Chapter V - The Sun and its Radio Emissions

The Optical Sun

The Sun, despite its brilliance in the daytime skies and the fact that it is essential to our very existence, is a middle-aged and very ordinary star by stellar standards: there are undoubtedly many millions or so which make up our Galaxy - although we have no means of knowing how many of any of these enjoy a system of satellites like that to which we and our eight sister planets belong. Its prominence comes solely from the fact that it is the nearest star to us by a long way, a mere 93 million miles distant (or about eight light minutes if we use the astronomer's yardstick, the time its light takes to reach us). The next nearest star is 4½ light years away, about 25 million million miles. The Sun nevertheless must be counted as the most important of the heavenly bodies to us because it is the only one we can study in detail, and it presents us with a laboratory in which conditions that cannot be realized on earth are accessible to our telescopes. In brightness the radio Sun is not as prominent as the visible Sun, but it shows remarkable fluctuations that are not paralleled at all in its visible light.

The Sun is a spherical ball of matter which is very hot, highly ionized and held together by gravity, the weight of overlying material being responsible, by compression, for raising the temperature near the centre to some 20 million °K. At this temperature the protons are synthesized into helium nuclei, the energy released finding its way to the surface where it is radiated away. Although the Sun is emitting energy at a rate equivalent to nearly 100,000 million (10^{11}) megatons every second (a megaton being the energy released from an explosion of one million tons of T.N.T.), it has enough hydrogen to provide fuel for nuclear fusion for further thousands of millions of years - despite the fact that it has been doing this for at least the last 4000 million years. The equivalence of mass and energy means that the Sun is losing mass as it disperses energy according to this staggering programme; it is, in fact, becoming lighter by some 4 million tons every second. Even at this rate its mass will not decrease by more than one per cent in the next 150 thousand million years!

There is a steady gradient of temperature from the intensely hot core to the visible surface, which is known as the photosphere, and is at a temperature of about 6000°K. This translucent outer border to the incandescent ball of gas which lies inside is remarkably thin, only a few hundred kilometers thick, and so the Sun's limb always appears perfectly sharp rather than fuzzy as might have been expected from its gaseous nature. The light emitted from the photosphere is a close approximation to that from a black body at a temperature of 5750°K. Above the visible surface, or photosphere, lies the solar atmosphere which extends to very great heights but is too tenuous to be visible except at times of total solar eclipse. It is in this rarefied atmosphere that practically all the solar radio emission has its origin. The lower part of this atmosphere, to a height of about 20,000 Km from the visible surface, is known as the chromosphere: this is seen at times of solar xxx eclipse as a thin red annulus surrounding the white disk of the photosphere. Above this and stretching to heights of millions of miles (the Sun's radius is about 700,000 km) is the corona in which, strangely enough, the temperature first rises gradually to a value in excess of 1 million °K, before falling away to the extreme cold of interstellar space. The existence of million-degree-temperatures in parts of the corona had been deduced from spectroscopic studies of absorption lines in the Sun's visible spectrum, but such high values were by no means widely accepted until unmistakable confirmation came from the early radio measurements of Pawsey and his colleagues at Dover Heights, Sydney.

The Sun provides us with a remarkably steady supply of light and heat, the only visible signs of changes being the dark patches or "sunspots" which come and go on the Sun's surface. It is perhaps natural that a careful watch should be maintained for sunspots in an era when blemishes ~~blmishes~~ on the face of the ~~Sun~~ Sun were taken as dire portents, and naked eye records of major apparitions date back as far as the fourth century B.C. They have been studied by means of telescopes since 1610, and Galileo's observations of apparent "imperfections" on the Sun's surface were so contrary to orthodox beliefs of the time as to ~~bring~~ bring him in serious conflict with the Inquisition. Sunspots appear as dark areas on the disk because they are regions where the temperature is somewhat lower than in the surrounding photosphere: they are often quite irregular in shape, and show a dark central "umbra" surrounded by a lighter"penumbra". Plate 1 shows a large group of spots on the Sun on inset is a close-up of the spot group. Individual spots may endure from 1 to 50 or more days, and appear to move across the disk because of the Sun's rotation: by this means the sidereal period of the Sun is known to be about 25 days in ~~equatorial~~ equatorial regions increasing to about 27 1/2 days at 45° latitude. Spots tend to appear in groups, in association with other phenomena, which indicate that they are manifestations of more general activity within the Sun: they all have strong magnetic fields.

A remarkable feature of sunspot behaviour is that individual spots appear in an unpredictable manner, but the number and area of spots at any time follow a regular cycle, the sunspot cycle, whose period averages about 11 years. This cycle is well established, particularly from a series of daily observations of sunspot number* which was instituted by Wulf in Zurich in 1849, and has been continued according to ~~hi~~ this scheme at a number

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*This is an arbitrary indication of sunspot activity adopted by Wulf, based on both the number and area: it is defined as K(10g+f) where g is the number of separate groups, f the number of individual spots, and K a factor which depends on the observer and the instrument he is using.

of centres throughout the world ever since - including Zurich [illegible]ere Wulf's original telescope is still being used for this purpose. At times of minima long spells can occur when no spots are visible at all: at maxima, spots are larger and more numerous, but some maxima have much higher average sunspot number than others. The magnetic polarity of the leading sunspot in a group reverses from one cycle to the next, suggesting that the complete solar cycle takes 22 years, and the amplitude of variation is more symmetrical if alternate cycles are plotted with reversed sign. (See Fig. 1). Despite many attempts to discover the origin of this regularity in solar behaviour the cause is still a mystery. The close correspondence between the sunspot period and that of the most massive of the planets, Jupiter, is the basis for a number of theories, but a recent one due to E.K. Bigg (who has done much to clarify the relationship between radio emission from Jupiter and the position of one of its satellites) suggests that the combined tidal effects of all the planets on the solar atmosphere (Mercury having a major effect) is sufficient to account not only for the cyclic variation, but also for the irregular amplitude from cycle to cycle. It fails, however, to reproduce the 22 year cycle of magnetic polarity.

