SOLAR RADIO BURSTS OF SPECTRAL TYPE V

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Summary

The properties of the metre-wave type V burst have been observed by interferometry in the frequency range 40–70 Mc/s, and by dynamic spectroscopy in the frequency range 5–210 Mc/s. Our investigations cover positions, movements, and angular sizes of the sources, and the spectrum and polarization of the emission.

Characteristic spectral features of the type V burst are its association with type III bursts (including inverted U bursts); large bandwidth; and duration (a slowly varying function of frequency) of a minute or so. There is no definite evidence for harmonic structure. In a minority of cases the type V continuum is detached from the preceding type III burst, thus giving a detached type V burst whose properties differ in some respects from those of the more common attached bursts. Type V sources occur at similar heights to type III sources, lie within $\frac{1}{3}R_\odot$ of the associated type III sources (except in the case of detached type V sources, which are usually greater than $\frac{1}{3}R_\odot$ from the type III source), and show similar dispersion of position with frequency. About a third of the type V sources show apparent movement on the disk, corresponding to speeds up to 2000 km/s. In size, also, the type V is similar to the type III source; the source size seems to be constant over the lifetime of the burst and the decay of intensity is exponential but some 10 times slower than for type III bursts. The directivity of the radiation is very low in contrast to that for type III bursts. The emission is only weakly polarized.

A model of the type V source, which accounts for most of the observed features, is suggested. In this model, coherent Čerenkov plasma waves are excited by fast electrons (speed $\sim\frac{1}{3}c$) ejected from a flare and oscillating between mirror points in a magnetic trap in the corona.

I. INTRODUCTION

The broad-band continuum radiation, appearing at metre wavelengths for a minute or so after a spectral type III burst, has been classified by Wild, Sheridan, and Trent (1959) as spectral type V. Subsequently the characteristics of the type were more fully described by Wild, Sheridan, and Neylan (1959), who proposed that the type V continuum was due to synchrotron radiation from relativistic electrons spiralling in magnetic fields high in the corona. About 3×10^{33} electrons with energies of at least 2 MeV were required to account for the observed intensity. The fast electrons were thought to be transported to large coronal heights as part of the electron stream responsible for the emission of the type III burst.

Stewart (1965), however, has shown that the speed of a type III disturbance is often remarkably constant, with a value of about $\frac{1}{3}c$, over a range of heights extending to at least two solar radii above the photosphere, and that the speeds for type III bursts followed by type V continuum appear to be the same as those

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for isolated type III bursts. Further, Stewart has advanced strong reasons for believing that the speeds of the *electrons* are the same ($\sim \frac{1}{3}c$) as the speeds of the *type III disturbances* which they constitute, i.e. there is no evidence for transverse (spiral) motion of the electrons. These speeds are much smaller than those required for the synchrotron theory of Wild, Sheridan, and Neylan (1959). Hence, if we wish to retain the postulate that the type III and type V bursts are generated by fast electrons with a common origin, the synchrotron theory of type V bursts must be seriously questioned.

A systematic study of the properties of the type V burst has therefore been undertaken with the object of arriving at a better understanding of this event. The parameters which have been studied are dynamic spectra; source position, movement, and angular size; and polarization and directivity of the emission. The presentation of the observational material in Sections III and IV is followed in Section V by a discussion of possible mechanisms for the emission of type V radiation and an outline of a tentative model for the type V source.

II. Equipment

The bursts studied have been selected from dynamic spectral records of the Dapto radio spectrograph during the period 1957–1962. The frequency range of this equipment has been progressively increased from 210–40 to 210–5 Mc/s. Information on source position, angular size, and polarization has been obtained from the Dapto swept-frequency and swept-phase interferometers. The construction and mode of operation of these instruments and the methods of data reduction have been described fully elsewhere (Wild and Sheridan 1958; Wild, Sheridan, and Neylan 1959; Sheridan 1963).

III. Observed Properties of Type V Bursts

(*a*) *Selection Criteria*

In their classification of the type V burst, Wild, Sheridan, and Trent (1959) described the spectra as broad-band enhancements often observed at the time of, or shortly after, the occurrence of type III bursts; such enhancements last from $\frac{1}{2}$ to 3 min and can reach very high intensities ($\sim 10^{-18}$ W m^{-2} (c/s)$^{-1}$) over a bandwidth of some tens of megacycles per second with the peak frequency usually below 100 Mc/s. However, this definition includes bursts which, because of spectral complexity and fine structure, and perhaps also superimposed type III bursts, seem to us to be unsuitable for a definitive study of the type V continuum. For the purpose of the present paper, therefore, we have used stricter selection criteria in that only comparatively pure continuum bursts with duration greater than 1 min at a frequency of ~ 50 Mc/s were selected. Dynamic spectra of some of these bursts are reproduced in Plate 1. It is probable that many of the more complex bursts which we have rejected will prove to be identical in all respects with our restricted sample of bursts.

(*b*) *Spectral Characteristics*

In nearly every case studied, the type III burst (or group of bursts) preceding the type V continuum could be identified by its clearly defined leading edge or by an abrupt change in intensity preceding the type V continuum. Usually the type V burst appeared as a diffuse prolongation of the type III burst and had a duration which increased as the frequency decreased (e.g. Plate 1(*e*)). Often the bursts extended to the lowest observed frequency. In a minority of cases the spectra showed a distinct break between the type III and the type V burst (e.g. Plate 1(*c*); discussion in Section III(*c*)). Such events will be referred to as *detached* type V bursts. Sometimes detached type V bursts have a high frequency spectral cut-off which initially drifts fairly rapidly to higher frequencies (Plate 2).

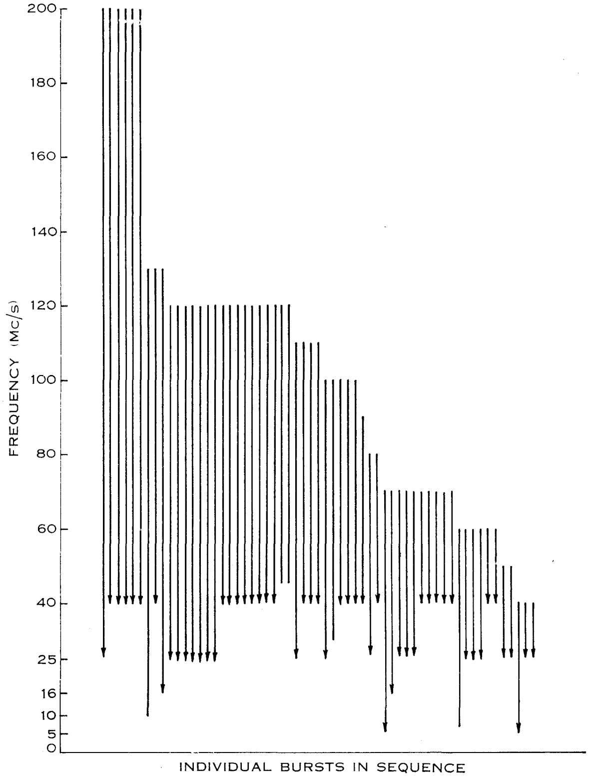


Fig. 1.—Observed initial bandwidths of 59 type V bursts. Arrows indicate that the lowest frequency was not recorded.

No clearly defined fundamental and second harmonic structure has been found in type V bursts, although some of the associated type III bursts have both fundamental and harmonic components. A few type V bursts have been observed in which the existence of harmonic structure is possible (e.g. Plate 1(*b*)). However, the large bandwidth of the type V burst would make the observation of harmonic structure difficult.

Example (*b*) of Plate 1 is one of a number of type V bursts in which there appears to be an association between the type V continuum and the fast frequency-drifting "inverted U" burst (Maxwell and Swarup 1958). The continuum appears within seconds of the disappearance of the U burst. It covers the same range of frequencies and lasts four or five times longer than the U burst (typical U burst duration is of the order of 10 s). This association may provide an important clue to the origin of the type V burst (see Section V).

Initial Bandwidth.—The initial bandwidths and upper frequency limits of 59 type V bursts are plotted in Figure 1. It can be seen that the type V bursts often extend to the lowest recorded frequency (indicated by an arrow in Fig. 1), while the starting frequency ranges from 200 to 40 Mc/s. For about half the bursts, the ratio of highest to lowest initial frequency is four or greater. Typically the type V burst is observed from < 40 to ~ 120 Mc/s. Some type III bursts also show similar large instantaneous bandwidths. However, part of the observed type III bandwidth,

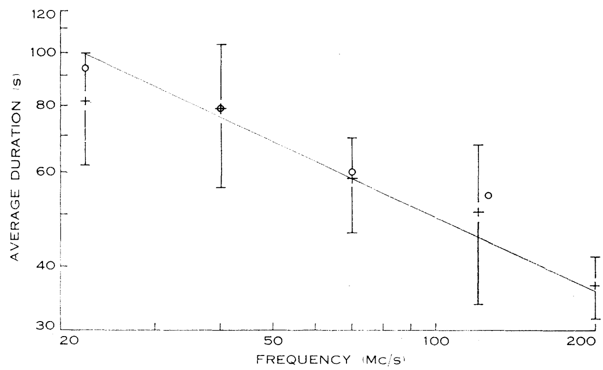


Fig. 2.—The average duration of 59 type V bursts plotted against frequency. Our results (indicated by +) are compared with those of of Thompson and Maxwell (1962) (indicated by ○) normalized to our duration of 79 s at 40 Mc/s. Bars indicate r.m.s. deviations for our values. The full line is the relation $T = 500/f^{\frac{1}{2}}$, with T in seconds and f in Mc/s.

especially at the lower frequencies, is probably due to the finite decay time of oscillation of the coronal plasma. Hence we conclude that the *excitation* bandwidth, which we define as that part of the total instantaneous bandwidth of the burst which is due to the simultaneous excitation in depth of the coronal plasma by virtue of the finite extent of the source region, is normally larger for a type V burst than for a type III burst.

