THE SPEED AND ACCELERATION OF THE SOURCES OF TYPE III AND TYPE V SOLAR RADIO BURSTS OVER LARGE DISTANCES IN THE CORONA

By R. T. Stewart*

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Summary

The outward velocity and acceleration through the solar corona of the disturbances responsible for the emission of 50 type III bursts recorded on the Dapto radio spectrograph are investigated by applying standard electron density models for the corona to the frequency drift of each burst. If current models for an active region are assumed, the velocities often remain unchanged from the lower corona out to heights of at least two solar radii above the photosphere. The mean velocity is about $\frac{1}{3}c$. Speeds of sources of type III bursts followed by type V continuum are similar to those for isolated type III bursts.

The constancy of the outward velocity over large distances in the corona implies that the speed of the electrons which constitute the disturbance may reasonably be identified with the observed speed of the source as a whole. If this conclusion is correct, the electron speeds are too low to account for type V continuum by the synchrotron hypothesis of Wild, Sheridan, and Neylan.

I. Introduction

The solar radio burst of spectral type III is characterized by short duration, large bandwidth, and rapid frequency drift. According to the plasma hypothesis (Wild 1950), the frequency drift of the type III burst (most clearly defined by its leading edge) is considered to be due to the outward movement of a disturbance which excites plasma waves of decreasing frequency as it moves through regions of the corona of continually decreasing electron density. The disturbance is thought to consist of a compact pulse of fast electrons ejected from the flare region during the flash phase.

Wild, Sheridan, and Neylan (1959) confirmed the plasma hypothesis for type III bursts by showing that as the disturbance moves through the corona successively decreasing frequencies are emitted from successively increasing heights. Combining interferometer and spectral data, Wild, Sheridan, and Neylan derived outward velocities extending from $0 \cdot 2c$ to $0 \cdot 8c$ with a mean value of $0 \cdot 45c$. Their observations were restricted to the frequency range 45–60 Mc/s. An alternative method of deriving source velocities on the assumption of radial† propagation is to convert frequencies into heights by applying a standard electron density model for an active region. This method has been applied over various frequency ranges by the following authors: Wild 1950; Wild, Roberts, and Murray 1954; Malville 1962; Elgaroy and Rodberg 1963; Hughes and Harkness 1963. These investigations have established the statistical

* Division of Radiophysics, CSIRO, University Grounds, Chippendale, N.S.W.

† Throughout this paper "radial" is used in the heliocentric rather than the geocentric sense.

behaviour of radial velocities over various restricted frequency ranges. If a density model such as the Newkirk model for an active region* (Newkirk 1961) or the 10 $\times$ Baumbach-Allen model (Allen 1947) is assumed, the results agree fairly well with the radial velocities derived by Wild, Sheridan, and Neylan (1959).

When investigations over various frequency ranges are combined there is some evidence for radial deceleration of the type III source with decreasing frequency (Malville 1962; Hughes and Harkness 1963). However, no systematic study showing the behaviour of *individual* type III source velocities with height has been attempted. The Dapto spectrograph records now cover a sufficiently wide frequency range for such a study. Often type III bursts are observed extending from 210 Mc/s to the lowest frequency (around 7 Mc/s), determined by ionospheric absorption (see Plate IV of Sheridan and Attwood 1962). On the Newkirk (1961) model mentioned above this represents a height range greater than two solar radii. The occurrence of a type III burst over such a large frequency range suggests that deceleration of the type III source, if it occurs, cannot be very substantial. Following this suggestion we have studied the variation of radial velocity with height in 50 type III bursts, 10 of which were followed by type V continuum. The latter bursts are of particular interest since it has been proposed that the continuum is due to synchroton radiation from relativistic electrons trapped in magnetic fields high in the corona (Wild, Sheridan, and Neylan 1959). If this hypothesis is correct, we might expect to find evidence of higher source velocities and possibly acceleration with height for type III bursts followed by type V continuum.