Since light and heat from the Sun is absolutely vital to the continuance of life here on Earth, and sunspots suggest that the Sun itself undergoes cyclic variations, many attempts have been made to discovery correlations between the sunspot cycle and virtually all natural pmkm phenomena, pleasant or otherwise, to which we are subjected. So far this has met with little success. There is an undoubted association between the pattern of ring growth observed in long-lived species of trees (e.g. the Californian redwoods) and the sunspot cycle, presumably in seasonal variations, but daxpi despite this no general or even a usable correlation between sunspots and weather has been revealed. The advent of radio, however, and particularly of the shorter wavelengths which have made possible round-the-world propagation using the reflecting properties of the ionosphere* has brought evidence that very great variations can occur within the ionosphere and that these are associated with activity on the Sun as indicated by the presence of sunspots. Regular measurements of the electron content of the ionosphere over extended periods made it clear that this varies by a factor of about ten from ~~xmxm~~ sunspot maximum to minimum, and that, in addition, sudden and catastrophic changes in the ionosphere tend to follow almost immediately after the eruptions or "flares" which optical observations have found to occur sometimes on the Sun, invariably in the vicinity of a sunspot area. The evidence thus provided from studies of the ionosphere that disturbed areas or <u>centres of activity</u> appear on the Sun from time to time has been amply confirmed from studies of its radio emission, because this too originates for the most part in the same regions. The presence of a sunspot is a visible but not a necessary indication of their existence.

Centres of activity develop in areas where - and almost certainly as a consequence of ~~thexx~~ this - intense magnetic fields are present, due to large scale electric current flowing in the ionized gases below the photosphere. The field is bipolar, i.e. has N and S poles, as though an enormous bar magnet were lying horizontally below the Sun's surface. The lines of magnetic force extend in huge arches or loops high into the solar atmosphere and provide invisible paths along which gas clouds, eruptive prominences, are sometimes seen to move. Heating of the solar plasma occurs where the field penetrates the photosphere, and produces brighter mottled patches known as <u>faculae</u> or <u>plages</u>: sometimes as the magnetic field develops

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*The upper reaches of the atmosphere from 90 km or so upwards, ionized by ultra violet light from the Sun.

sunspots appear. Above the centre of activity (generally indicated by the spots) prominences may also appear - bright clouds rising high above the photosphere and sometimes seen to be in spectacular movement when viewed in the characteristic light emitted by hydrogen or calcium. Finally, for reasons not yet fully understood, activity may build up to the stage where dramatic explosions occur within an active area, resulting in the emission of fantastic amounts of energy, particularly at radio wavelengths. Only very rarely are these explosions visible to the naked eye. Their appearance, however, in the red Hα line emitted by ionized hydrogen, is of a sudden and intense brightening of the area; hence they are known as "flares". In very large flares the energy released from the Sun may amount to many millions of times that of the largest nuclear bomb man can yet produce. It is not surprising, then, that during such catastrophic events not only intense radiation but huge chunks of the solar atmosphere should be hurled out into space - a potential danger to astronauts and the source of major events in our own atmosphere when in due course they reach us. This occurs some 8 minutes after the flare for the radiation components (which travel with the speed of light) and up to 24-48 hours later for the particles constituting the solar plasma.

The Radio Sun

The radio emission from the Sun can be divided into three recognizably different components: that from the quiet Sun, a steady background which is present at all times and is merely thermal radiation from a hot body; a slowly varying component which is associated with sunspots and has its origin in the active areas; and a series of intense but intermittent and relatively short-lived emissions known as "bursts" which are related to flares and other eruptive phenomena in the Sun's atmosphere. Figure 2 shows how the brightness temperature for these various components varies with wavelength.

The Quiet Sun

We saw in Chapter 1 that the first successful attempt to receive solar radio waves was made by Southworth in 1942: he used a sensitive centimetre-wave receiver developed for radar purposes, and his results indicated a temperature of some thousands of degrees K, in agreement with the generally accepted idea of a 6000° Sun. The current picture of the behaviour of the Sun as a radio transmitter began to emerge from the work of Pawsey and his associates in Sydney in 1946, and 1947. The earliest records showed that, although there were fluctuations in the level from day to day which seemed to be associated with sunspots (see Fig. 3), there was a general background intensity at a wavelength of 1.5 metres below which the signals did not fall - and this level was that which would be expected from a black body at a temperature of about one million (10^6)°K. Measurements made at shorter wavelengths showed lower temperatures, the trend with wavelength varying gradually from 1 million degrees K at 1.5 metres to 10,000°K at a few centimetres. Fig. 4 shows how temperature varies with wavelength in the solar atmosphere. The explanation for this varying temperature throughout the corona was arrived at independently by Martyn in Australia and Ginzberg in the U.S.S.R. in 1946, from considering the propagation of thermal waves in an ionized medium whose electron density was known (from optical observations) to vary with height. A body can only emit thermal radiation if it is capable of absorbing it, the absorption coefficient of an ionized gas being proportional to the square of the wavelength (see page). They showed that conditions in the corona were such that it could absorb metre wave radiation and therefore that it could emit it also, the observed intensity at the earth indicating origin in a body at a temperature of 1 million °K, i.e. this is the temperature at the level in the corona at which metre waves originate. The corona is almost completely transparent to very short radio wavelengths, which, however, are almost completely absorbed at chromospheric levels. The observed intensity of solar radio waves of centimetre wavelengths corresponds to origin in a source [illegible] equivalent temperature 10,000°-20,000°K i.e. temperatures which optical observations also indicate for those regions. As we observe at different radio wavelengths, therefore, we can explore different levels in the solar atmosphere, from several radii (1 million miles) to a hundred thousand miles above the visible surface.

