PART III

SHOCK WAVES AND PLASMA EJECTION

SHOCK WAVES AND THE EJECTION OF MATTER FROM THE SUN: RADIO EVIDENCE

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Abstract. The passage of shock waves and ejected matter through the solar corona can produce type II and type IV radio bursts. This paper reviews the observations of these types of bursts and their interpretation, with particular emphasis on recent work.

1. Introduction

The first radio evidence of disturbances travelling out through the solar corona came from the observation that some metre-wave bursts were progressively more delayed at lower observing frequencies. With the introduction of the first radio spectrograph by Wild and his colleagues these bursts were recognized as a distinctive type of solar radio burst which became known as a type II burst. The interpretation of this type of burst, since confirmed in a variety of ways, is that a disturbance travelling out through the corona excites the local plasma at each height to radiate at a frequency close to f_p, the local plasma frequency, and also at twice that frequency. Since the electron density law for the corona is known, at least approximately, the variation of frequency with time can be interpreted as an increase of height with time; velocities ranging from about 200 km s^{-1} up to 2000 km s^{-1} or more are deduced. Since these velocities are appreciably greater than the sound velocity in the corona ($\sim$150 km s^{-1}) and greater than or of the order of the probable value of the Alfvén velocity in the corona, it is generally accepted that the disturbance responsible for a type II burst is a collisionless magnetohydrodynamic shock wave.

Important characteristics of the spectra of these bursts are: (a) the relatively narrow bandwidth of drifting ridges of emission, sometimes as little as a few megahertz, although sometimes very much broader; (b) the frequent occurrence of fundamental and second harmonic components (with almost identical features); and (c) the splitting of both the fundamental and harmonic components into two bands $\sim$10 MHz apart for the fundamental, twice as much for the harmonic. For an example see Figure 1. Band-splitting is observed in many type II bursts, but not all.

The most direct confirmation of the plasma hypothesis comes from position measurements with a swept-frequency interferometer by Wild *et al.* (1959) and Weiss (1963); for bursts near the limb of the Sun they found that low frequencies apparently originated higher in the corona than high frequencies. At any one frequency the source did not move. Another piece of confirmatory evidence has come from simultaneous optical and radio observations. A number of cases have been reported of eruptive prominences seen rising above the solar limb at the same time and with about the

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same speed as type II bursts observed in the radio spectrum (Giovanelli and Roberts, 1959; Warwick, 1965; McCabe and Fisher, 1970).

At about the time of the first spectral results (Wild and McCready, 1950; Wild, 1950), Payne-Scott and Little (1952), observing at a single frequency with a two-element interferometer, detected sources moving outward through the corona at velocities of 500 to 3000 km s^{-1}. Some years later, using observations made with the Nançay interferometer at 169 MHz, Boischot (1958) studied similar sources moving at several hundred kilometres per second out to great distances from the Sun. He named these bursts type IV and described them as a broadband emission varying smoothly in time, typically preceded by a flare and a type II burst. Since then it has been recognized that a solar flare event can include a number of broadband continuum phenomena. Because these have all been termed type IV bursts we must use the name 'moving type IV burst' for the radio bursts of relevance to this paper.

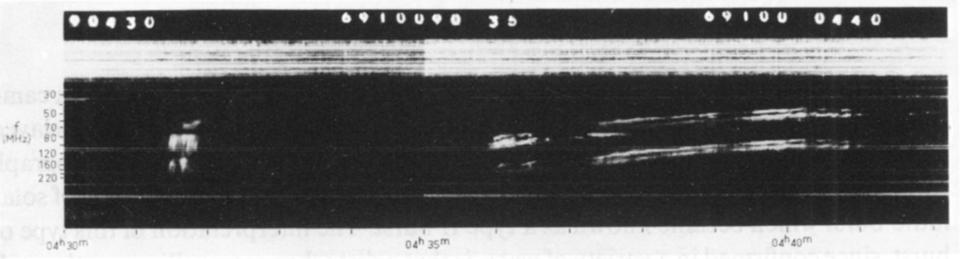


Fig. 1. Examples of a dynamic radio spectrum of a type II burst showing harmonic structure and split bands. At any point on the spectrum the whiteness of the record indicates the intensity of radiation received at that time frequency. Signals at constant frequency are terrestrial interference. (From Smerd *et al.*, 1973.)

Studies of the Earth's magnetic field often reveal periods of perturbation. The sudden commencement of many of these 'geomagnetic storms' is attributed to a disturbance from the Sun impinging on the Earth's magnetosphere. In view of their movement out from the Sun it was natural to investigate type II and type IV bursts and the flares which produce them as a probable cause of geomagnetic storms. Indeed a strong correlation was found. However, I leave further discussion of this subject and of more direct observations of shock waves in interplanetary space for Dr Hundhausen.