II. Measurement of Source Radial Velocity

(a) *The Method of Measurement*

The radial component of velocity v_r was derived from the formula (Wild, Sheridan, and Neylan 1959)

$$t_{f2}-t_{f1} = \left(\frac{1}{v_r}-\frac{1}{c}\cos\alpha\right)\left(R_{f2}-R_{f1}\right)+\tau(\alpha), \tag{1}$$

in which it is assumed that the source moves radially outwards and that all radiation of frequency f originates at the same radial distance R_f from the centre of the Sun. The effect of non-radial propagation will be discussed later. $t_{f1}-t_{f2}$ is the difference in times taken by two signals of frequency f_1 and f_2 to propagate from their points of origin to the observer. This time difference depends on the heliocentric angle α between the path of the disturbance and the Sun–Earth line. The first term on the right-hand side of (1) is obtained from simple geometrical considerations on the assumption that the velocity of propagation is exactly c, while the second term $\tau(\alpha)$, the differential group delay between the f_1 and f_2 signals, is the correction required to allow for departures from this assumption. $\tau(\alpha)$ can become appreciable when the path of propagation passes through regions whose refractive index departs significantly

* Newkirk's model corona is just 4·33 times the maximum equatorial law given by van de Hulst (1950). For heights less than $1R_\odot$ the electron density (cm^{-3}) is given in functional form by $N = 8\cdot27\times10^{4+4\cdot32/\rho}$, where ρ is the distance from the centre of the Sun in units of the optical radius $R_\odot$. For greater heights we have used van de Hulst's tabulated values multiplied by 4·33.

from unity (e.g. near the appropriate plasma level). Evaluation of $\tau(\alpha)$ can be difficult and depends critically on the model atmosphere used (Jaeger and Westfold 1950). Wild, Sheridan, and Neylan (1959) have plotted $\tau(\alpha)$ against $\sin\alpha$ (for $f_1 = 45$ and $f_2 = 60$ Mc/s) assuming the Newkirk model for an active region. Their calculation shows that $\tau(\alpha) \sim \tau(0)$ and is small provided $\alpha \lesssim \frac{1}{4}\pi$, but that $\tau(\alpha)$ becomes large as $\alpha \rightarrow \frac{1}{2}\pi$. However, a precise value of $\tau(\alpha)$ cannot be determined as it depends on assumed propagation conditions in the solar corona. Wild, Sheridan, and Neylan assumed that propagation occurred rectilinearly through a spherically symmetric atmosphere. In the case of type III bursts, however, processes such as scattering from small-scale irregularities in the corona and refraction by a quasi-symmetrical solar atmosphere are likely to be important.

Table 1

CONSTANTS USED IN THE DERIVATION OF RADIAL VELOCITY

For definition of symbols see text

f_1 (Mc/s)	f_2 (Mc/s)	Newkirk Active Region Model			10 × Baumbach-Allen Model		
		$\tau(0)$ (s)	R_{f1} ($R_\odot$)	R_{f2} ($R_\odot$)	$\tau(0)$ (s)	R_{f1} ($R_\odot$)	R_{f2} ($R_\odot$)
135	200	0·09	1·27	1·15	0·14	1·39	1·24
70	120	0·15	1·51	1·31	0·23	1·73	1·44
42·5	70	0·25	1·78	1·51	0·24	2·06	1·73
26	40	0·31	2·16	1·82	0·16	2·40	2·08
16	24	0·34	2·70	2·23	0·28	2·80	2·46
12	16	0·24	3·00	2·70	0·14	3·20	2·80