A striking outcome of the theory of thermal emission by the Sun was the prediction that the Sun should appear to be brighter around its rim at centimetre and decimetre wavelengths. This is a consequence of the fact that waves emerging obliquely have a longer path through the atmosphere and so are emitted from a higher level where the temperature is also hotter; limb brightening is not evident at metre wavelengths, one reason for this being that there is not a positive temperature gradient in the outer corona where they originate. Theoretical treatments of the theory of thermal emission were, however, limited by incomplete knowledge of physical conditions in the chromosphere: optical observations of the chromospheric radiation at times of eclipse gave information about the relationship between electron density, and temperature but did not allow these quantities to be determined separately. J.H. Piddington, in Australia, showed that a second relationship between these quantities was provided from a determination of the radio spectrum from 1 to 50 cms; By combining the two he derived the density and temperature independently and thus provided data which led to a quantitatively more satisfactory model of the chromosphere.

Some years elapsed before the predicted limb brightening effects were observed, primarily because this called for a radio telescope of considerably better resolving power than had ever been used before. Attempts made to determine the brightness distribution across the Sun by observations taken as the Sun was being eclipsed by the moon, but the most effective means of deriving this has been provided by the series of radio diffraction gratings developed by Christiansen at the

Radiophysics Laboratory in Sydney. The first of these devices consisted of 32 6 ft diameter paraboloids erected along the edge of a water supply reservoir on the outskirts of Sydney. Later he combined the grating principle with that of the ~~Mill~~ Mills Cross and the resultant crossed-grating interferometer (see Plate II) produced the first picture of the radio Sun by scanning its surface in successive strips with an effective pencil beam 3 minutes of arc in diameter.

Several attempts to obtain a brightness distribution for the Sun using spaced aerial interferometry had failed to confirm the predicted ~~limit~~ limb brightening, and the first evidence of this came from one-dimensional brightness distribution determined by Christiansen by means of his original grating in 1953: his measurements were made at a wavelength of about 21 cms (but <u>not</u> of the hydrogen line). Fig. 5(a) shows the superposition of a number of distributions in which the individual curves show the effects of localized bright areas (the slowly varying component) and the lower envelope of the emission due to the quiet Sun. If it is assumed that the brightness distribution is circularly symmetrical a map of the quiet Sun derived from this data is shown in Fig. 4(b).

Maps of the Sun derived from Christiansen's crossed grating interferometer in 1958 and 59 show the same oval shape with limb brightening in equatorial regions and limb darkening at the poles, as in Fig. 4(b), which represents conditions at sunspot minimum, ~~bt~~ but with about double the brightness. A somewhat similar result has been obtained by other observers i.e. the brightness of the quiet Sun varies by a factor of about 2 from maximum to minimum of the sunspot cycle.

The Slowly Varying Component

Daily plots of the intensity of solar radio emission vary markedly in character over the radio spectrum. as may be seen from Fig. 6. At metre wavelengths there is a relatively constant base level, together with occasional intense increases (the bursts, which are discussed later page) but no marked correlation with sunspot area (lowest curve in Fig. 4) decimetre and centimetre wavelengths, on the other hand, the outstanding features is a marked increase in level with increase in sunspot area, and there are no signs of bursts. If the daily flux density is plotted against sunspot area a high correlation between them is seen to exist, and a substantial flux remains when the curve is extrapolated to zero sunspot area (see Fig. 7). This is defined as the contribution from the quiet Sun, the excess flux density on any day being due to the slowly varying component.

Covington, in Canada was the first to obtain direct confirmation of the emission from a sunspot area when he observed during an eclipse in November 1946 and found a temporary decrease in intensity when a large spot group on the disk was obscured. Similar results were obtain in Australia by Christiansen, Yabsley, Mills and Piddington and Hindman on 50 cms and 10 cms respectively during the eclipse of 1 November 1948. The former group obtained very convincing results by observing at three widely separated sites; the path taken by the Moon was different at each site so emitting areas could be located at the intersection of the Moon's limb as seen from each site. See Fig. 8. They found that most of the bright areas were close to visible sunspots, or where spots were present on the previous rotation, and that they accounted for about 1/5 of the total radiation from the Sun on that day. The average brightness temperature of these active areas was about 5 million °K.