Films of the Sun's disk photographed in the wings of Hα occasionally reveal curved fronts, spreading out across the chromosphere from a flare at about 1000 km s^{-1}. This type of event, sometimes known as a Moreton wave, has been interpreted as the skirt of a coronal shock wave made visible by the perturbations it produces in the chromospheric material it passes over (Uchida, 1968; Meyer, 1968). In a number of cases the flares which produced Moreton waves also produced type II bursts (Wild, 1969a, b; Uchida *et al.*, 1973; Uchida, 1973; Smith and Harvey, 1971), and it has been suggested that these two phenomena may be different aspects of the same shock front. I expect that Dr Bruzek will include Moreton waves in his discussion.

2. Type II Bursts

In recent years the Culgoora radioheliograph has literally added a new dimension to observational solar radio astronomy, and most of the new data on type II bursts has come from this instrument. However, before we examine these data in detail, it is as well to recognize the major difficulties encountered in the interpretation of any observations of the positions of type II bursts.

Consider the well-known formula

$$\mu^2 = 1 - f_p^2/f^2,$$

which determines the refractive index μ of an electromagnetic wave of frequency f in a plasma where the plasma frequency is f_p and the magnetic field is so weak that its effects can be ignored (a good approximation for the corona). Clearly near the source of a type II burst the fundamental component ($f \simeq f_p$) will be severely refracted, and even the effect on the second harmonic will not be negligible ($f \simeq 2f_p$). In fact rays traced in simple smooth coronal models show that from the Earth we should not be able to observe fundamental components, except at the centre of the disk, and that near the limb even the second harmonic source should be invisible. Yet limb flares sometimes produce type II bursts for which both fundamental and second-harmonic components are recorded. It has long been assumed (Roberts, 1959) that small-scale inhomogeneities of the corona scatter the radiation above a source into directions along which it can reach the Earth.

The difficulty then is to relate the apparent position and size of a source to the true position and size. The simplest assumption, first introduced by Shain and Higgins (1959) and widely adopted since, is that the net effects of scattering and subsequent refraction tend to cancel, leaving the apparent position close to the true position.

Unfortunately we have little information about the amplitude and scale of the density inhomogeneities which determine the scattering properties of the solar corona. Observations of the angular sizes and scintillation of radio sources occulted by the corona have been used to investigate scattering further from the Sun in the region of the solar wind. By extrapolating these results it is possible for us to make a guess at the scattering properties lower in the corona. Numerical work based on this estimate has been published recently which provides useful statistical data on the probable effects of scattering (Fokker, 1965; Fokker and Rutten, 1967; Steinberg *et al.*, 1971; Aubier *et al.*, 1971; Steinberg, 1972; Caroubalos *et al.*, 1972; Riddle, 1972a, b, 1974; Leblanc, 1973). So far most of these calculations have been carried out for a spherical corona, although Riddle (1972b, 1974) has considered a source on the axis of a coronal streamer. The results of all this work are to suggest that the simple assumption introduced by Shain and Higgins (1959) is misleading. In fact, the apparent position of a fundamental source near the limb, radiating at 80 MHz will lie outside the true position by $\gtrsim 2'$, whereas the second harmonic source will appear inside its true position by a similar amount. Although these calculations are only based on guesses about the coronal inhomogeneities, their predictions are consistent (assuming a point emitter) with observations of the size of type III bursts, and the observed relative positions of fundamental and second-harmonic sources.

A number of earlier deductions were based on the assumption that the apparent position exactly equals the true position: these results should be re-evaluated. They include the high-density electron density law deduced from burst position observations (see e.g. Wild *et al.*, 1963) and the 'backward' emission hypothesis proposed by Smerd *et al.* (1962). Furthermore, in view of the remaining uncertainties, it is hazardous to make any interpretation of the data if that interpretation could be upset by shifting the source position by about 2′.

With these uncertainties in mind we shall now examine some of the results which have emerged from studies of the data from the Culgoora radioheliograph, and consider what clues these results give about the nature of the type II shock front. Because special circumstances have given extra significance to a few particular observations, these will receive special attention.

2.1. EXTENT

It has been suggested (Wild, 1969a, b; Uchida *et al.*, 1973) that when type II bursts and Moreton waves are observed simultaneously they are different manifestations of a single shock wave. If this is the case we should expect the type II source to subtend a very large angle at the flare. Alternatively, since at one frequency we see only the region of intersection of the moving shock front with one plasma level in the corona, we might expect to see a source which moved across the Sun as the outward motion of the shock shifted the point of intersection across the Sun.

Type II sources observed at 80 MHz are often very extensive, $\frac{1}{2} R_\odot$ or more is typical (Wild, 1970a). Since this is much greater than the spread due to scattering, estimated either from the theoretical work quoted above or from observations of the apparent sizes of other types of burst, there is no reason to doubt that these large sizes are real. On occasions too, progressive shifts of a type II burst position have been observed and interpreted as due to shock intersecting the 80 MHz plasma level at an angle (Dulk, 1970a; Riddle, 1970a; Smerd, 1970). The total shift, 4′ or more, is probably sufficient to eliminate the suspicion that it may be due to complicated propagation effects.