Because of the uncertainty in the precise value of $\tau(\alpha)$ and the possibility of this correction term becoming appreciable for large values of α, we have selected for study 40 type III bursts with disk longitudes less than $\frac{1}{4}\pi$. However, since type V bursts are observed preferentially from the limb (Wild, Sheridan, and Neylan 1959) 6 of the 10 type V bursts studied had disk longitudes greater than $\frac{1}{4}\pi$. The disk longitudes were determined from the Dapto swept-frequency interferometer records or from associated flare positions on the assumption that the burst position is radially above the flare region. For the 50 bursts studied we have assumed $\tau(\alpha) = \tau(0)$. The value of $\tau(0)$ was calculated by the method of Wild, Sheridan, and Neylan (1959) for the six frequency ranges listed in Table 1, assuming two alternative density models, namely (1) 10 × Baumbach-Allen model (Allen 1947) and (2) Newkirk model for an active region (Newkirk 1961). The two models were chosen for their differing density gradients at heights greater than $1R_\odot$ above the photosphere, where reliable radio observations of electron density are not available. Values of $\tau(0)$, R_{f1}, and R_{f2} for the two density models are listed in Table 1. Of the 50 bursts selected for study only 5 had definite harmonic structure. These bursts were converted to fundamental frequencies, and the remainder were assumed to be fundamentals for reasons given by Wild, Sheridan, and Neylan (1959).

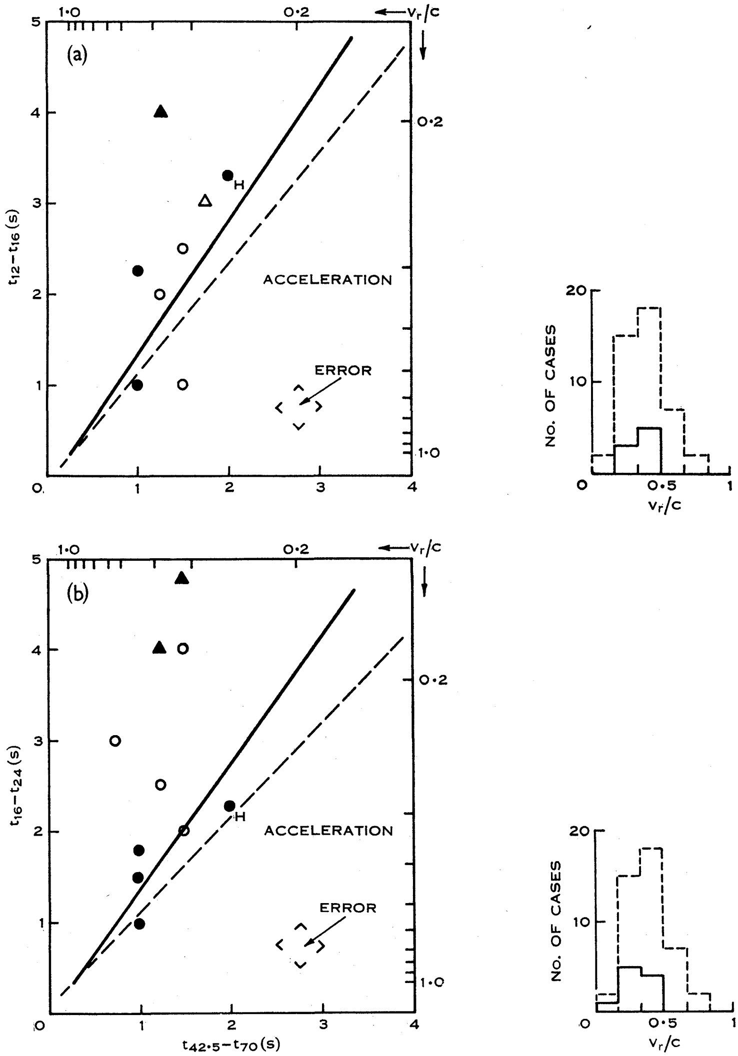
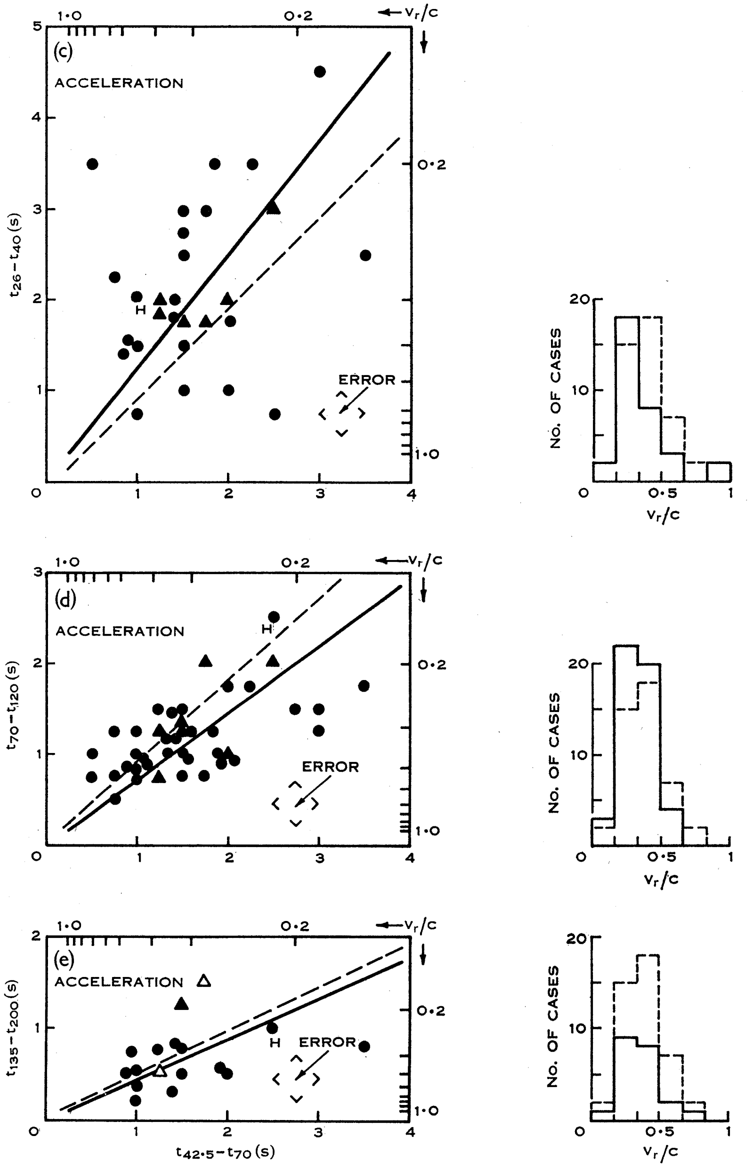


