perfect. By limiting consideration only to pips on one chart having peak amplitudes of three or more times their surroundings, it was always possible to find their counterparts on the other chart. The duration and time of occurrence agreed to one tenth of a second which was as close as measurement allowed. Also the shape of the pips appeared the same; so it was deduced that the same phenomenon was being observed at the two frequencies. Unfortunately the amplitude of a given pip on the two charts was rarely the same. About one fifth of the pips showed amplitudes within 10% of each other and perhaps one in a hundred showed amplitudes equal within 2%. As weaker and weaker pips in a given group were considered, the above correllation became poorer and poorer until the small wiggles were entirely random. These were believed to be merely the spectral tails of pips at frequencies quite far removed from that of observation. From these results it may be deduced that the spectral width of a pip at 160mc is only a few percent of its mean frequency. The spectral width may be defined as the frequency band within which the intensity is one half or more of the peak intensity. This small spectral width may or may not hold at substantially longer or shorter wavelengths.

Looking over the charts gave the impression that the medium amplitude and weak pips showed more mearly equal amplitudes than the very strong pips, which unfortunately were few in number. If this be true, it may be that there is an inverse amplitude versus spectral width relationship. However measurement at only two frequencies is not capable of producing quantitative results on this subject. Some effort was made to get setup at three nearby frequencies equally spaced. With such apparatus it should be possible to select pips having spectral distributions centered on the middle frequency. Comparison of the relative amplitude of side frequencies versus absolute amplitude of center frequency should then give quantitative information upon any spectral width versus amplitude relationship. Unfortunately the growth of other work at Sterling made it quite difficult to secure a wide enough clear part of the spectrum in which to operate such apparatus.

Amplitude of the Transients

These pips become less and less conspicuous at shorter and shorter wavelengths because the thermal background level of solar energy is steadily rising. The best frequencies to observe them are at meter instead of centimeter wavelengths.

Occasionally a high background level was encountered at 160mc which might last from a few hours to a couple of days. The charts invariably showed a very rough top with the pen in constant motion. Inspection indicated the high background to be merely the aggregate of innumerable small pips which produced the rough top. This is entirely different from the high steady backgrounds encountered at 480mc where the phenomenon was thermal as perviously described under section on thermal enhancement.

On wavelengths longer than a couple of meters the thermal background of solar radiation becomes so low that it is quite difficult to detect. At these frequencies the transients are really the only manifestation of solar emissions. They have been reported well into the decameter range[8,9,10] and are apparently of great intensity when they occur. From the evidence secured at Sterling and that of other investigators it is certain that the intensity of these pips is proportional in a positive way to wavelength. Their frequency of occurrence however seems to be small at both the very short and the very long wavelengths with a maximum per unit time somewhere about two meters wavelength. This has, perhaps, some relation to their mechanism of production in the solar atmosphere. It seems that the charge and density circumstances may be more auspicious at the particular level wherein this wavelength of pips is originated.

Source of the Transients

The above paragraphs are primarily descriptions of experiments designed to measure some of the parameters of the phemonemon in question. Precisely how the pips originate is unknown. However their short duration and small spectral width make it clear they must originate in a very limited region of the solar atmosphere. Also the mechanism must be a nonthermal process which converts some type of mechanical or radiant energy into meter waves. Attempts have been made to correllate the occurrence of pips with various optical phenomena. The results have not been successful, as might be expected. This is because the sources of meter waves, where the pips are most abundant, are far out in the solar corona. They originate at levels where it is not possible to observe optically at any time except during a total eclipse. These pips, like spots, etc. are results and not causes of general solar activity. Even on days of low optical activity a few pips will be encountered. They are not associated with any prominent objects such as spots in a direct way. However inspection of the charts suggests the pips are most likely to be present during the birth and growth of spots. It is during these times that the high variable background is usually encountered at 160mc. After a spot has matured it may be around for a long time but no extraordinary radio emissions will be detected. A few times a spot has had two periods of growth with a stable period between. The pips were predominently present during the growth periods.

The bursts are sometimes associated with flares. However the life of a flare is many times that of a typical burst and some of the largest flares have produces rather minor radio emissions. It seems that the temperature of a flare is more related to its ability to make radio waves than its mere size. The progressive type burst has been described[5]. Another type exists where the disturbance begins substantially simultaneously at all frequencies. These two types seem to be the same phenomenon except for the way in which the energy is supplied. The former is probably actuated by some pressure wave travelling outward at a relatively low velocity; while the latter is probably actuated by ultraviolet light. Both types are present during a period of solar activity and it is usually quite difficult to untangle them. The simultaneous type may ultimately be associated with the far ultraviolet radiations from a hot flare. Bursts of both types are merely aggregations of pips of the type described above. The mechanism of a burst is the same as a pip, only on a grand scale. Details of the mechanism are unknown. To a first approximation it may be surmised that the pip has its origin in turbulence and charge nonhomogeneities in the solar atmosphere. Also it seems apparent that the effectiveness of these anomolies is in a direct way proportional to the sharpness of the interfaces in terms of wavelengths. If this be true, the circumstances would favor more powerful pips at the longer wavelengths which is esactly what the experimental evidence shows. Probably the volume of solar atmosphere associated with a pip is quite small, perhaps a cubic kilometer or possibly even a few cubic meters. If, and when, techniques are devised which will enable the solar atmosphere to be inspected in detail at radio wavelengths much more will be learned than merely attempting to analyse the gross solar radiation. Some hope is held out by the recent development in Australia of a scanning interferometer.

References

1. "Decimeter Solar Radiation & Sunspots", J. F. Denisse, Comptes Rendus, 16th May 1949, Vol. 228, No. 20, Pp.1571-2

2. "NRL Aleutian Radio Eclipse Expedition", Hagen, Haddock & Reber, Sky & Telescope, March 1951, Vol 10, No.113, Pp111-3

3. "Solar Intensity at 480mc", Grote Reber, Proc. IREF, January 1949, Vol 36, Nol, P 88.

4. "50cm Solar Radiation During Eclipse", Christiansen, Yabsley, & Mills, Australian Journal Scientific Research, Part A, December 1949, Vol 2, No 4, p 506-523.

5. "Motion in Solar Atmosphere by Radio Measurements", G. Reber, Science, 23rd March 1951, Vol 113, no2934, p 312-4

6. "Fine Structure of Solar Radio Waves", G. Reber, Meeting of American Astronomical Society, Tucson Arizona, December 28th, 1949.

7. "Shape of Pulses of Solar Radio Energy", S. E. Williams, Nature, 17th July 1948, Vol 162, no 4107, p 108

8. "Bursts of Solar Radiation at Meter Wavelengths", Ruby Payne-Scott, Australian Journal of Scientific Research, Part A, July 1949, Vol 2, no 2, p 214-228.

9. "Galactic Radiation at 18.3 MC", C. A. Shain, Australian Jounal of Scientific Research, Part A, September 1951, Vol 4, No 3, P 258-267.

10. "Solar Noise Observations", Report #CEI/34/5 of Chief Engineers Office, Radio Research Office, Dominion Physical Laboratory, Department of Scientific & Industrial Research, Wellington, New Zealand