The most direct evidence for the existence of a slowly varying component, and that its origin lies in localized active areas which are often associated with sunspots, came from observations with Christiansen's crossed grating interferometer (see page). Fig. 9. shows a picture of the radio sun obtained by scanning strip by strip with an effective 3' pencil beam, together with a sketch showing the location of visible sunspot groups on that day: the correspondence is obviously very close. [illegible] even higher correlation is found, however, between the emitting regions - which are sometimes called radio plages - and areas of hot gas which appear brighter than their surroundings when viewed in calcium light and are consequently known as calcium plages. Investigations made at centimetre wavelength with longe baseline interferometers giving high resolution, in particular by Kundu, indicate that the radio plage has a concentrated nucleus comparable in size with the underlying sunspot, and the radio emission from it is strongly circularly polarized: in addition there is emission from a wider area, corresponding to the calcium plage.

The fact that the temperatures measured in the active areas responsible for the slowly varying component are not greatly higher than those known to exist in the solar atmosphere, and that no sudden or rapid variations in the emission are ever observed suggest that it originates as thermal radiation in hotter regions which can occur in the vicinity of sunspots. Optical observations show that regions of very high electron density, known as coronal condensations, tend to occur over active areas, reaching perhaps to heights of 100,000 km, and it seems virtually certain that free-free transitions within this over dense region are responsible for the emission. The spectrum of the radiation is generally in accord with a thermal xx origin, although evidence was obtained during the International Geophysical Year (I.G.Y.) that there is a peak in the spectrum for strong radio plages below 10 cm wavelength which is inconsistent with a thermal origin. This has been interpreted as due to an additional component arising from the processing of electrons around the lines of force of the magnetic field of the sunspot, resulting in the emission of low harmonics of the gyro frequency.

The radio plages are especially important as the seat of occasional extremely intense disturbances, of durations varying from seconds to days, which are known as bursts.

Bursts

The third component of solar radio frequency emission consists of a series of rapidly varying bursts of which at least five distinct types can be recognized at metre wavelengths. They occur over a wide range of wavelengths, from less than 1 cm to about 50 metres, are always associated with active regions, and appear at the time of a flare. At short wavelengths they are of short duration, of lower intensity and simple structure, but become increasingly complex as the ~~maximum~~ wavelength increases, and sometimes continue for many hours at metre wavelengths. Figure 10 illustrates their typical appearance at different wavelengths. Microwave bursts have their origin in the upper levels of the chromosphere, or base of the corona, below the flare region but the metre wave bursts, on the other hand, are generated high in the corona, sometimes as much as several solar radii above the surface. Their high brightness temperatures, up to 10^{12}°K ~~xxx~~ and rapid variations in intensity preclude origin in thermal processes and both synchrotron and plasma mechanisms are involved.

Hey, in the course of studying records of the severe interference to British radar sets which occurred in February 1942, was the first to point out that these powerful emissions from the Sun at metre wavelengths were associated with the central meridian passage of a large active spot group, and with the occurrence of a large solar flare. ~~Xxxx~~ Because of their transient nature and variety of form early observations proved difficult to interpret, although there was an undoubted correlation with flare activity. A classical observation of a large outburst in March 1947 by Payne Scott, Yabsley and Bolton at Sydney ~~kix~~ highlighted an important feature (illustrated in Fig. page), namely that the time of arrival was progressively later at longer wavelengths. The need for a different type of radio telescope to study phenomena which varies with both frequency and time ~~infx~~led to the development by the Sydney group, under J.P. Wild and his colleagues of a series of "dynamic" radio spectrographs. In this device a receiver is tuned rapidly over a range of wavelengths, and the output modulates the brightness of a spot of light on a cathode ray tube whose face is photographed on moving film. Fig. 11 show diagrammatically an idealized record produced by different types of burst. The principle of Wild's spectrograph has been followed in many other countries, particularly at several centres for solar studies in the U.S.A. Our current picture of these complex phenomena is based almost entirely on information derived from them, and from swept-frequency interferometers which allow the location of the source in the solar atmosphere to be determined. The recent completion by Wild of his radioheliograph by means xm of which xxxxxxx second-by-second pictures are obtained of the centres of 80 MHz emission is however, adding a new dimension.

Until comparatively recently it was considered that centres of activity behaved quite independently, the only linkage between them being within the Sun itself, and presumably in the magnetic fields that interlace the photosphere. The first clue that distant centres might be connected by other means came from the suspicion that flares occurred in different centres at similar times too often to be accounted for by chance. In the early 1960's evidence began to accumulate of solar flares triggering off other activity, the triggering agent moving with a velocity of the order 2000 km/sec. The Radioheliograph is now beginning to provide detailed instances of interaction of this kind: Plate IV shows a series of radioheliograms in which shock waves from a flare (with associated type II burst) trigger other centres more than 10^6 km away several minutes later. One way in which this could happen is illustrated schematically in Fig. 12. In this case it is clear that the initial shock wave is a travelling disturbance which serves to <u>release</u> energy in the subsequent eruptions. The time delays which are involved are usually of the order of minutes, i.e. consistent with the velocities deduced from the movement as Type II bursts (see below).

Since the advent of the Radioheliograph a new kind of phenomenon has been revealed in which remote sources are interconnected on a time scale of seconds: Fig. 13 shows pictures taken at 2 second intervals, showing the rapid alternation of bright points at the extremities of a large diffuse source which occurred on 25 February 1968. This implies communication between the positions of activity at a speed which is an appreciable fraction of that of light, probably by means of fast particles, which travel along arched paths guided by the weak magnetic fields which link active centres. Our understanding of the detailed mechanisms involved is still far from complete but there is a growing impression that correlated burst activity of this kind is associated with and a forerunner of major flare activity.