Average Duration.—The average duration of 59 bursts is plotted in Figure 2 as a function of frequency. The points are consistent with the relation $T = k/f^{\frac{1}{2}}$ (where T is the average duration in seconds, f is the frequency in Mc/s, and $k = 500$) although the exponent of f may be varied by at least $\pm 30\%$. This relation is consistent with the results of Thompson and Maxwell (1962), who measured the ratios of the average durations of a large sample of type V bursts at frequencies between 125 and 25 Mc/s. Their results are also shown in Figure 2.

(c) *Position Measurements*

Position measurements for 24 type V bursts, obtained with the Dapto swept-frequency interferometer, are listed in Table 1. This interferometer measures one coordinate (parallel to the observer's east-west line) of the centroid of an isolated source situated on or near the solar disk. Measurements can be made, at intervals of $\frac{1}{2}$ s, to an accuracy of $\pm 2'$ of arc, effectively simultaneously at 5 Mc/s intervals over the frequency range 40–60 Mc/s. Following Wild, Sheridan, and Neylan (1959) and Weiss (1963), we have neglected possible effects of refraction (both regular and irregular) in the solar corona and the ionosphere.

Position and Movement on the Disk.—In 18 of the 24 cases the initial position of the type V source could be determined unambiguously from the interferometer and spectrograph records. By "initial position" we mean the first available measurement after the start of the type V burst; this measurement is not always made at the start of the type V burst. In five of the six remaining cases there was no discontinuity in the position record or gaps in the spectrum, so that the type III and initial type V positions were taken to be coincident. In only one case, that of August 14, 1961, 0059 U.T., was there any real uncertainty.

Initial and final type V positions, averaged over the frequency range 45–60 Mc/s, are compared with the average positions of their associated type III bursts in Figure 3(*a*). A histogram of the differences between the type III and initial type V positions is given in Figure 3(*b*). We see from Figure 3(*b*) that 12 out of 23 cases have a position shift greater than the reading error ($1'\cdot 5$) and that these 12 include 7 detached, or apparently detached, type V bursts for which the difference in position is at least $3'$. Only one detached burst has a position difference less than $3'$. We see from Figure 3(*a*) that the shift in position is unrelated to the position on the disk, and is not obviously larger for final than for initial type V positions. Hence, if any movement occurs in the type V source it is usually small and unrelated to the position on the disk. This result has been confirmed by a systematic search of the interferometer records for changes with time in the position coordinates at fixed frequency. Of the 24 cases plotted in Figure 4, 11 showed movements less than the errors of measurement ($\sim$ 1 min of arc/min). Of the remaining 13, 9 are considered to be reliable; but of these 9, only 2 had a movement on the disk of more than 3 min of arc/min. If these displacements correspond to real source movements, the speeds are of the order of 2000 km/s.

When the time interval between the type III and the type V initial position measurements exceeds a few seconds, the position of the type V source at the start of the burst may be estimated by backwards extrapolation of the movement of the source. When this is done, we find that at the start of the burst the type V source does not, in general, coincide in position with the associated type III source. The discontinuity in position appears to be larger for detached than for attached bursts. A convincing case of an abrupt position change between a type III and a detached type V burst is illustrated in Plate 2; the position is fairly stable during the type III burst and then suddenly changes to a second stable position during the type V burst.

TABLE 1

POSITION, VISIBILITY, AND POLARIZATION FOR TYPE V SOURCES

Date	Starting Time of Burst (U.T.)	Average Position Coordinate* (min of arc)			D, A, or N.R.†	Movement on Disk of Type V Source‡		Dispersion of Position Coordinate with Frequency §			Average Fringe Visibilities ‖				Percentage Modulation of Polarization of Type V Emission	
		P_{III}	P_V			Rate¶	Duration (s)	III (min of arc)	V (min of arc)	Range (Mc/s)	ξ_{III}		ξ_V		40 Mc/s	60 Mc/s
			Initial	Final							L.B.	S.B.	L.B.	S.B.		
1957																
July 4	0030	+19·5	+12·0	+12·0	D	Nil		−3·8	−1·8	45–55	0·40[a]		0·30[a]			
1958																
July 27	0341	−15·3	−14·7	−17·1	A	−2·9	50	−2·2	+1·6	45–60						
28	0318	−19·3	−17·8	−18·5	A	Nil		Nil	−1·8	45–60						
Aug. 24	0216	−21·8	−20·1	−19·6	A	+0·7	45	+2·9	−1·0	45–60						
Dec. 10	0220	+19·8	+25·7	+25·7	D	Nil		+1·8	+2·5	45–60						
1959																
Feb. 12	0201	+12·6	− 3·7		D											
18	0324	+11·1	+16·7	+13·6	A	−4·3	43	−7·1	−3·1	45–55						
March 26	0257		−36·6	−37·1	N.R.	Nil			−7·8	45–60						
May 8	0249	+25·6	+26·1	+28·5	A	+2·4	60	+4·2	+4·7	45–55	0·31		0·24	0·77	7·0	
July 14	0338	− 5·0	− 4·7	− 9·4	A	−1·2 +1·0	240	+1·0	−3·9	45–60	0·54		0·30	0·80	20·0	18·0
16	0137	−36·0	−35·0	−36·0	A	Nil							0·23	0·75	6·0	
	0235	−30·0	−33·2	−30·6	A	+12·5 −4·6	24 30	−8·6	−10·3	45–55	0·14		0·25	0·65	6·0	
Dec. 8	0117		−19·0	−18·8	N.R.	Nil			−3·7	45–60	0·57		0·40			9·5

Table 1 (*Continued*)

Date	Starting Time of Burst (U.T.)	Average Position Coordinate* (min of arc)			D, A, or N.R.†	Movement on Disk of Type V Source‡		Dispersion of Position Coordinate with Frequency§			Average Fringe Visibilities‖				Percentage Modulation of Polarization of Type V Emission	
		P_{III}	P_V			Rate¶	Duration (s)	III (min of arc)	V (min of arc)	Range (Mc/s)	ξ_{III}		ξ_V		40 Mc/s	60 Mc/s
			Initial	Final							L.B.	S.B.	L.B.	S.B.		
1960																
Jan. 29	0144	+20·8	+25·0		D			+9·1	+5·8	45–60	0·60		0·35		8·5	
Feb. 4	0550														10·0	10·0
18	0059		+27·0	+24·9	N.R.	−1·4	90		+1·0	45–60					5·0	
June 15	0252	−25·8	−23·2	−24·0	A	−0·5	90	−1·4	−0·7	45–55	0·25	0·76	0·27	0·75		
			−16·6	−10·0	D	+18·0	22									
20	0127		−27·9	−27·9	N.R.	Nil			−4·5	45–60	0·33					
											0·35[a]		0·22[a]	0·57[a]		6·6
June 27	0330	−26·1	−29·5	−29·8	D	Nil		−14·6	−10·7	45–60			0·23	0·82	38·0	
Aug. 12	0045	−22·8	−22·9	−25·2	N.R.	−2·0	68	+4·6	+1·6	45–60					8·0	13·0
	0305		−29·5	−28·8	N.R.	+0·7	56		−1·4	45–60	0·35	0·63	0·36	0·63	13·0	
											0·15[a]	0·61[a]	0·18[a]	0·67[a]		11·0
1961																
Aug. 11	0125	+21·0	+22·5		D	+15·0?	30				0·43		0·32	0·80		
14	0059		− 1·9	− 0·8	D	+1·0	69		+2·1	45–60					7·0	
Sept. 29	0124	+23·0	+19·5		D	Nil					0·34	0·64	0·36	0·50	0	

* Averaged over the frequency range 45–60 Mc/s. +east, −west of centre of disk.

† A, attached type V burst; D, detached type V burst; N.R., type V burst not resolved from type III burst. See text.

‡ Measured at fixed frequency (effectively 50 Mc/s).

§ $P_{45}-P_f$.

‖ Measured at 40 Mc/s unless [a] for measurement at 60 Mc/s.

¶ Measured in units of min of arc/min.