2.2. VARIABILITY

On occasions the brightness distribution of type II sources has been observed to vary very rapidly, with a time scale of about 1 s. So far these fluctuations have not been identified with any spectral features, although Wild (1969a) has suggested that these variations might be related to herringbone structure in type II bursts, which also has a very short time scale (Roberts, 1959). Since herringbone structure may be the key which relates the theories of type II and type III emission (Smith, 1971), further study of this matter is desirable.

2.3. Split bands and bright lanes

Type II burst spectra often show fine structure consisting of bright peaks ~10 MHz apart which follow the general drift of the burst. Often two very similar components are observed (e.g. Figure 1) and these are termed 'split bands'. On other occasions the brightness and drift-rate variations of the peaks do not appear correlated and there may be more than two of them; these we term 'bright lanes'. An example is shown in Figure 2. Split bands have received much more attention in the literature than lanes.

There are currently two possible theories of split bands (the reasons for discarding the earlier 'magnetic' and 'Doppler' theories are reviewed by Wild and Smerd (1972)). One theory due to McLean (1967) proposes in essence that parts of the shock front which are parallel to the surfaces of equal electron density will emit intensely at a single frequency whereas the emission from other parts of the shock front will be spread thinly across a range of frequencies. In a simple streamer structure (Newkirk, 1961) there are likely to be two different parts of the shock front which emit intensely at two slightly different frequencies, the amount of splitting being determined by the geometry of the corona.

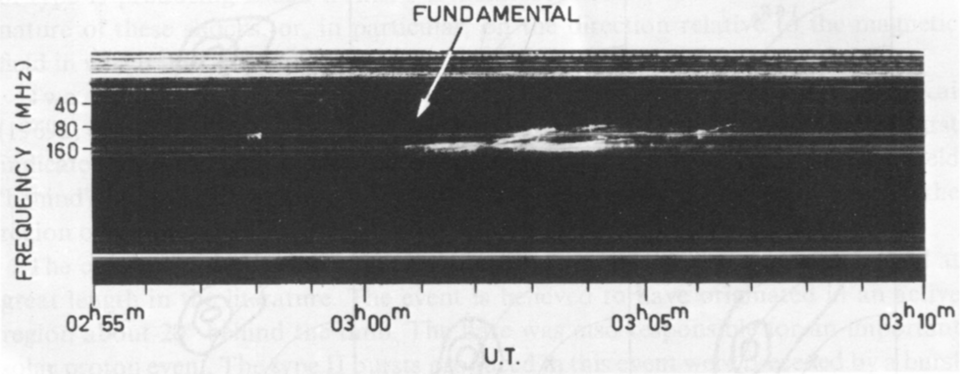


Fig. 2. Spectrum of the type II burst of 1969 October 3 showing multiple bright lanes in the harmonic component. (From Dulk, 1971.)

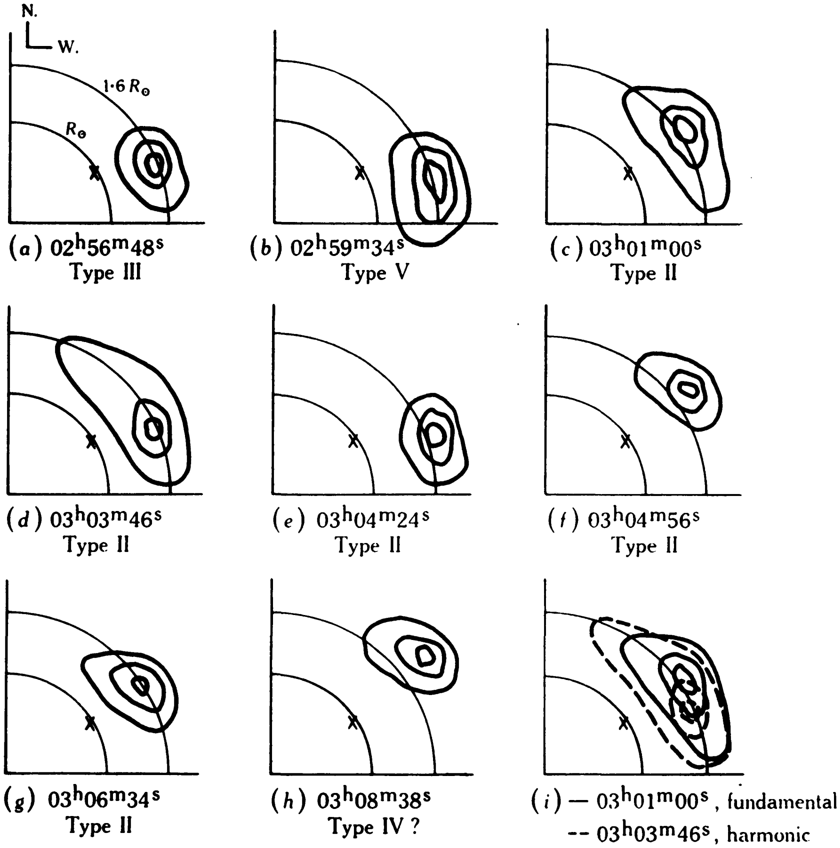
Smerd *et al.* (1973) proposes rather that the two bands of a split-band burst correspond to emission from in front of and behind the shock front. Since the density behind a shock is greater than in front the upper-frequency band comes from behind the lower-frequency band from in front. In this theory the amount of splitting is a measure of the Mach number of the shock; Smerd *et al.* find values in the range $M_A \simeq 1.2$ to 1.7.