The chief characteristics of the five different classifications into which metre-wave bursts are divided are as follows: The designations were assigned roughly in the order in which they were recognized all of them being named by Wild and his group with the exception of Type IV which is due to the French group at .

Type I - Noise Storms

Long series of short-lived narrow band bursts, sometimes s superimposed on a slowly fluctuating continuum background, are the most prominent of the variable components of solar emission: these are known as Type I. They may occur at the rate of hundreds per hour during periods of intense activity, and sometimes continue for days: they rarely occur at wavelengths below about 1 metre, but around sunspot maximum Type I bursts are present for about one tenth of the time.

Individual bursts last for one tenth to ten seconds, and many of them show a frequency drift which may be positive or negative at rapid rates, sometimes approaching that of Type III. The radiation from storm centres is strongly circularly polarized and comes from regions above certain sunspots, the probability of a particular spot being responsible for a Type I noise storm increasing with its size. The emission often appears only when the spot is near the centre of the disk implying that it takes place radially being confined to a narrow cone. A minority of storms follow flares, but not necessarily large flares. The storm areas usually occupy relatively stable positions above, but not necessarily radially above, the associated visible sunspot and are located at heights between about 0.3 and 1.0 solar radii above the photosphere.

The flux density of the bursts would indicate impossibly high temperatures at their source of up to 10^{10}°K if the source were thermal, so non-thermal processes must be involved. Apart from the temperatures the characteristics to be explained are the occurrence of bursts and continuum, both circularly polarized; and emission in a relatively narrow cone. These can be satisfactorily accounted for in terms of either synchrotron radiation or radiation resulting from the scattering of longitudinal plasma waves by irregularities in the xxxx corona; insufficient is known about noise storms at this stage to be able to decide between these alternatives, although there is some preference for the former. The polarization of bursts and the continuum is usually the same, suggesting that the continuum may arise from the superposition of a very large number of bursts, but differences are occasionally observed and bursts and continuum may well be separate but closely related phenomena.

<u>Type II Bursts</u>

Type II bursts are outstanding disturbances whose principal characteristic is a drift of the main spectral features from high to low frequencies at rates up to 1 MHz. In addition they have sharp features and narrow bandwidth which, as often as not, are closely duplicated at double the frequency, i.e. the emission occurs at both fundamental and harmonic frequencies. Type II bursts have a duration of about 10 minutes and are associated with large flares, about 30 per cent of flares of importance 3 being accompanied by Type II bursts, against only about 2 per cent of flares of importance 1 being accompanied by Type II bursts. They usually do not coincide either with the commencement or the maximum phase of flares but have their beginning from 5 to 20 minutes after that of the flare. A distinctive characteristic of the emissions is that the polarization is random.

The existence of narrow band features that duplicated at too harmonically-related frequencies which themselves drift in frequency at a regular rate is clear evidence of electrons oscillating at a characteristic frequency, and one that is capable of continuous variation. The only mechanisms in the solar atmosphere meeting this requirement are plasma oscillations, and electrons spirally in a magnetic field. The latter is ruled out since it is impossible for the fundamental gyro frequency to escape from the corona because of attenuation in the overlying regions, and it is generally accepted that Type II bursts indicate plasma oscillations in progress. The regular drift is toward lower wavelengths is interpreted as the result of a ~~distxxxx~~ disturbance moving outwards in the corona, exciting plasma oscillations as it goes: the electron density decreases steadily with height in the corona and so the frequency excited by the disturbance also decreases. A clear consequence of an origin in this way is that the source of the bursts should be located progressively higher in the atmosphere as the wavelength gets longer. This has been adequately verified, in particular by Wild and his associates in Sydney using swept frequency direction finders. An apparent anomaly is that the harmonic emission from Type II bursts sometimes appears to come from much lower heights in the solar atmosphere. This could be accounted for if the harmonic radiation were generated mostly in a backwards direction, when it would be reflected at a lower level in the corona where the electron density was high enough so that it would appear to come from the image of its source in the corona. This backwards emission is, in fact, predicted by a theory of burst generation developed by Ginzburg and Zheleznyakov in the U.S.S.R.

The observations indicate that the disturbance exciting the plasma oscillations moves radially outwards at a speed of

1000-2000 km/sec, which is roughly ten times the velocity of sound in the corona. A supersonic velocity of this magnitude suggests that the disturbance is a shock wave, probably originating from the same explosion within the Sun which is responsible for a stream of high speed electrons that is known to precede a type II burst. These fast electrons similarly excite plasma oscillations which are our Type III bursts. It has been known for many years that magnetic storms on the Earth's surface and auroral displays are closely associated with active areas on the Sun, and that these manifestations sometimes appear 36 hours or so after a major flare. This time interval suggests that the origin of the particles whose entry into the Earth's atmosphere is responsible for the magnetic and auroral effects is almost certainly plasma ejected from the Sun.

Type III

Type III bursts, the most common of the metre wave bursts, were first recognized in 1949 on records taken in Sydney by Wild and his co-workers: at sunspot maximum the average rate of occurrence is about 3 per hour, duration of individual bursts being about 10 seconds. There is a strong tendency for these emissions to occur in groups of 10 or so, the individual members of the group often being regularly spaced: that they have a common origin is indicated by the fact that they have similar spectral features and originate from the same source area in the corona. They are very closely associated with flares - of any size - and usually occur near its start.