Thus the evidence suggests that there is often a real discontinuity in position between type III and type V sources. Since we observe only the projection on the solar disk, such a discontinuity in position coordinates may represent either a radial

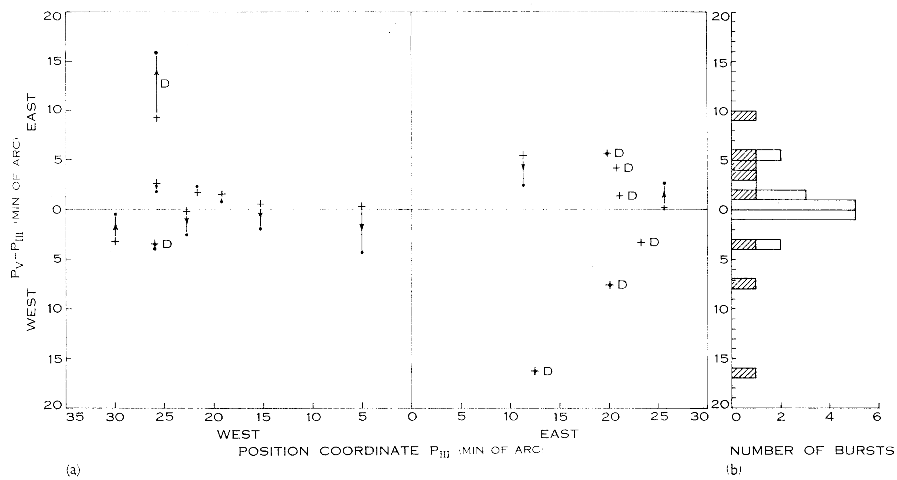


Fig. 3(a).—Comparison of observed initial (+) and final (●) positions of 17 type V bursts averaged over the frequency range 45–60 Mc/s with the average positions of the associated type III bursts. Detached type V bursts are indicated by D.

Fig. 3(b).—Distribution of the differences $P_V - P_{III}$ between 23 initial type V positions and the associated type III positions; includes six cases where the type III and type V positions could not be resolved, for which we have assumed $P_V - P_{III} = 0$. Cross-hatching refers to detached type V bursts.

or a tangential displacement between the two sources. On the first assumption, the observed angular displacements correspond to the physical displacements shown in

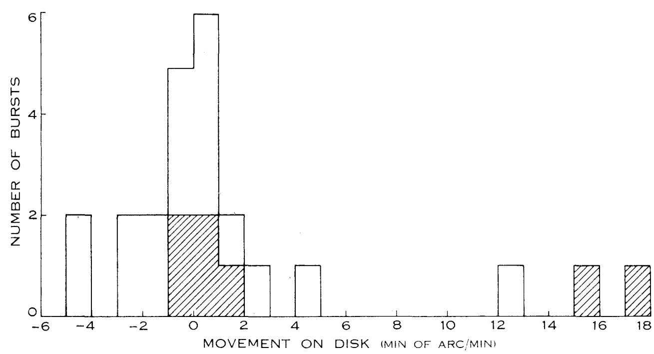


Fig. 4.—Histogram of the estimated movement on the disk, in min of arc/min, of the position coordinates (effectively at 50 Mc/s) of 24 type V bursts. Cross-hatching refers to detached type V bursts.

Figure 5(b); on the second, to those in Figure 5(c). The histograms clearly show that the great majority of attached type V sources are initially located within a distance of $\frac{1}{3}R_{\odot}$ of the type III position. For detached type V sources the positional shifts, which become measurable some 30 s or so after the type III position measurements, are usually greater than $\frac{1}{3}R_{\odot}$.

Average Height.—From the results of Figure 3 we would expect the average height of the type V source to be similar to that of the type III source. In order to

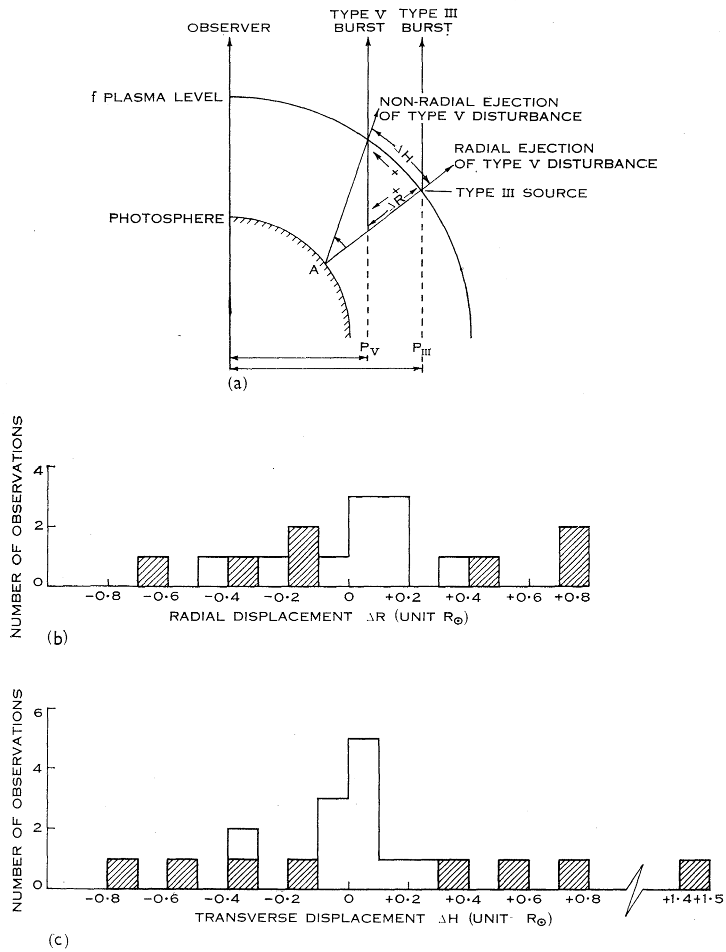


Fig. 5(*a*).—Model used to interpret displacements between type III and type V sources.

Fig. 5(*b*).—Histogram of the possible radial displacements between 17 type V and associated type III sources.

Fig. 5(*c*).—Histogram of the possible horizontal displacements between 19 type V and associated type III sources.

In (*b*) and (*c*) cross-hatching refers to detached type V bursts.

determine the average height directly, we have plotted in Figure 6 the average initial position coordinates (effective frequency $\sim$ 50 Mc/s) of 10 type V bursts against the positions of the associated solar flares. A type V burst was considered flare-associated if it occurred between the time of start and maximum intensity of a flare. If we assume that the type V disturbance is ejected radially from a flare situated at the photosphere (an assumption which may not apply to the two possible detached type V bursts included in Fig. 6) and that the radio emission travels towards us along a rectilinear path, then the regression coefficient for the points of Figure 6 gives directly the height above the centre of the Sun of the type V source at 50 Mc/s. This height is $(2\cdot 1 \pm 0\cdot 2)R_\odot$. It is close to the height of $(2\cdot 07 \pm 0\cdot 1)R_\odot$ found by

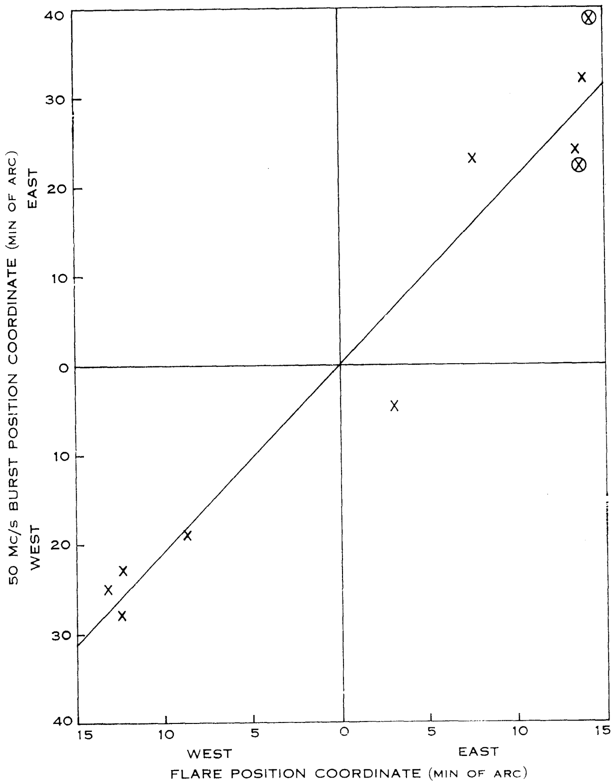


Fig. 6.—Plot of the 50 Mc/s position coordinates of 10 type V bursts against the associated flare coordinates. The full line (slope $2\cdot 1 \pm 0\cdot 2$) is the least squares fit to the data. Circled points refer to possible detached type V bursts.

Morimoto (1964) for 30 type III bursts at 52·5 Mc/s. Direct measurements thus confirm our inference, from Figure 3, of the similarity between the average heights of the sources of type III and type V bursts. Hence, if we accept the plasma hypothesis* for type III bursts, it appears that type V as well as type III emission originates at or near the local plasma level.

* According to the plasma hypothesis (Wild, Sheridan, and Neylan 1959) the type III burst is excited by an outwardly moving disturbance which generates plasma waves of decreasing frequency f (Mc/s) $= 0\cdot 009N^{\frac{1}{2}}$ (cm$^{-3/2}$) as it moves outwards through regions of the coronal plasma of decreasing electron density N. The disturbance is thought to consist of a compact group of fast electrons (velocity$\sim \frac{1}{3}c$) ejected from the solar flare region during the flash phase. The local plasma level corresponding to a given frequency f is simply the height in the solar atmosphere at which that frequency is generated in accordance with the formula quoted above.