Fig. 1.—Plots showing the statistical behaviour of radial velocity with height. *Left-hand side:* Plots of the observed time delays $t_{f1}-t_{f2}$ against the time delay for the 42·5–70 Mc/s frequency range. The full and dashed lines refer to constant radial velocity v_r on the Newkirk model for an active region and on the $10\times$Baumbach-Allen model respectively. Values of v_r/c shown on the diagrams refer to the Newkirk model. Triangles refer to type III bursts followed by type V continuum, and circles to type III bursts without continuum. Full symbols refer to measurements within reading errors of $\pm\frac{1}{4}$ s while open symbols refer to large errors. H refers to readings taken from bursts with harmonic structure in which case fundamentals were plotted. *Right-hand side:* Histograms (full lines) of radial velocities derived from the observed time delays and the Newkirk model for an active region. In each case the dashed histogram refers to velocities derived for the 42·5–70 Mc/s frequency range. [Fig. 1 *is continued on the opposite page.*]

Fig. 1 (*Continued*)



(*b*) *Statistical Results*

In Figures 1(*a*)–1(*e*) time delays for the five frequency ranges 12–16, 16–24, 26–40, 70–120, and 135–200 Mc/s have been plotted against a sixth range 42·5–70 Mc/s. The last range was selected as abscissa in these plots because it was traversed by nearly all type III bursts used. The diagrams show the statistical behaviour of radial velocity with height. The velocity scales shown on the right-hand side of the diagrams of Figure 1 indicate values of v_r/c calculated from equation (1) using