Observations of slightly different positions of the two components of split band bursts have been interpreted as evidence in favour of McLean's (1967) theory (Dulk, 1971; Labrum, 1969; Wild and Smerd, 1972). However Smerd *et al.* (1973) point out that we should also expect a shift if both bands were emitted from a single source;

the source will shift appreciably between the times of observation of the two bands at a given frequency, and also for the fundamental component the propagation effects will be different for the two frequency bands.

Unfortunately the number of clear cases of split bands observable at a single frequency (80 MHz) is very small. It is to be hoped that future observations at 43, 80 and 160 MHz with the modified Culgoora radioheliograph may help to choose between these theories.

Figure 3 (from Dulk, 1971) shows the 80 MHz positions of the multiple bright-lane burst illustrated by Figure 2. In these and other cases (Riddle, 1970a; Kai, 1969a) the large shifts between the positions of the different bright lines leave little doubt that different parts of the shock front cause the different lanes. We shall return to the problem of patchy shock fronts shortly.



(*a*) $02^h56^m48^s$ Type III

(*b*) $02^h59^m34^s$ Type V

(*c*) $03^h01^m00^s$ Type II

(*d*) $03^h03^m46^s$ Type II

(*e*) $03^h04^m24^s$ Type II

(*f*) $03^h04^m56^s$ Type II

(*g*) $03^h06^m34^s$ Type II

(*h*) $03^h08^m38^s$ Type IV ?

(*i*) — $03^h01^m00^s$, fundamental
-- $03^h03^m46^s$, harmonic

Fig. 3. Culgoora radioheliograph 80 MHz contours for a number of times during the type II burst of Figure 2. The inner and outer circular quadrants have radii 1 $R_\odot$ and 1.6 $R_\odot$ respectively. (From Dulk, 1971.)

Weiss (1963) noted that position observations of many type II bursts reveal the existence of multiple shocks, propagating in different directions. In some cases it is possible that these multiple shocks are in fact parts of one shock front propagating with different speeds in different directions (Kai, 1969a). It seems quite plausible that other events, such as the very complex event described by Riddle and Seridan (1971), might also fit this interpretation. As multiple bright lanes are a very common feature of type II bursts this interpretation would imply that radiation from a number of different parts of a shock front is typical of this phenomenon.

2.4. REFLECTION AND REFRACTION OR GUIDING

We know the coronal magnetic field and density distributions to be highly inhomogeneous, and it is only to be expected that these inhomogeneities affect the propagation of type-II-producing shock fronts. Furthermore theoreticians do not agree on the nature of these shocks, or, in particular, on the direction relative to the magnetic field in which they propagate (see Dulk *et al.* (1971a) for details).

Two events have contributed to our understanding of this matter. In one case Kai (1969a) drew attention to the fact that the position of components of a type II burst indicated that the shock front had been stopped or reflected by the strong field 'behind' the flare; apparently the type II shock front could not propagate across the region of strong field.

The other case, 1969 March 30, described by Smerd (1970), has been discussed at great length in the literature. The event is believed to have originated in an active region about 20° behind the limb. The flare was also responsible for an important solar proton event. The type II bursts produced in this event were preceded by a burst which outlined half the solar limb (Figure 4): three type II bursts occurred in widely separated locations. (We note the possibility of an extended, patchy shock front consistent with the discussion in the preceding sub-sections.) However, the most significant deduction from this observation is that the shock front must have followed a curved path from the flare to at least two of the sources. Smerd (1970) concludes that the shock was either guided along the coronal magnetic field or refracted by suitable structure in the corona. Furthermore, Dulk *et al.* (1971a) have shown that the shock path was along the coronal magnetic field, whatever the cause of the curved path. The curved path and the propagation along magnetic field lines both seem to be of considerable significance for the theoretical description of type II shock waves.

Dulk *et al.* (1971a) examined the data from a number of other bursts for information about the direction of motion relative to the magnetic field but were unable to draw any firm conclusions. However, they did give other arguments which suggest that type II shocks may travel approximately along the magnetic field: often the position of a type II burst coincides with the positions of associated type III bursts, and the latter are certainly guided along the magnetic field. In addition, type II bursts which extend to very low frequencies (less than 20 MHz, say) must be moving approximately radially outward in a region where the magnetic field is also approximately radial, combed out by the solar wind.