Dispersion of Position with Frequency.—The dispersion of position with frequency for type V bursts, measured as the difference between the 45 and 60 Mc/s

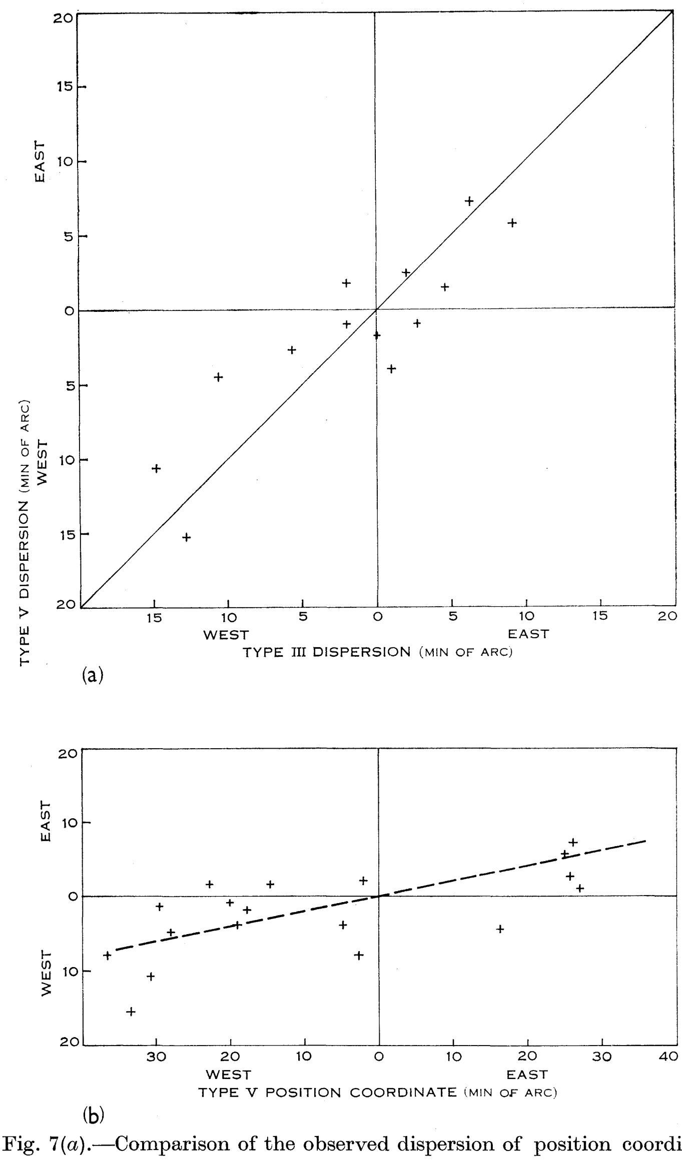


Fig. 7(*a*).—Comparison of the observed dispersion of position coordinate with frequency for 13 type V and associated type III bursts. Dispersion is measured as the difference between the 45 and 60 Mc/s position coordinates.

Fig. 7(*b*).—Relation between dispersion and 52·5 Mc/s position coordinate for 18 type V bursts. The dashed line gives the average relation found by Wild, Sheridan, and Neylan (1959) for type III bursts.

position coordinates, is plotted in Figure 7(*a*) against the dispersion of the associated type III burst, and in Figure 7(*b*) against the initial type V position coordinate (effective frequency, $52 \cdot 5$ Mc/s). In a few cases dispersion has been measured over a 10 Mc/s interval and extrapolated to 45–60 Mc/s. It can be seen that the dispersion is of the same magnitude for type III and type V bursts, and increases with distance from the centre of the Sun in a way similar to that found by Wild, Sheridan, and Neylan (1959) from a large sample of type III bursts (dashed line on Fig. 7 (*b*)). Now the systematic dependence of dispersion upon disk position of the source is a strong argument for the validity of the plasma hypothesis for type III bursts (Wild, Sheridan, and Neylan 1959; Weiss 1963). Hence the similarity between the *average dispersion* of position with frequency for type III and for type V bursts leads us to consider seriously the suggestion that type V emission, as well as type III emission, may be produced by plasma waves excited by fast electrons.

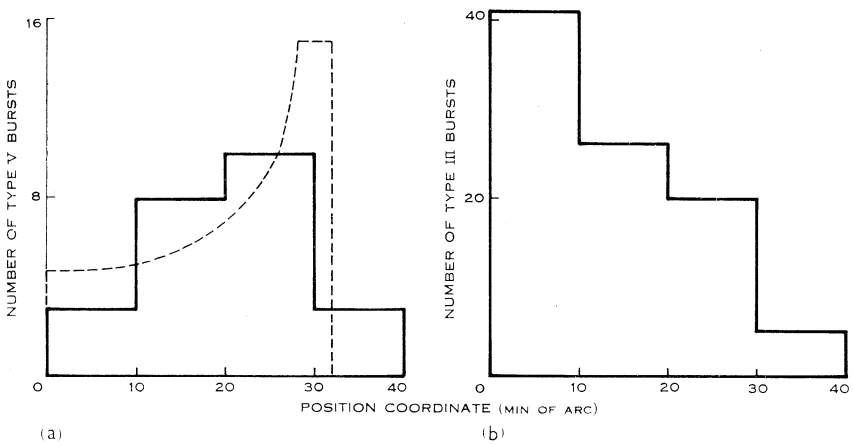


Fig. 8(*a*).—Observed disk distribution for 24 type V bursts. The dashed line gives the distribution predicted for a source with a wide cone of emission ($\sim 2\pi$ sr).
Fig. 8(*b*).—Observed disk distribution for type III bursts (Wild, Sheridan, and Neylan 1959).

Disk Distribution.—The disk distribution of the average position coordinates of 24 type V bursts is given in Figure 8(*a*). The peak in the histogram between 20′ and 30′ indicates that most type V bursts are seen near the radio limb. (The radius of the 50 Mc/s plasma level is approximately 30′.) The dashed line is the disk distribution calculated on the assumption that the radio sources originate radially above flares uniformly distributed in longitude but restricted to within latitudes $\pm 40°$. Such a distribution was found by Thompson and Maxwell (1962) for the flares associated with type V bursts and has been confirmed by our own data.

The reasonable agreement between the two distributions is direct confirmation that the type V source is equally visible from any position on the solar disk, and we conclude that its cone of emission must be of the order of 2π sr. By way of contrast, the distribution for type III bursts found by Wild, Sheridan, and Neylan (1959), which is reproduced in Figure 8(*b*), suggests that the type III burst probably has a much narrower cone of emission than the type V burst.

(*d*) *Angular Size Measurements*

A measure of the angular size of a solar radio source can be obtained from the degree of modulation or fringe visibility ξ* of the interference pattern obtained with the Dapto swept-phase interferometer. Measurements are made at either 40 or 60 Mc/s with a long baseline (1 km) or short baseline ($\frac{1}{4}$ km).

In Figures 9(*a*) and 9(*b*) we compare the maximum and average recorded fringe visibilities of 12 type V and associated type III bursts. Because measurements were not taken continuously, but at the discretion of the operator, the largest recorded ξ is not necessarily ξ_{max} and the average $\bar{\xi}$ is not necessarily a true time average for the whole duration of the burst. For these reasons, it is difficult to compare the

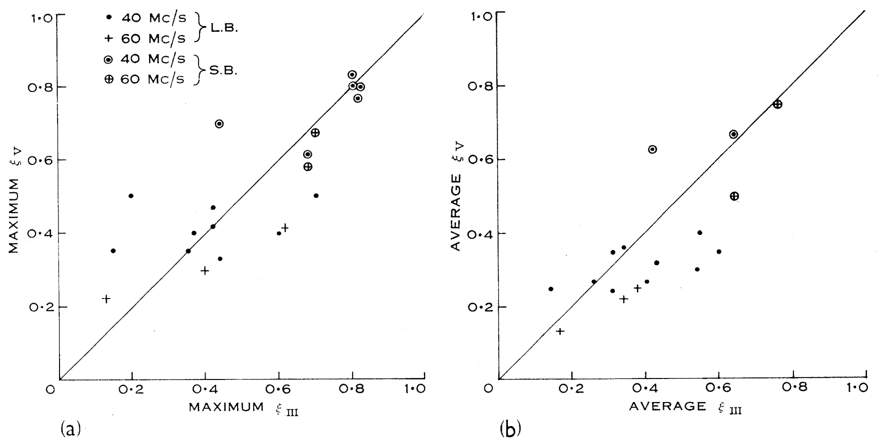


Fig. 9.—Comparison of the long-base (L.B.) and short-base (S.B.) fringe visibilities of 12 type V and associated type III bursts. (*a*) Maximum recorded fringe visibility; (*b*) average recorded fringe visibility. Slopes of the full lines are 45°.

fringe visibilities of the bursts accurately, but the data of Figures 9(*a*) and 9(*b*) suggest that $\xi_V \approx \xi_{III}$, i.e. the type V burst has approximately the same angular size as its associated type III burst. The same result is implicit in Figure 10, although the scatter in the diagram is considerable, especially for points that refer to type V bursts. In Figure 10 simultaneously measured values of short-base and long-base fringe visibilities, for type V and associated type III bursts, are compared. The large scatter indicates that the type V burst has by no means a standard shape or size.

In the absence of sufficient data to specify the brightness distribution of the type V source, we introduce the angle $\theta = 2\pi(L-S)/W$, where L and S are respectively the long-base and short-base position coordinates, and W is the long-base lobe width. θ is a fairly close estimate of the relative phase angle between the two measured Fourier components of the brightness distribution, i.e. those corresponding to the long and short baselines of the aerial system. (If the short baseline had zero length,

* ξ gives the ratio of the moduli of the Fourier components of the source brightness distribution at angular frequencies of 0 and a/λ, where a is the aerial spacing, and λ is the observed wavelength.