A distinctive feature of Type III bursts is their spectra which shows a rapid frequency drift from high to low frequencies, the rate increasing with increasing frequency. Harmonic structure is present but the instantaneous bandwidths are fairly broad (10-100 MHz) and so fundamental and harmonic emissions tend to merge on the records. The bursts are in general randomly polarized but a proportion of them show partial circular polarization.

The presence of both fundamental and harmonic emissions together with a progressive drift in frequency pointed again to [illegible] origin in plasma oscillations triggered by a moving disturbance in the solar atmosphere. The velocity is obviously much greater than that of the Type II disturbances; the value derived from a knowledge of the electron densities and hence plasma frequencies at various heights in the corona is of the order 0.4 the velocity of light. Wild and his collaborators also followed the movement of the source with a swept frequency interferometer and found a systematic variation of height with frequency as is predicted from an origin in plasma oscillations. The speed derived in this way confines the high value arrived at from electron densities mentioned above. See Figure 12. This is believed to be a stream of electrons ejected in the flare process which initiates Cerenkov radiation in the solar plasma, at heights of the order of one solar radius above the photosphere. The characteristics of the electron streams are not well known at the present time but it seems that they are associated with most, if not all, flares and that their ejection coincides with the commencement of the eruption in the flare region which is responsible for the surges seen optically. They are almost certainly responsible as well for a simple burst often observed at centimetre wavelengths simultaneously with the ~~Typ~~ Type III burst, and for the bursts of X-rays which balloon observations indicate are emitted from the Sun at ~~h~~ the same time. Both are probably generated as the electrons shoot through the chromosphere.

Type IV

This is the classification given to continuum type emission, i.e. relatively featureless emission covering a wide range of wavelengths, which follows a major solar flare. It was originally considered as part of the intense emission or Type I noise storm which is known to follow solar outbursts but was first recognized as a distinct phenomenon, and labelled as Type IV by Demisse and Boischot, of the French radio astronomy group at Nancay. It is distinguished by origin in a source of considerable angular extent

(7-12 minutes of arc) which is associated with large flares, starts late in the lifetime of the flare and continues for extended periods, from hours to days. Type IV bursts are almost invariably preceded by a Type II burst, and occur on about 20 per cent of the latter events. They fall into two distinct categories which appear to be distinct phenomena, with differing characteristics: these are referred to as "moving" and "stationary". The source of the moving Type IV burst initially moves outward from the associated flare with speeds of the order 1000 km/sec and may sometimes reach a height of 5 solar radii or more above the photosphere - the greatest heights from which radio emissions have been detected. Unlike Types II and III, however, the Type IV emissions occur over a wide band (down to centimetre wavelengths) and at any one time, come from <u>the same position in the atmosphere</u>. Their duration may be up to several hours during which time partial circular polarization is observed. These characteristics favour a synchrotron origin rather than in plasma oscillations, as proposed by Denisse. The "moving" phase of the Type IV disturbance is followed by the "stationary" phase during which the source is located in a fixed position above the original active centre and the emission may become strongly circularly polarized and continue for many hours or even days. In this phase the source is smaller in size (3-5 minutes of arc) and has a narrow cone of emission, indicated by the fact that stationary Type IV disturbances do not often occur from flares which are near the Sun's limb. Their characteristics indeed, are very like those of the continuum in Type I noise storms, and the two may in fact be identical. As for Type I storms it is not possible to decide between an origin in synchrotron or plasma oscillations, but the latter appear to be the more likely.

Type V

These are the most recent of the various variable components to be distinguished. The Type V burst is a broad band continuum which sometimes follows a type III burst, much as Type IV follows Type II outbursts. Maximum intensity occurs at wavelengths above 2 metres. They occur in association with only about 10 [illegible] cent of Type III bursts and tend to occur near the limb of the radio sun. Occasionally the emission from them drifts with frequency, corresponding to a source moving at a speed of around 1000 km/sec, but this is not common, nor has radiation at harmonic frequencies been observed. Intensities are too high for a thermal origin, and the lack of features peculiar to plasma oscillations points to an origin in synchrotron radiation. This has not yet been established, however, and the origin of Type V bursts is still uncertain.

Microwave Bursts

The occurrence and characteristics of bursts at microwave frequencies have not been studied as intensively nor systematically as at metre wavelengths, and no unified system for classifying them has been adopted. An outstanding characteristic of the short-period variable emissions which are observed in this range, however, is the simplicity of their structure compared with that found at long wavelengths. On the basis of their appearance on records of total flux at a single frequency microwave bursts can be divided into three main types, namely the gradual burst, the impulsive burst and the microwave version of the Type IV burst. Examples of these are illustrated in Fig. 13.

The duration of gradual bursts is a few tens of minutes, commencing closely with the start of the optical flare and reaching a maximum at or after the flare reaches its maximum phase. The source size is small, from 1 to 2.5 minutes of arc at 3 cm, and the emission is usually partially circularly polarized: brightness temperatures are of the order 10^6°K. The origin of the gradual bursts is believed to be thermal emission from a dense hot region at the top of the chromosphere which probably plays a significant part in the generation of the flare.

The majority of bursts at microwave frequencies are impulsive (90 per cent at a wavelength of 10 cms), but even at sunspot maximum it is not often that more than 3 per day are observed, so they must be counted as a relatively rare occurrence.