When we recall that the best-developed type II theories assume shocks travelling perpendicular to the magnetic field, the importance of these conclusions is evident.

2.5. INTERPRETATION

Many of the observations discussed in the previous subsections reveal a patchy structure in type II sources. Why do these bursts brighten in some places and miss other regions between the bright parts? It may be because:

(a) refraction of shock waves by magnetic and density structures of the corona

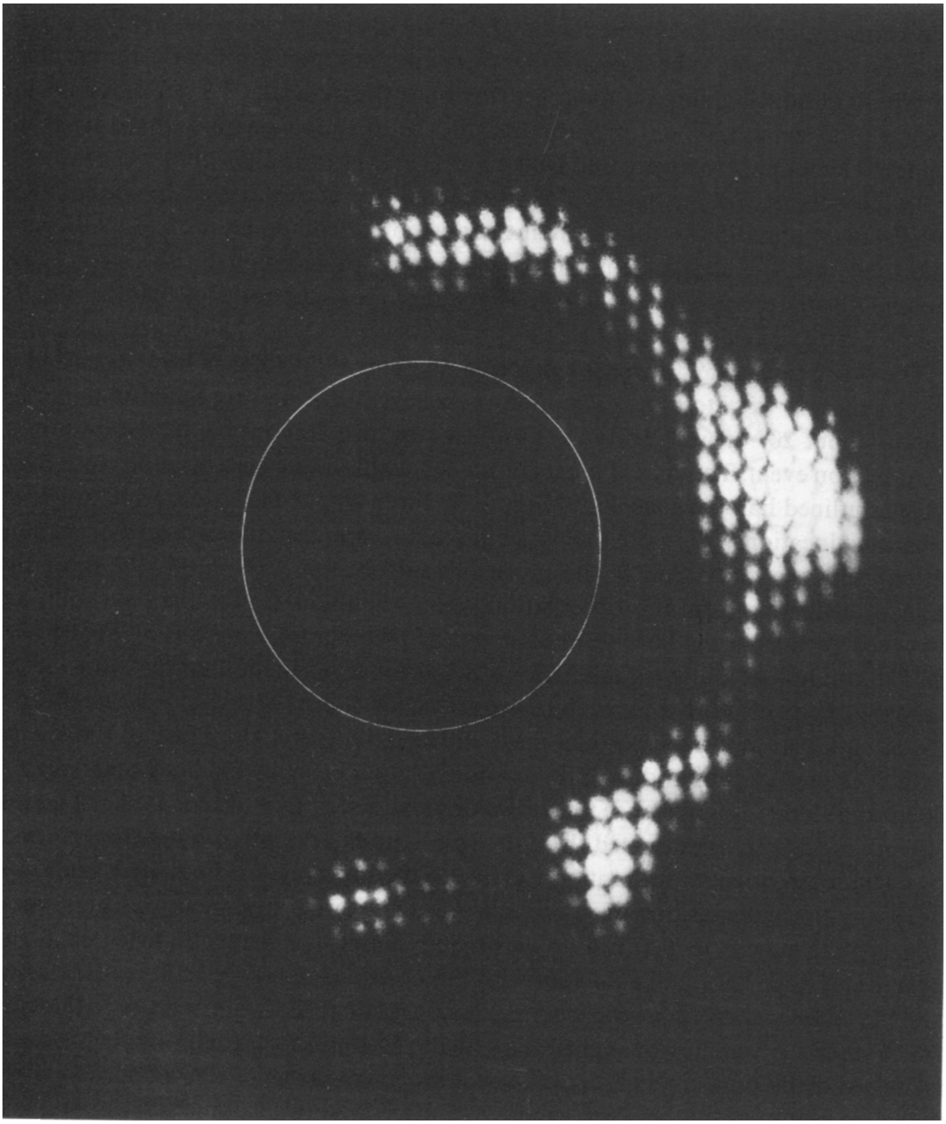


Fig. 4. A radioheligram from the event of 1969 March 30 caused by a flare behind the limb. Later in this event type II bursts appeared in three different places. (From Smerd, 1970.)

channels the shock energy into regions of low Alfvén velocity (e.g. Uchida, 1968, 1970, 1973; Uchida *et al.*, 1973; Smerd, 1970; Kai, 1969a);

(b) the shock is strongest where the Alfvén velocity is lowest and therefore presumably radiates the strongest emission from there (e.g. Dulk and Smerd, 1971);

(c) regions where the shock front is normal to the density gradient radiate intensively at one frequency, whereas the radiation from other regions is spread more thinly across the spectrum (McLean, 1967);

(d) deviations of the corona from spherical symmetry modify the propagation of the electromagnetic radiation to contribute to the uneven appearance of type II sources. However, the fundamental radiation would be affected much more than the second harmonic (e.g. Riddle, 1970a).

These four possible effects are not mutually exclusive, in fact, it seems quite probable that each plays a role. When we succeed in evaluating the relative importance of these different effects, observations of the structure of type II bursts should add to our knowledge of the underlying coronal structure.