θ would be precisely the relative phase angle.) In Figure 11, θ is plotted against the ratio of long-base fringe visibility to short-base fringe visibility for measurements during 15 type V bursts; the plot shows that $|\theta| < 90°$ and $\xi_{L.B.} < \frac{1}{2}\xi_{S.B.}$ in most cases. Applying some simple concepts of Fourier transforms to this result we conclude that the east-west profile of a type V source tends to show a single peak but is often asymmetrical.

If we interpret the above results in terms of the core-and-halo model* of Weiss and Sheridan (1962), we find the average half-power core width of a type V source to be $\sim 5'$ at 40 Mc/s. Since most type V sources are seen near the radio limb,

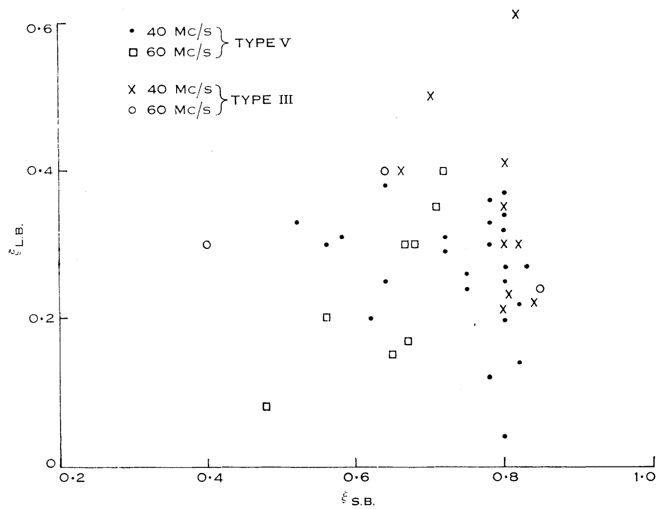


Fig. 10.—Plot of simultaneously measured long-base and short-base fringe visibility pairs for 15 type V and associated type III bursts.

this measured width of $\sim 5'$ probably refers to the depth of the type V source rather than to its width. In any case, scattering of the emitted radiation by coronal irregularities may produce an apparent enlargement of the source.

(e) *Temporal Development*

In four cases we were able to obtain a reliable indication of the temporal development of a type V source. These cases suggest that the angular size remains fairly constant over the lifetime of the burst and that the intensity decays approximately exponentially with time from an early maximum value. The average time-constant for the decay is of the order of 30 s at 40 Mc/s. We may compare these results with those for type III bursts, which have been found to have an exponential decay with a time-constant between 2 and 3 s at 40 Mc/s (unpublished data) and an

* $\xi_{L.B.}$ and $\xi_{S.B.}$ measured at 40 Mc/s, combined with $\xi = 0$ at zero frequency, are fitted by the sum of two Gaussian curves representing the "core" and the "halo". It is arbitrarily assumed that the halo has a half-power width of 40′.

angular size which increases slightly during the decay of the burst (Weiss and Sheridan 1962).

(*f*) *Polarization*

Prior to this investigation no systematic study of the polarization of type V bursts had been made, although Wild, Sheridan, and Neylan (1959) reported in a preliminary finding that type V bursts may often be polarized. Our results show that type V emission is, at most, only weakly polarized.

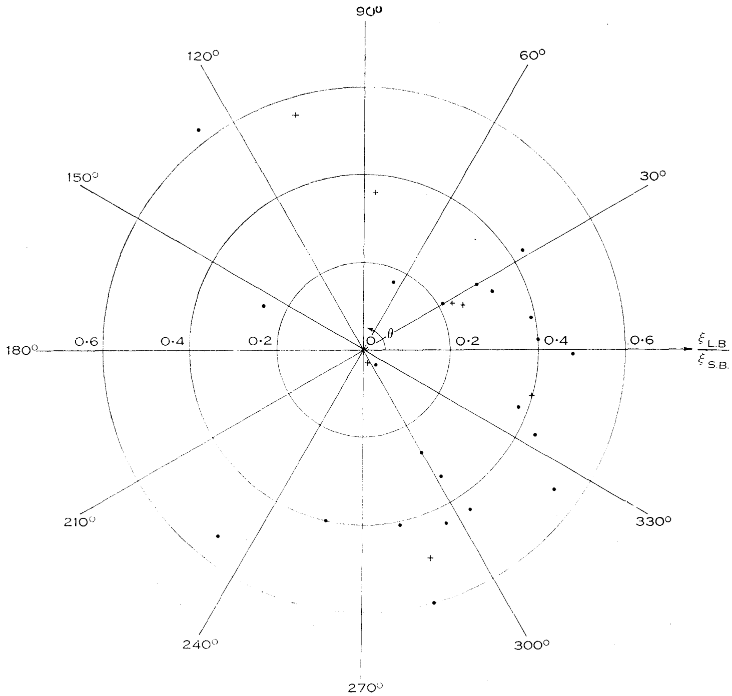


Fig. 11.—Distribution of relative phase angle θ (degrees) with ratio of long-base to short-base fringe visibilities $\xi_{\mathrm{L.B.}}/\xi_{\mathrm{S.B.}}$ at 40 Mc/s (●) and 60 Mc/s (+). The phase angle θ is defined in Section IV(*d*). Data are from 15 type V bursts.

The Dapto equipments can be used to give a measure of the degree of polarization of incident radiation and of the difference in phase between two received polarization components by replacing the two aerials of the interferometer by a pair of crossed rhombics. Measurements are made at 40 and 60 Mc/s over a bandwidth of 50 kc/s. Unfortunately not enough parameters are measured to specify the polarization completely, but when the phase of polarization is near $\frac{1}{2}\pi$ the degree of modulation of the interference pattern is a good estimate of the degree of polarization of the circular component.

A histogram of the degree of modulation (M) for 14 type V bursts, mostly measured at 40 Mc/s, is given in Figure 12. Only two bursts have $M > 11\%$. The corresponding phase angles are randomly distributed. Even for the two cases when M is large, the phase angle is not near $\frac{1}{2}\pi$, that is, the apparent polarization is elliptical. However, from past experience we have become suspicious of measurements of linear or elliptical polarization with the present equipment and believe the observed polarization could be due largely to the effect of ground reflections. Other observations and theoretical considerations of Faraday rotation suggest that linear polarization from the Sun can be observed only with very narrow bandwidths (Hatanaka 1956; Akabane and Cohen 1961). For these reasons we conclude that the type V emission is, at most, weakly polarized. Lack of data has prevented any direct comparison of the relative polarization of type V and associated type III bursts.

IV. The Event of July 14, 1959

The type V burst of July 14, 1959, whose spectrum and other properties are illustrated in Plate 3, is unusual from several points of view. The complete flare event of July 14, which formed part of a complex of anomalous activity in the same plage region in mid July, was particularly energetic. Not only was the optical flare,

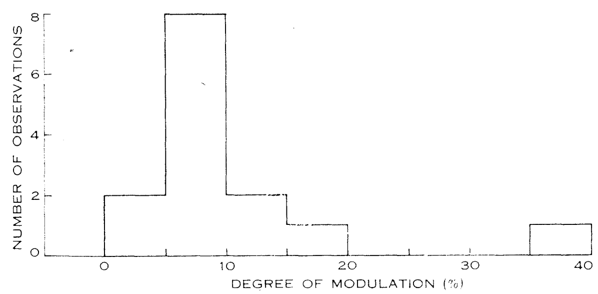


Fig. 12.—Distribution of the percentage modulation of polarization of 14 type V bursts.

of importance 3+, very complex; the type III–V burst was followed by at least two type II bursts and a sustained type IV burst (Plate 1 of Weiss 1963), and the flare was accompanied by a sudden ionospheric disturbance and followed by solar cosmic rays and a major geomagnetic storm.

Since the energy of the optical flare is unusually high, it is tempting to ascribe the abnormally long duration (9 min) and large bandwidth ($>$ 200 to $<$ 25 Mc/s, the largest recorded) of the type V emission to excitation by exceptionally energetic electrons. The high rate of drift of the leading edge of the type III bursts at 0340 U.T., although difficult to measure, affords some support to this view. By converting frequencies into heights using the Newkirk (1961) model for an active region and correcting for group retardation effects (see Stewart 1965), we find that at heights $\sim 1 R_{\odot}$ above the photosphere the speed of the type III source (at 0340 U.T.) is about $\frac{1}{2}c$; the speed at lower heights may well be larger. The polarization of this burst is also unusually high (20–30%; exceeded by only one other type V burst).

The radio source is located close to the centre of the disk, and the dispersion of position with frequency, although in the correct sense, is not marked. The source movement is complex, an initial movement to the west reversing to east near 0344 U.T.; the rate of movement, ~ 1 min of arc/min in either direction, is typical of type V bursts as a class. One of us (Weiss 1963), in describing the evolution of the radio event at metre wavelengths, has suggested that the complex source movement may be linked with loop-shaped flare brightenings, one pointing eastwards and the other westwards.

An interesting and unusual feature is the fine structure which appears in the spectrum at low frequencies near the end of the type V burst. This fine structure takes the form of individual slowly drifting bands with narrow bandwidths and durations of a minute or so. It seems to be similar to, although broader in bandwidth and longer in duration than, very narrow band slow-drift features occasionally found embedded in or following type III associated continuum; this finer structure has already been described by Thompson and Maxwell (1962). In the July 14 burst, the drift rates of the more prominent features range from $-0\cdot04$ to $-0\cdot06$ (Mc/s)s^{-1}, corresponding to outwards source speeds of 700–1300 km/s at heights near $1\cdot2R_{\odot}$ above the photosphere. These speeds are similar to those of the sources of type II bursts, but there seems to be no direct connection between type II bursts and the drifting bands under discussion.