$\tau(\alpha) = \tau(0)$, cos $\alpha = 1$, and the Newkirk active region model. To show the effect of different density models we have drawn lines of constant radial velocity. The full lines refer to the Newkirk model while the dotted lines refer to the $10 \times$ Baumbach-Allen model. We conclude from Figure 1 that the disturbance responsible for the emission of a type III or type V burst moves, on the average, with a radial velocity approximately independent of height above the photosphere and a mean radial velocity of $\sim \frac{1}{3}c$. Most of the observations in Figure 1 lie within the reading error of the lines of constant velocity. The few points lying outside this region may represent real acceleration or deceleration. Alternatively, they may represent slight departures from the assumed density models. We have excluded from the study any fast frequency-drift bursts such as inverted U bursts which show large radial deceleration often to zero or negative velocities. The distribution of points is similar for type III bursts accompanied by type V continuum (triangles) and for type III bursts without continuum (circles). Because of the magnitude of the reading error ($\pm\frac{1}{4}$ s) our conclusions are almost the same for the two models, even though their densities differ considerably at frequencies less than 40 Mc/s. However, the $10 \times$ Baumbach-Allen model gives a few more cases of radial deceleration than the Newkirk model. The radial velocities derived from the Newkirk model with the $\tau(0)$ and cos α corrections applied to equation (1) for the six frequency ranges are plotted as histograms on the right-hand side of Figure 1. In each case the dashed histogram refers to the 42·5–70 Mc/s frequency range. In every frequency range the majority of velocities lie between $\frac{1}{6}c$ and $\frac{1}{2}c$, again indicating that *on the average* the radial velocity remains constant with height from $0 \cdot 2R_{\odot}$ to $2 \cdot 0R_{\odot}$ above the photosphere and has a mean value of $\sim \frac{1}{3}c$. This result is consistent with previous determinations of radial velocity for type III bursts.

Wild, Sheridan, and Neylan (1959) using interferometer position data to determine $R_{f2} - R_{f1}$ of equation (1), derived values of v_r extending from $0 \cdot 2c$ to $0 \cdot 8c$ with an average value of $0 \cdot 45c$ for the 45–60 Mc/s frequency range. Hughes and Harkness (1962) and Malville (1963) derived radial velocities from the frequency drift rates of type III bursts recorded in the frequency ranges 400–25 Mc/s and 41–9 Mc/s respectively. The former used the $10 \times$ Baumbach-Allen density model and the latter used the Newkirk model for an active region. Hughes and Harkness found velocities of the order of $0 \cdot 4c$, with some evidence for radial deceleration over the 400–25 Mc/s frequency band. Malville derived an average radial velocity of $0 \cdot 24c$ for the 41–9 Mc/s frequency range. Neither Hughes and Harkness nor Malville took into account the $\tau(\alpha)$ correction in their derivation of v_r. This omission would lead to underestimates of v_r, particularly at low frequencies (see Table 1).

(c) *Results of Individual Cases*

So far we have considered only the statistical behaviour of radial velocity with frequency. In Figure 2, values of v_r have been plotted for individual cases. The plots are arranged in order to show the variation of the behaviour of source velocity with frequency in 30 bursts for which v_r was derived over at least three frequency ranges. Corresponding height ranges (assuming the Newkirk model) are also given on the figure. The diagram shows a few cases of radial acceleration and deceleration (top left-hand corner and bottom right-hand corner respectively), and a greater number of intermediate cases in which v_r remains constant or varies irregularly with frequency. Some of this irregular variation is probably caused by reading errors. Examples in which v_r was derived over at least five of the six frequency ranges are replotted in