Discussing (b), Wild and Smerd (1972) not that regions of maximum density and minimum magnetic field exist along the essentially radial core of coronal streamers; they cite this in favour of type II shocks travelling essentially parallel to the magnetic field.

The approach to (a) being developed by Uchida shows great promise of explaining Culgoora radioheliograph observations (Uchida, 1973). In this approach the shock is treated like a small amplitude magnetohydrodynamic fast-mode wave, propagating at all angles to the magnetic field.

3. Moving Type IV Bursts

A moving type IV can really only be distinguished from the various other phenomena known as 'type IV' with positional observations. Even so there is likely to be doubt about events seen near the centre of the disk.

Fortunately the outward motion of these sources carries them clear of the region of low refractive index. Consequently observations of the position, size and brightness distribution of these bursts are more readily interpreted than for type II bursts. For 80 MHz observations of 12 moving sources, Smerd and Dulk (1971) found that the average distance to which a burst could be followed was about 4 $R_\odot$, where $\mu \gtrsim 0.98$.

The first result of consequence to come from two-dimensional observations with the Culgoora radioheliograph is that the term 'moving type IV' appears to cover a variety of different phenomena – all different manifestations of explosive energy release in flares. The following four types have been recognized.

3.1. MAGNETIC ARCH

Wild (1969c) described the prototype magnetic arch. Essentially it consisted of three sources: an unpolarized source (with polarized edges) marking the apex of the arch and two other sources, strongly circularly polarized in opposite senses, which apparently marked the intersections of the arch with the 80 MHz plasma level. These sources moved apart in a manner consistent with an arch rising in the corona while its feet spread out.

Of the 25 moving type IV sources so far observed at Culgoora and reported in the literature, at most six cases might fit this model, although none of the other cases has the compelling simplicity of the prototype.

3.2. ADVANCING FRONT

The only burst definitely of this type so far observed is the burst of 1968 October 23/24 reported by Kai (1970). However, Kai (1973, private communication) finds that two or three other bursts have features in common with the prototype. Figure 5 illustrates the geometry of this burst. Two type II bursts occurred above a flare a few degrees from the limb. After the second of these, an extended arc-shaped source appeared above the limb and expanded outward, in a continuation of the general outward motion implied by the type II burst. The speeds of the second type II burst, and of the arch were both about 1400 km s^{-1} (Figure 6). The longest-lived section of the arch reached a maximum distance of 2.9 $R_\odot$ from the centre of the Sun. Throughout this event the source was only weakly polarized (<20% LH) – in contrast to the magnetic arch.

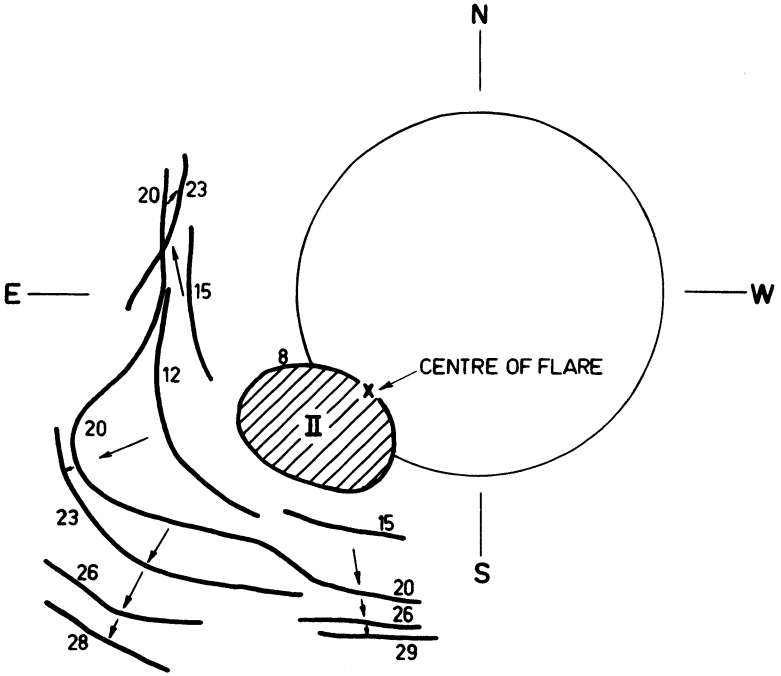


Fig. 5. Summary of radioheliograph observations of the advancing front type IV burst observed on 1968 October 23/24. The shaded area indicates the region of the two type II bursts. The thick lines indicate the ridge line of the extended type IV source for successive times, which are indicated in minutes after the onset of the flare (23^h51^m). (From Kai, 1970.)