V. A Proposed Model for the Type V Burst

Before considering a model of the type V burst, it will be useful to summarize the observed characteristics considered in the preceding section. These characteristics, which must of course be satisfied by any model, are listed below.

(i) The peak flux may exceed 10^{-18} W m^{-2}(c/s)$^{-1}$ for the more intense bursts.

(ii) The excitation bandwidth is large—often 100 Mc/s or more—and the bandwidth is approximately equal to the centre frequency.

(iii) The mean observed durations are consistent with a law of the form $T = 500f^{-\frac{1}{2}}$. The decay of the intensity is approximately exponential.

(iv) There is no definite evidence of harmonic structure.

(v) In some cases the type V continuum is detached from the preceding type III burst and shows drift towards higher frequencies.

(vi) If the type V burst is detached, the source is usually at a distance of more than $\frac{1}{3}R_{\odot}$ from the associated type III source; if the type V burst is not detached, it usually lies within $\frac{1}{3}R_{\odot}$ of the associated type III source.

(vii) The type V source height at 50 Mc/s is, *on the average*, very close to the type III source height and both are presumed to lie near the local plasma level.

(viii) On the average, the dispersion of position with frequency is the same for type III and type V sources.

(ix) Type V sources appear to be single, often asymmetrical, and similar in size to type III sources. The size is probably constant over the lifetime of the burst.

(x) Most type V sources are stationary on the disk but some show movements which may represent transverse motions with speeds of the order of 2000 km/s or more.

(xi) Type V radiation is remarkably isotropic.

(xii) Type V emission is only weakly polarized or completely unpolarized.

In formulating a model we shall start with the basic assumption that the type V burst is produced by fast electrons with speeds comparable to those responsible for the type III burst. According to Stewart (1965), these speeds are $\sim \frac{1}{3}c$, and remain substantially constant over wide ranges of heights in the corona. Now the equivalent temperature of an electron with a speed of $\frac{1}{3}c$ is only 2×10^8 °K, which is very much less than the brightness temperatures observed in type V bursts. For, by inserting the observed flux density ($S \sim 10^{-18}$ W m^{-2} (c/s)$^{-1}$ at $\lambda = 7\cdot5$ m) and source size (diameter $\sim 5'$, subtending a solid angle $\Omega \sim 2\times10^{-6}$ sr) into the standard formula

$$S = 2\cdot77\times10^{-23}\, T_{\mathrm{b}}\, \Omega/\lambda^2 \qquad \mathrm{W\ m^{-2}\ (c/s)^{-1}},$$

we obtain $T_{\mathrm{b}} \sim 10^{12}$ °K. Hence the type V emission cannot be thermal in origin nor can it be due to any other non-coherent emission mechanism such as synchrotron or gyro radiation. Synchrotron radiation is, of course, also excluded on the grounds that speeds $\sim \frac{1}{3}c$ fall in the non-relativistic domain ($\epsilon \ll m_0 c^2$). Two known non-thermal mechanisms remain: amplified gyro radiation and coherent plasma waves (Wild, Smerd, and Weiss 1963). Amplified gyro radiation can almost certainly be excluded on the grounds of the large bandwidths observed in type V emission. Thus we may conclude that the type V burst, like the type III burst, has its origin in coherent plasma wave excitation. This conclusion is supported by the observational items (vi), (vii), and (viii) above.

With these considerations in mind, we propose the following model (Fig. 13).

(i) The type III and associated type V bursts are produced by a cloud of electrons with velocities $\sim \frac{1}{3}c$ ejected from a common origin, and spreading out over a considerable region near the flare where the coronal magnetic field configuration diverges from below.

(ii) Part of the electron cloud is guided approximately radially away from the flare region, i.e. without encountering any substantial transverse component of magnetic field. These electrons give rise to the type III burst (see Weiss and Wild 1964).

(iii) The remainder of the electrons are initially guided along field lines with a substantial transverse component and become trapped at the heights at which the type V burst is observed.

(iv) These electrons excite coherent plasma waves as they oscillate in depth within the trap, so producing the broad-band type V burst.

We would expect the basic requirements of diverging lines of force and adequate injection area to be a common feature of solar active regions. Our model is therefore consistent with the comparative commonness of short-lived continuum following

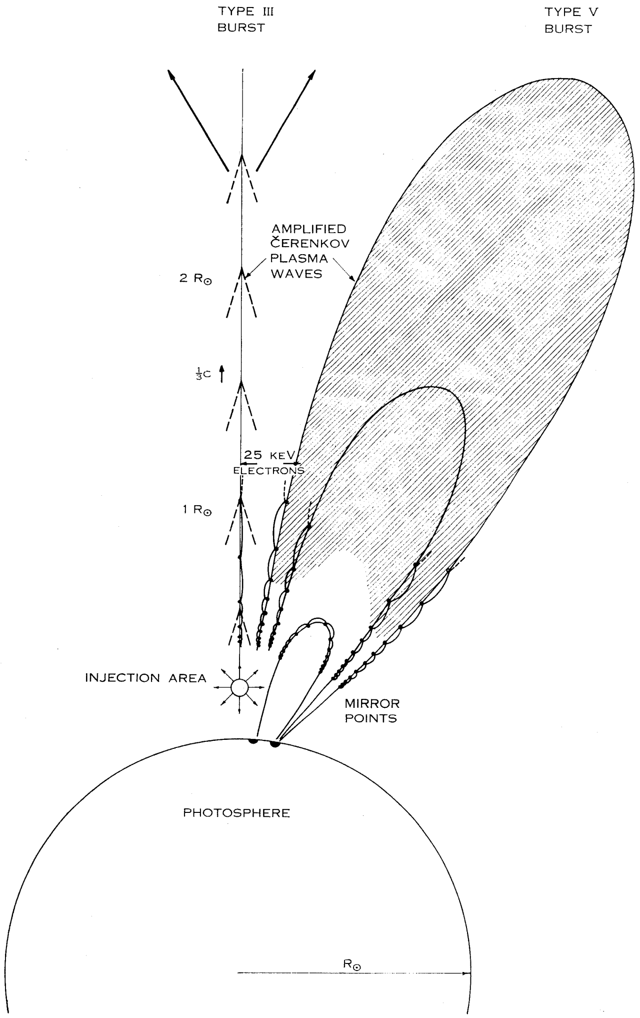


Fig. 13.—Proposed model for the physical state of the solar corona at the time of a type V burst. The magnetic configuration is such that some of the fast ($\sim$ 25 keV) electrons ejected during the flare are trapped in the corona for a minute or longer. It is suggested that the trapped electrons generate plasma waves which, after conversion to electromagnetic radiation, produce the type V continuum.

type III bursts, since it does not demand conditions in the solar atmosphere which can be regarded as rare. We do not envisage that the trap be a region of completely disordered magnetic field; rather, we suggest, as indicated schematically in Figure 13, that the electrons may be confined by repeated reflection between two regions (mirror regions) of converging magnetic field lines. Presumably, however, some measure of disorder as well as short-lived temporal changes in the magnetic field configuration near the flare during the injection period, perhaps associated with mass motions following the flash phase of the flare, are required for trapping to occur at all.

According to the model the discontinuity in position, $P_{\mathrm{V}}-P_{\mathrm{III}}$, is a measure of the horizontal displacement between the centroids of the type III and the type V sources, and indicates the extent of the divergence of the magnetic field lines from the quasi-radial path taken by the type III electrons. We note in passing that the observed angular size of the type III source (Weiss and Sheridan 1962) and that of the type V source, both $\sim 5'$ (or less if apparent sizes are substantially increased by scattering), are consistent with this interpretation of the displacements we find between the two sources.

(*a*) *Excitation of Plasma Waves*

We shall continue our discussion of the burst characteristics expected from the model by now considering the excitation of plasma waves. The equilibrium theory of excitation of coherent plasma waves (in which the wave amplitude is limited by collisions between the fast electron stream and the background plasma) gives for the source brightness temperature, under conditions appropriate to type III bursts, the formula (Wild, Smerd, and Weiss 1963)

$$T_{\mathrm{b}} = 10^{16}(N_{\mathrm{s}}/N)^{8}(\bar{v}/v_{\mathrm{th}})^{9}. \tag{1}$$

In this expression N_{s}/N is the ratio of stream to coronal density, and $\bar{v}$ and v_{th} are respectively the average velocity of the stream and the thermal velocities of the coronal electrons (to which the velocity dispersion within the fast electron stream has been equated). Provided that the generation of plasma waves and the efficiency of their conversion into electromagnetic waves are not affected by the magnetic field and by the circumstance of trapping, we find from (1) that bunches of electrons with a speed of $\frac{1}{3}c$ would require a density $\sim 10^{6}$ cm^{-3} to explain the observed intensities of type V bursts. If the equilibrium amplitude of the plasma wave is not reached, the required electron density will be larger; we may presume in this case (Terashima, personal communication) that the intensity of the burst will still depend rather strongly on the density and velocity of the trapped electrons. However, there has as yet been no theoretical investigation of the excitation of coherent plasma waves by bunches of fast electrons spiralling with substantial pitch angles along magnetic field lines, and formula (1) and the corresponding formula in the non-equilibrium theory may require revision.