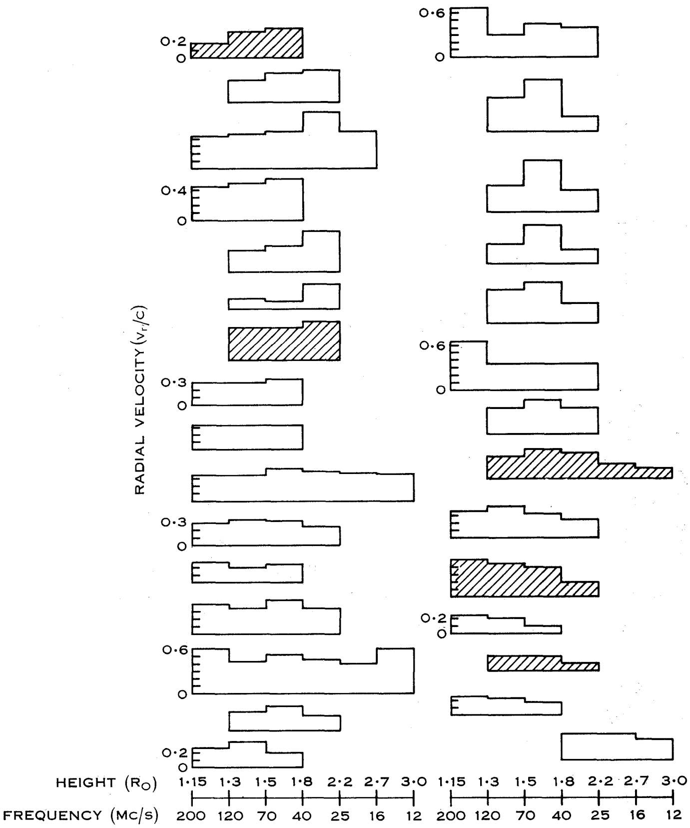


Fig. 2.—Plots of radial velocity for 30 individual type III bursts. The height of each block represents v_r/c. Cross-hatching refers to type III bursts followed by type V continuum. The abscissa gives the frequency range and corresponding height range on the Newkirk model for an active region.

Figure 3, together with the reading errors. In Figures 3(a) and 3(b), v_r remains constant from 200 to 12 Mc/s, that is, from $1 \cdot 15R_0$ to $3 \cdot 0R_0$ above the photosphere. Figure 3(c) may represent slight radial acceleration but the reading errors are quite large. In Figure 3(d) the reading errors are small and there appears to be radial deceleration from 70 to 12 Mc/s.

We conclude from Figure 2 and Figure 3 that the radial velocities derived for individual bursts show a tendency to remain constant over a great range of heights.

III. Discussion

In Section II source velocities were derived on the assumption of radial propagation. Although this assumption is likely to be valid for the majority of cases studied,