They are, however, associated with flares, not necessarily large [illegible]ares: appear near the beginning of the optical flare; and are fairly uniformly distributed over the Sun's disk. Their spectrum is a broad-band continuum at microwave frequencies which does not extend to metrewaves, and ~~thax~~ their duration a few minutes, during which brightness temperatures in the range 10^7-10^9°K are attained. Synchrotron processes are almost certainly involved in producing microwave impulsive bursts, but there is not enough information at the present time to determine details of its origin.

A <u>microwave Type IV</u> burst is the name given to the emission of a continuum for an extended period (5-40 minutes) at microwave frequencies in close association with a flare: it is often preceded by an impulsive burst. Radiation is emitted over a very wide band which has been observed to wavelengths as low as a few millimetres and extends strongly to metre wavelengths for the more intense bursts which accompany large flares: on the other hand if a Type IV metre-wave burst occurs it is almost invariably associated with a microwave counterpart. Its spectral characteristics are complex, however, and suggest that two or more distinct components may be involved. Brightness temperatures are in the range 10^7-10^9°K or higher and the emission is often partially circularly polarized, although sometimes a composite source is observed which includes a large region showing no polarization. The ~~mxg~~ origin of the radiation is certainly a non-thermal process, probably distinct from those which produce the Type IV metre wave bursts, but insufficient data is available to fill in the details.

Use of radio spectrographs more recently has also revealed several distinctive types of burst which are peculiar to decimetre wavelengths, in the 400-800 MHz range. They show a drift with frequency at fast and intermediate rates, which may be forward or reverse: sometimes both occur together, giving the typical record a "herring-bone" appearance. They may occur at the same time as Type III bursts, but are not high frequency extensions of them. The origin appears to be outward-moving disturbances which excite plasma xxx waves.

Radio Emission and Solar Flares

A convenient way to summarize the characteristics of the various types of burst radiation emitted by the Sun is to consider the part they play in solar flares.

All bursts are directly related to some aspect of a flare, the only possible exception being some Type I activity during noise storms. Conversely, all flares are accompanied by at least a Type III burst: the series of short sharp puffs of high speed electrons emitted at that time coincides with the beginning of the eruption in the flare region, and an impulsive microwave burst may occur also at that time. If the eruption is only a minor one - of not more than importance 1 on the scale of 1 to 3 used to classify flares - the metre wave activity, declines after the bursts have subsided. Larger flares commence in the same way, i.e. with a <u>gradual onset</u>, accompanied by puffs of high speed Type III electrons followed by a relatively quiet phase of several minutes duration. Then comes a <u>flash phase</u>; more Type III bursts with microwave accompaniments, and sometimes an associated Type V continuum, the optical explosive phase of the flare in Hα light coinciding in time with this activity. The most characteristic feature of the flash phase however is the appearance of Type II burst, with its sharp outlines and harmonic structure that drifts slowly towards lower frequencies as shock waves generated at the initial explosion trigger plasma oscillations on their way out through the solar atmosphere. In the largest flares decay of the Type II activity is followed by the onset of continuum emission over a very broad band, the Type IV burst, which may continue on for many hours.

The most prominent feature of solar radio frequency emissions at metre wavelengths. The Type I noise storms, have their origin in regions above certain sunspots, but do not appear to be so intimately connected with explosive flare activity as the other burst types. This may be due to the fact that they are emitted radially in a xxxx narrow cone-shaped beam and hence only appear to be associated with flares when these occur near the centre of the Sun.

Burst and Solar Terrestrial Relationships

In the study of the Sun, as in other branches of astronomy, radio and optical methods are beautifully complementary, the special attribute of radio astronomy being that it is concerned with electrons in action under conditions which often produce no visible radiation at all. The invisible processes may often be the more fundamental, particularly in a completely ionized mass of gas, like the solar atmosphere.

The first indication of new light on the origin of those disturbances came with the discovery of Type II bursts as an indication of a disturbance moving outwards in the solar atmosphere. It had been known for some time that great magnetic storms and auroral displays on the Earth followed the appearance of major flares on the Sun by a time delay of about 36 hours. The velocity of their source (1000-1500 km/s) was just about right to explain this time delay and suggested that the terrestrial effects were caused by particles from the Sun itself, expelled by the disturbance from the outer reaches of the solar corona. As further evidence became available however it has become clear that the Type IV burst which some times accompanies the Type II is the more fundamental event: The probability of a terrestrial magnetic storm following a Type II burst is high only when a Type IV burst is also present. Observations of Type II-Type IV associations can thus provide advance information of the possibility of major magnetic storms.

The radio emissions from the Sun are produced solely by electrons, but suggest that conditions capable of accelerating the much heavier protons may sometimes be present also. That this is, in fact, the case was established when Boischot and Denisse in 1957 found that the rare cosmic ray increases observed at ground level, and due to the arrival of high-speed solar protons, were associated with Type IV radio emissions.

Finally, microwave bursts have been found to be intimately associated with bursts of X-rays from the Sun, both high energy X-rays which are recorded directly by balloons and rockets (before they are absorbed in the Earth's atmosphere), and the lower energy X-rays which are responsible for the sudden disturbances in the ionosphere, and the consequent radio fade outs. The ionospheric disturbance takes the form of increased ionization at the D-region level (~ 80 km), which results in greatly increased absorption of waves that normally reflected from the higher ionospheric layers. Long distance short wave radio communication is thus wiped out during fade-outs.