(*b*) *Burst Duration*

Turning now to the burst duration, we first note that injection into the trap will occur over only the very short time—a few seconds or less is suggested by the duration of type III bursts—for which the electrons are accelerated near the flare region. Once injected, the source electrons will oscillate in depth between their respective mirror points. If the only process leading to loss of energy of the trapped electrons were the excitation of coherent plasma waves and their subsequent dissipation, the lifetimes of the trapped electrons would be much greater than the observed lifetimes of type V bursts. Using the observationally determined parameters for the type V burst (peak flux density at the Earth 10^{-18} W m^{-2} (c/s)$^{-1}$, bandwidth 100 Mc/s, and cone of emission 2π sr) we find a peak rate of emission of $\sim 10^{20}$ erg/s. The total energy available for emission as electromagnetic radiation, on the other hand, is 10^{23} erg, assuming an efficiency of 10^{-7} for conversion of plasma waves into electromagnetic radiation (Wild, Smerd, and Weiss 1963). In arriving at this figure for the available energy, we have adopted an electron density of 10^6 cm^{-3} (Section V(a)), an average velocity of $\frac{1}{3}c$, and linear dimensions for the source of $2\cdot5\times10^9$ cm, corresponding to the source dimensions of 5′ deduced in Section III(d).

The duration of type V emission will therefore be determined by the length of time for which the electrons remain trapped or are able to generate plasma waves. Three factors which may limit burst duration in this manner are:

(i) Loss of energy of trapped electrons by Coulomb collisions with the coronal plasma. That this process may be important is suggested by the high power to which the velocity is raised in formula (1).

(ii) Redistribution of pitch angles. This redistribution may occur through scattering on magnetic irregularities or through coulomb collisions between fast electrons and the coronal plasma. The redistribution of pitch angles, which is also a cause of partial trapping, may limit the duration of the burst emission either by causing leakage of electrons from the trap, thus reducing the ratio N_s/N in (1), or by randomizing the directions of motion of the stream electrons, thus inhibiting the generation of coherent plasma waves. The ratio of the energy exchange time to the redistribution time in the corona is so large ($\sim$ 1000 according to formulae given by Spitzer 1956) that the redistribution of pitch angles is probably of greater importance than energy loss in determining the duration of the burst (see below).

(iii) Upward drift of mirror points. Owing to collisions, the average pitch angle of the trapped electrons will increase. There will consequently be, on the average, a steady upwards drift of the mirror points towards an equilibrium condition in which the electrons gyrate with large pitch angles near the tops of the magnetic loops. The burst would therefore finish first at the high frequencies and then at successively lower frequencies, as is qualitatively observed.

As an indication of the times involved in the second process (collisional redistribution of pitch angles), we have computed the deflection time t_{D}, which is the average time taken for pitch angles to be changed by 90° owing to Coulomb collisions, from the formula given by Spitzer (1956), namely,

$$t_{\mathrm{D}} = m^2v^3[8\pi e^4 \ln\lambda\cdot\{\phi(x)-G(x)\}N]^{-1}. \tag{2}$$

In this formula, e and m are the charge and mass of the electron with velocity v; N is the particle density of the plasma; λ is a slowly varying function of density and temperature; $\phi(x) = \mathrm{erf}(x)$, $G(x) = \{\phi(x)-x\phi'(x)\}/2x^2$, with $x = (m2kT)^{\frac{1}{2}}v = v/v_{\mathrm{th}}$. Under the conditions relevant to our problem, $\ln\lambda \sim 25$ and $\phi(x)-G(x)\sim 1$; hence (2) becomes

$$t_{\mathrm{D}} \sim 2\cdot5\times10^{-20}v^3/\bar{N} \qquad \text{seconds,} \tag{3}$$

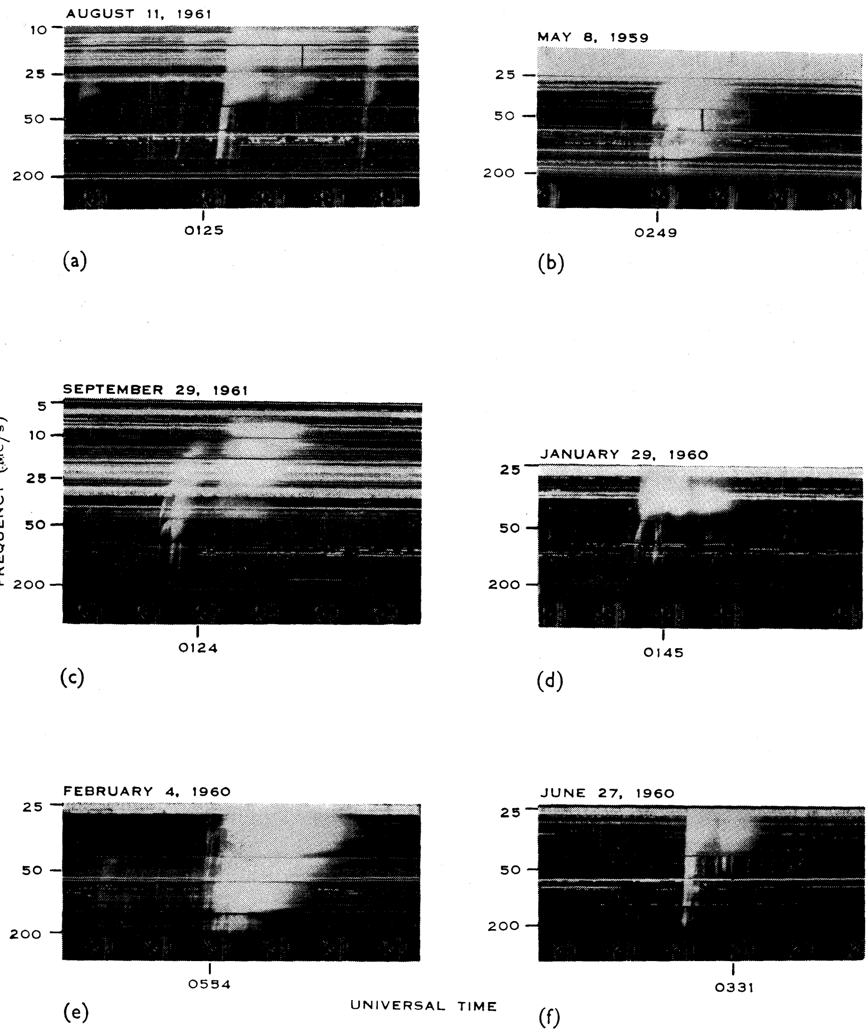
where the density $\bar{N}$ (cm^{-3}) has been taken as the average density over the trajectories of the electrons, and v is in cm/s. In order to estimate the average density of plasma encountered by an electron oscillating between mirror points located near the chromosphere, we have calculated by numerical integration the average particle density along the undisturbed spiral path of an electron gyrating in the magnetic field of a dipole buried $0\cdot 1R_{\odot}$ below the photosphere. The result, $\bar{N} = 6\times 10^8$, 3×10^8, and 2×10^8 cm^{-3} respectively for electrons whose maximum heights correspond to the 100, 40, and 20 Mc/s plasma levels in a Newkirk model active region, is seen to be insensitive to the trajectory of the particle. Taking $v \sim \frac{1}{3}c$ and the above values of $\bar{N}$ we obtain from (3) the redistribution times $t_{\mathrm{D}} \sim 40$, 80, and 120 s for frequencies of 100, 40, and 20 Mc/s. These times are of the correct order for type V bursts (see Fig. 2); they are, however, sensitive to the velocity and would be increased, for example, to $t_{\mathrm{D}} \sim 140$, 280, and 420 s if v were increased to $\frac{1}{2}c$. The abnormally long (duration 10 min) burst of July 14, 1959, described in Section IV, has already been noted as a possible example of a type V burst generated by abnormally energetic electrons.

(c) *U Bursts and Type V Bursts*

The magnetic field configuration of re-entrant loops in our model for the type V burst is similar to that proposed by Maxwell and Swarup (1958) for the guidance of the source of the inverted U burst. This similarity is consistent with the observed close relationship between the two varieties of bursts, to which attention was drawn in Section III(a), and it is interesting to explore the possibility that the two types of burst are due primarily to differences in the injection conditions. At one extreme we have the set of conditions envisaged earlier in this discussion—injection occurring over a large area and over a considerable length of time, perhaps with a large velocity dispersion. The ensuing continuum emission constitutes the type V burst. At the other extreme, the electrons may be injected with high, approximately uniform velocities over a very short interval of time and over a small area; under such conditions the electrons will almost certainly remain bunched over the whole of their first passage along a magnetic loop. If the field intensity where the magnetic loop rejoins the chromosphere is low, the electrons will encounter no mirror point and be lost. The result is an inverted U burst. If, on the other hand, the magnetic field intensity at re-entry into the chromosphere is large, the pulse of electrons is reflected. Scattering occurs unless the electron stream is fast and approximately mono-energetic; since a series of U bursts is never observed, scattering must become important during the second passage along the loop, resulting in an inverted U burst followed by continuum (e.g. Plate 1(b)).