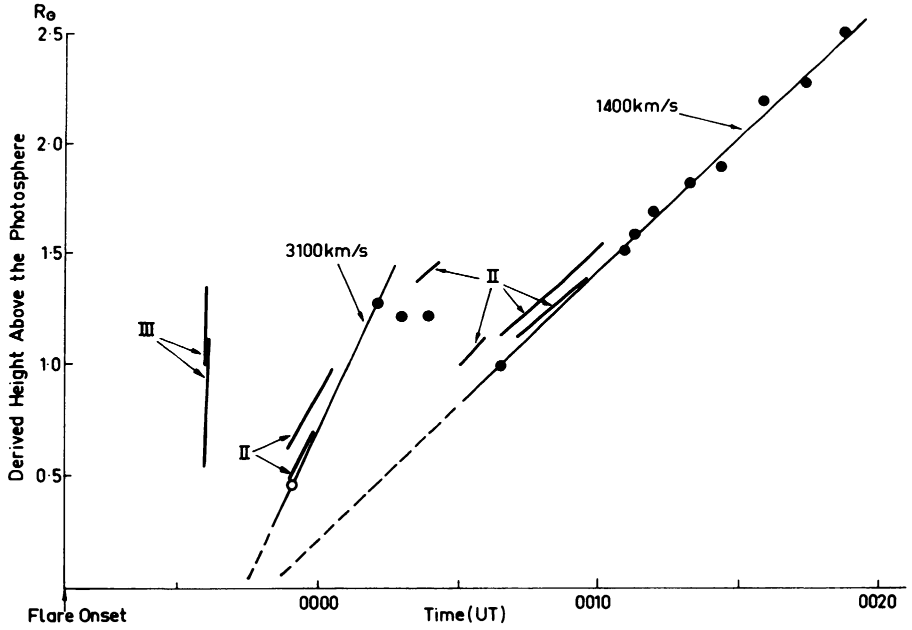


Fig. 6. For the event of 1968 October 23/24 (see Figure 5), comparison of the heights of the type II bursts (derived from the spectrum) and the height of the type IV burst from the heliograph observations. (From Kai, 1970.)

The large extent perpendicular to the direction of motion, the continuity with the type II burst and the lack of polarization appear to be the distinctive features of this burst.

3.3. JET

Another type of burst, of which only one clear example has yet been observed, is the jet described by Riddle and Sheridan (1971). Following a flare and two complicated type II bursts, which appeared at a succession of different positions (Figure 7) the type IV source appeared as a row of bright patches forming a jet. Most of the individual brightenings moved out along the jet, as shown by Figure 8. On a number of occasions the components of the jet brightened in rapid succession, each one doubling its brightness for a second or two. This whole sequence lasted about 7 s. These brightenings have been interpreted as due to bursts of electrons travelling with speeds ~0.5 *c* along the jet and radiating brightly from each source. This interpretation resembles the type IV model of Warwick (1968).

Both the unusual source geometry and the sequential brightenings suggests that this jet is a distinct type and not just a variant of the most common type, 'the isolated source', which will be described in the following paragraph.

3.4. ISOLATED SOURCE

This term, introduced by Smerd and Dulk (1971), also covers many cases in which

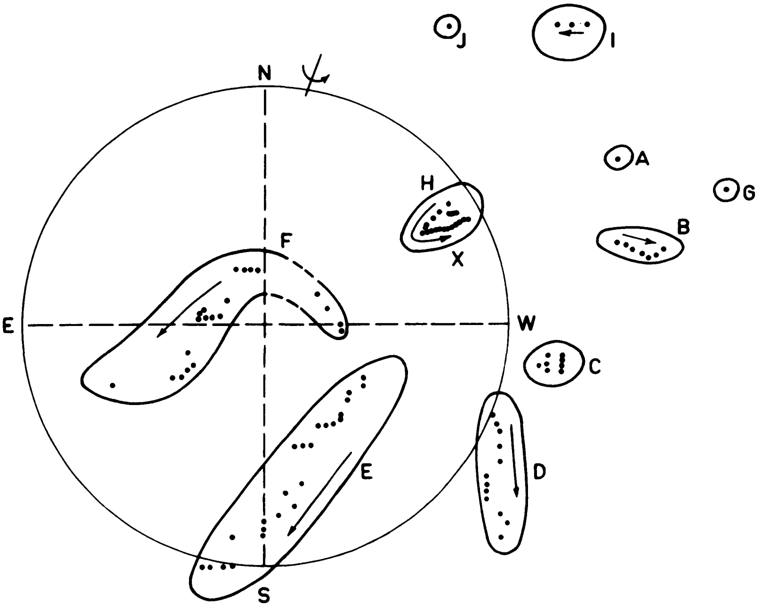


Fig. 7. Centroid positions of the many sources observed during the early phase of the event of 1971 January 24/25. Most of the positions refer to type II bursts. The letters indicate approximately the sequence in which the sources appeared and the arrows indicate the direction of apparent movements. (From Riddle and Sheridan, 1971.)