The sequence of events in the solar atmosphere which result in the emission of radio bursts appears to be generally as follows. First, in the initial stages of a flare some heating occurs in a localized region of the chromosphere, perhaps to a temperature of 10^6°K: this produces the visible brightening, which first led to the discovery of flares. There is also an increase in the centimetre wave emission - a gradual microwave burst - and perhaps some low-energy X-rays as well. Some flares do not develop any further but for those that do the next stage, the <u>flash phase</u> is a much more dramatic one, in which there is an explosive release of energy, probably as a result of the collapse of a magnetic field.

The initial explosion releases, firstly, sharp bursts of fast electrons (Type I) which race through the solar atmosphere at half the speed of light, exciting plasma oscillations (Type III) at successive levels as they go. Other electrons become caught up in the strong spot-group magnetic fields in the chromosphere and follow helical paths around the lines of force with consequent emission of synchrotron radiation (Type V). A second consequence of the initial explosion (which is almost certainly a nuclear "bomb") is the ejection of a vast cloud of ionized gas, the turbulent shock-front at its leading edge exciting plasma oscillations (Type II) at successive levels in the corona as the whole gas cloud moves rapidly outwards. The gas carries within itself a magnetic field in which high-energy electrons and protons are trapped: the electrons remain held by the field and radiate by the synchrotron process (Type IV) until their energy is gradually dissipated by collisions. The protons, however, may finally manage to escape when the cloud reaches great heights in the solar atmosphere and are sometimes detected on earth by the cosmic ray increases they produce at ground level.

The still-moving cloud of gas, if large enough, is finally ejected from the Sun and travels out into space. When it reaches the vicinity of the Earth the shock front plays havoc with the Earth's magnetic field and storms of varying severity are recorded. The plasma particles, deflected towards the polar regions because of their electric charges, signal their arrival by temporarily jolting electrons out of their usual orbits in air molecules high in our atmosphere, and so initiate spectacular auroral displays. They have a devastating effect too on the upper reaches of the ionosphere, and communication circuits can be adversely affected for periods of up to several days.

It is somewhat anomalous that we have a better fundamental understanding of what goes on in the interior of stars, and of the Sun in particular, than of the complex happenings on its surface. Despite the fact that the Sun has been observed visually for centuries it was the advent of radio methods in the late 1940's which brought new perspectives and new lines of attack. The beginnings were promising but the fruits have been disappointingly meagre in their contribution to our understanding of the basic processes producing the varying radio emissions. The most significant event in recent years has probably been the completion of the Radioheliograph; its second-by-second panorama of activity across the whole disk has already revealed features that were totally unexpected but the wealth of new and detailed information which it is providing will undoubtedly contribute in a major way to a solution of some at least of the problems of solar activity.

Type	Duration	Emission Process	Angular Size of Source (min of arc)
Quiet Sun	Continuous	Thermal	Whole Sun
Slowly Varying Component	Days or months	Thermal	Plage area
Metre Wave Bursts			
Type I	Bursts $\sim$1 sec Storm: few hours to days	Plasma? Synch?	Burst 1-6 Storm centre 5-10
II	5-30 min	Plasma	6-12
III	Bursts $\sim$10 sec Group $\sim$1 min	Plasma	3-12
IV ma moving	10 min to 2 hour	Synchrotron	6-12
IV mb stationary	Few hours to days	Plasma Synchrotron	3-6
V	$\sim$1 min	?	3-12
Microwave Bursts Gradual	Tens of minutes	Bremsstrahlung	From <1 to >2.5
Impulsive	1-5 minutes	Ditto and Synchrotron	1-1.6 at 3 cm
IV μ	5 min to 1 hour	Synchrotron	2-4

SOLAR RADIO EMISSIONS

$R_{\odot} = 7 \times 10^5$ km
432,000 miles

Height of Source Above Photosphere	Polarization	Cone of Emission	Variability	Exciting Agency	Drift Rate	Temperature °K	Relationship with other Phenomena
	Random	Wide	11-year period	Free-free transitions of electrons		10^6	
	Random	Wide	With sunspot or Calcium Plage area	"		$\sim 2+10^6$	
0.2-1.0 $R_{\odot}$	Circular	Narrow?	Slow	?		$\sim 10^9$	
0.2-1.0	None	Wide	Complex	Ascending shock front $\sim 10^3$ km/sec		$< 10^{11}$	Solar protons, geomagnetic storms
0.2-2.0	None or partial	Wide	Group of simple bursts	Ascending electron stream, c/s		$> 10^{11}$	Initial expansion of flare.
0.5-5.0	Weak	Wide	Smooth	Electrons trapped in expelled plasma		$\sim 10^{11}$?	Solar protons, geomagnetic sto
0.2-1.0	Moving	Narrow	Slow with some fine structure	Descending electron stream trapped in field			
0.2-2.0	Weak	Wide?	Smooth	Same as Type III		$\sim 10^{11}$	Initial expansion of flare
?	None or partial circular	Wide?	← Smooth	Thermal and super thermal electrons near flare and plage		10^6	Compression before and during flare
0.05 over flare	Partial Circular incr. with λ	Wide	← Usually simple	Electron stream from flare region		10^9	Initial expansion of flare. Burst of hard X-rays.
overflare	Partial circular increasing with λ	Wide	← Smooth but some fine structure	Trapped electrons		10^9	