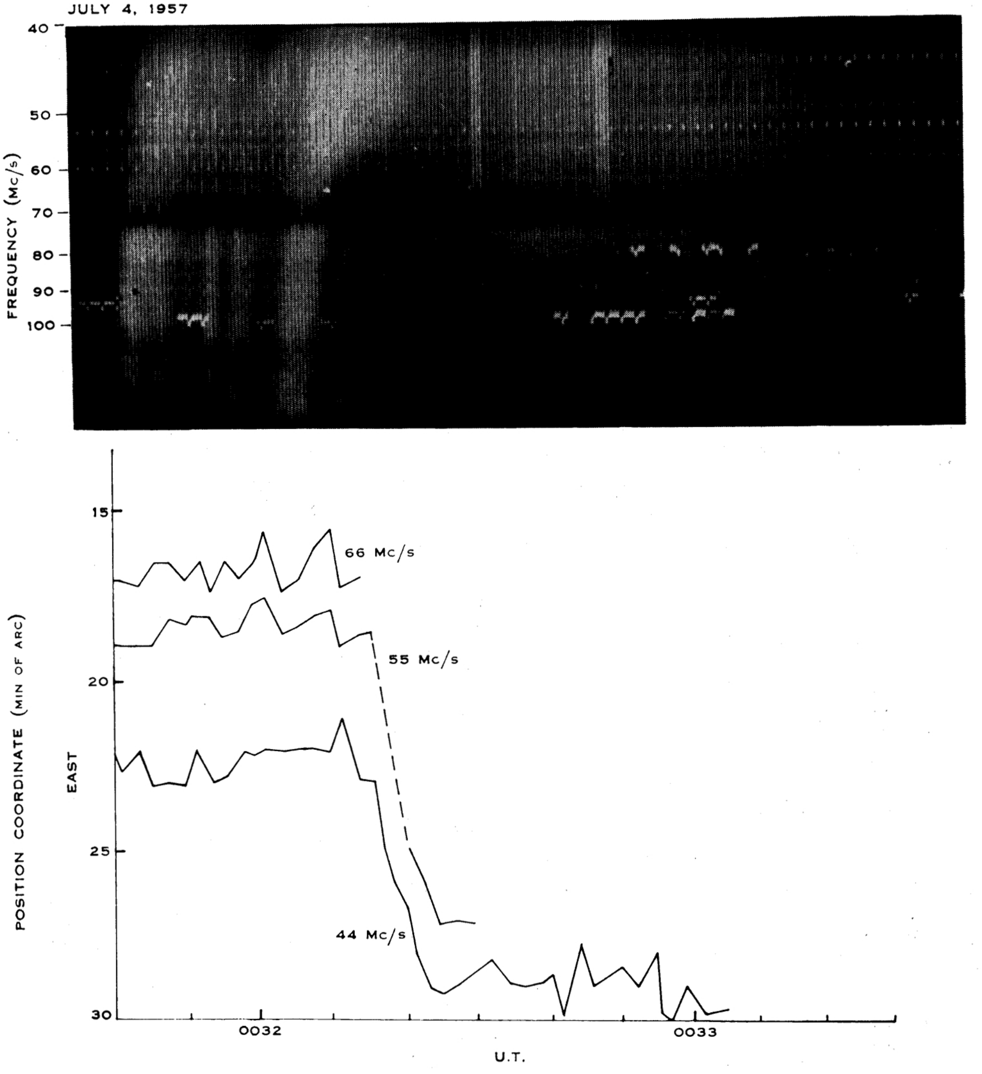
The detached type V burst seems to be a very significant phenomenon for which we have no satisfactory explanation. However, two possible explanations for the detachment of the continuum from the preceding type III burst seem worth mentioning. The time interval between the type III burst and the start of the detached type V burst may represent the time required for the electrons to bunch together closely enough, relative to the coronal plasma, to reach the critical stream density implied by formula (1). Alternatively, it is possible that a detached type V burst is a diffuse, trailing limb of a slow, dispersed U burst.

TYPE V SOLAR RADIO BURSTS



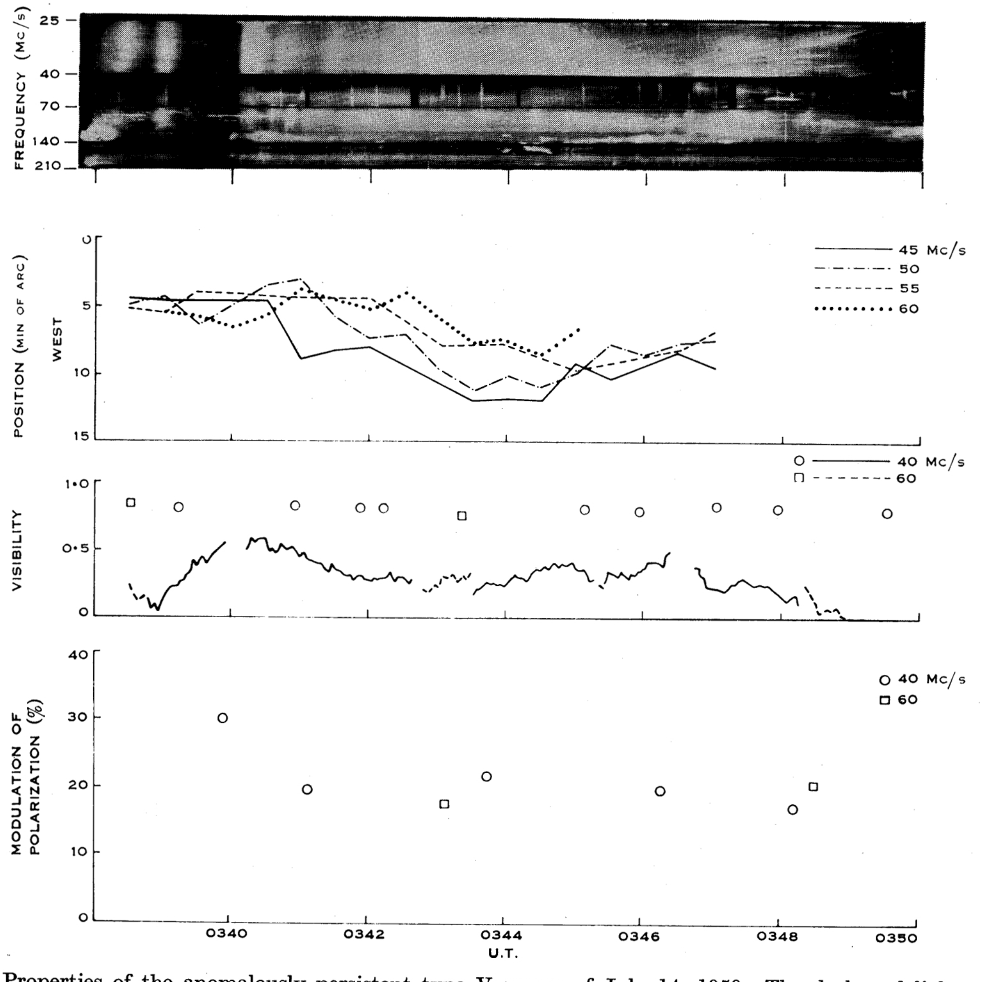
Examples of type V bursts illustrating: *attached* bursts, e.g. (*b*), (*d*), (*e*); *detached* bursts, e.g. (*a*), (*c*), (*f*); a high frequency cut-off remaining steady, e.g. (*a*), (*c*), (*d*), or drifting to higher frequencies, e.g. (*f*); a close relationship in frequency between inverted U bursts and type V continuum with a suggestion of harmonic structure, e.g. (*b*).

TYPE V SOLAR RADIO BURSTS



Example of a detached type V burst in which the high frequency cut-off drifts to higher frequencies, and in which there is a large discontinuity in position between the type III and type V burst. The position coordinate is stable during the type III bursts but suddenly changes to a second stable position as the type V burst appears. Since lobe identification was not available the ambiguity in position was resolved by appeal to the associated flare position (13° N., 23° E.).

TYPE V SOLAR RADIO BURSTS



Properties of the anomalously persistent type V source of July 14, 1959. The dark and light bars crossing the dynamic spectrum are of instrumental origin. The large bandwidth and long duration of this burst may be attributed to excitation by exceptionally energetic electrons. The complex source movements may be associated with two loop-shaped flare brightenings, one eastwards and the other westwards. Full and broken lines in source visibility measurements refer to the long-baseline (1 km) interferometer; open circles and squares, on the other hand, refer to measurements with the short-baseline ($\frac{1}{4}$ km) interferometer.

VI. Conclusion

With the assumption that the electrons producing the type V emission have a similar origin and similar speeds to the type III electrons, we have shown that a model of the type V source in which trapped electrons excite coherent plasma waves is able to account for many of the observed properties of the type V burst. In particular, our model gives a plausible explanation of the several points of similarity between the characteristics of type III and type V sources.

Nevertheless, we are conscious that the model we propose can only be regarded as tentative. The suggestion that the type V source is laterally displaced from the type III source, is one which will be subject to a more satisfactory observational test as two-dimensional brightness distributions become available. This geometrical configuration is, of course, a consequence of the proposed magnetic configuration and does not depend on the hypothesis that the type V continuum originates in plasma waves excited by fast electrons. The recognition of definite harmonic structure in type V bursts, which is hindered by the large bandwidth, would be valuable confirmation of our ideas. In the meantime, a theoretical investigation of the conditions under which a cloud of electrons, gyrating about field lines in a magnetic trap, is able to generate coherent Čerenkov plasma waves is desirable; particular emphasis will be required on the dependence of polarization and intensity on the pitch angles of the electrons, and on whether a broad cone of emission (which is not an inherent characteristic of radiation generated at a critical level) can be produced under these conditions.

VII. Acknowledgments

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