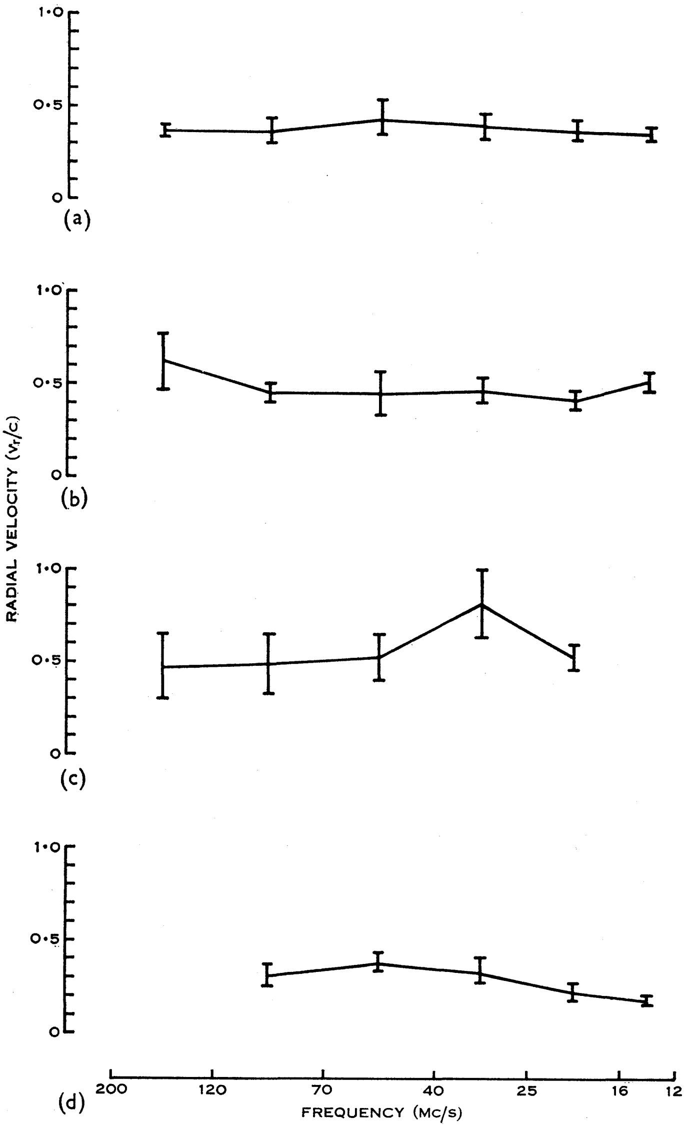


Fig. 3.—Plots of radial velocity against frequency for four type III bursts for which reliable measurements were possible over at least five of the six frequency ranges. Errors are shown by bars.

there is evidence in the scatter of type III positions for occasional departures from radial injection (Wild, Sheridan, and Neylan 1959). However, we infer from Dapto data (unpublished) that type III sources are rarely ejected at angles larger than 30° to the radial direction. Hence the derived radial velocity may be taken as representative of (though on the average slightly lower than) the actual speed of the disturbance. Furthermore, our conclusion that type III disturbances often travel at approximately constant radial velocities over large distances in the corona implies that the paths of these sources are approximately rectilinear. It should, however, be emphasized that we have omitted from the study bursts which show obvious large radial deceleration, and which may be due to the source being guided along a curved path. The few cases of marked radial acceleration and deceleration found in this study may also represent occasions when the escaping path is curved.

Wild, Sheridan, and Neylan (1959) proposed that the type V continuum was due to synchroton radiation from type III electrons partially trapped in the magnetic field high in the corona. Electron energies of at least 2 MeV ($v \geqslant 0 \cdot 95c$) were required to account for the observed intensity. However, we shall show below that the radial velocities derived in this paper ($\bar{v}_r \sim \frac{1}{3}c$) are incompatible with such high electron speeds.

The constancy of the radial velocity of the disturbance with height leads us to consider the speed of the individual electrons which we suppose to constitute the type III source. If the source is guided quasi-radially outwards through the corona by a magnetic field configuration such as that contemplated by Weiss and Wild (1964), the individual electrons can travel faster than the source as a whole, owing to their spiral path. However, if spiralling does occur with substantial pitch angles, the radial velocity of the source could only remain constant if either (1) the pitch angles and therefore the magnetic field remained constant with height, in which case our observations would imply that the magnetic field intensity should often be independent of height over the range $0 \cdot 2R_{\odot}$ to about $2 \cdot 0R_{\odot}$, or (2) if the pitch angles are redistributed by collisions in such a way that the radial velocity of the source as a whole remains constant. It seems extremely unlikely that such special conditions could prevail as commonly as the observations would indicate. An alternative explanation for the constant source speeds, and one more in keeping with our rudimentary picture of magnetic fields high in the corona, is that the motion of the electrons is essentially rectilinear (i.e. the pitch angles are very small) even at heights as low as $0 \cdot 2R_{\odot}$ above the photosphere. In the absence of other deceleration mechanisms, the source speed will remain unchanged to great heights in the corona, even if the magnetic field intensity further decreases to very small values. On this interpretation, the speed of the individual electrons is to be identified with the observed speeds of type III sources, i.e. $\frac{1}{3}c$ on the average. Electrons with these speeds could not account for type V emission by the synchroton mechanism. However, Ginzburg and Zheleznyakov (1958) have shown that a pulse of such electrons can yield the observed type III intensities by the coherent plasma wave mechanism, and this interpretation will be considered in a subsequent paper in relation to type V bursts (Weiss and Stewart 1965).

IV. Acknowledgments

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