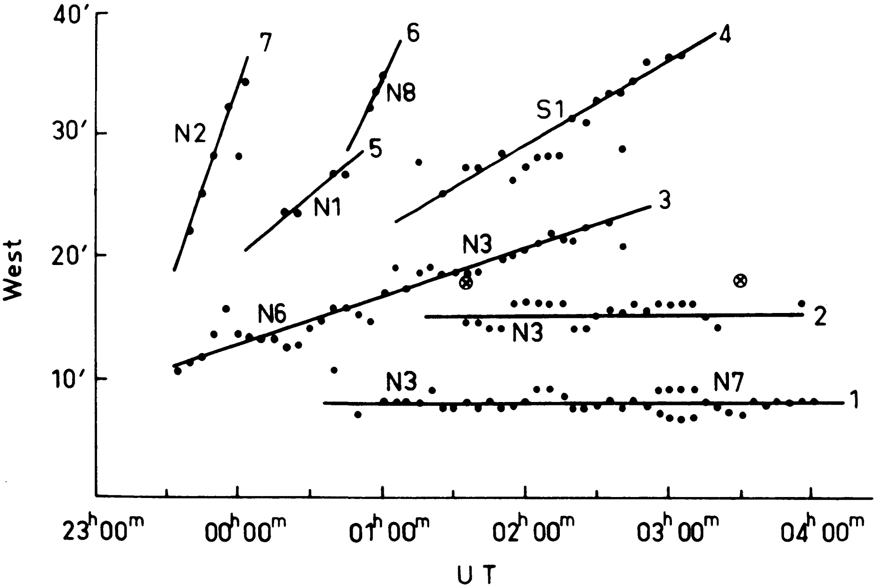


Fig. 8. Position west of the solar centre as a function of time for the sources (numbered 1 to 7) of the jet observed 1971 January 24/25 immediately after the type II burst of Figure 7. The north-south coordinate in minutes of arc is indicated by symbols such as N3. Two type III bursts are indicated by a circled cross. (From Riddle and Sheridan, 1971.)

the source is observed to break up into a number of sources moving with similar velocities. The majority of moving type IV bursts appear to fit this classification; we shall look briefly at two examples.

Sheridan (1970) reported observations of a type IV burst out to a record distance of more than 6 $R_\odot$ (exceeding the 5 $R_\odot$ reported by Riddle (1970b) for 'Westward Ho'). The event started with a flare seen on the disk, and an ejected prominence seen beyond the limb in Hα. Shortly afterwards a stationary unpolarized source (flare continuum) appeared above the position of the prominence. After this had faded another, polarized, source appeared in about the same position and moved out at a steady speed of about 290 km s^{-1}. As it moved the degree of polarization increased from 30% RH to about 90% RH. Late in the event the source split into four, all RH polarized and all moving slowly apart. By the time the furthest source reached 6 $R_\odot$ they were all fading rapidly and could not be followed any further.

For a second example I have chosen the burst of 1970 April 19, described by Dulk and Altschuler (1971). From Figure 9 we can see the general sequence of events. The flare occurred at 56°E, 10°S starting at 00^h47^m UT. A group of type III bursts, a possible type II burst and a flare continuum occurred above the flare. The flare continuum remained approximately stationary for a few minutes, then started to move out at an average projected velocity of 880 km s^{-1}. A storm continuum source (sometimes called stationary type IV) appeared later above the flare site. Figure 10

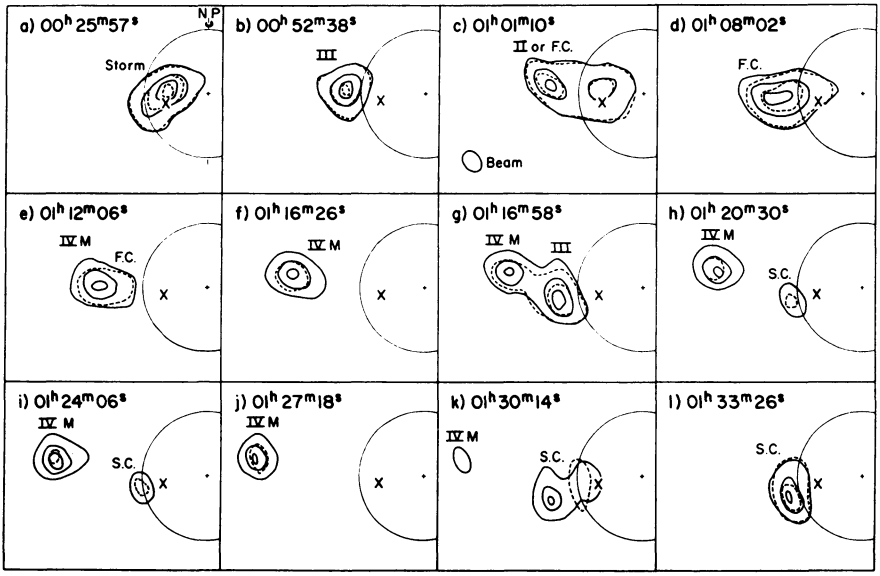


Fig. 9. Contours of radio brightness from the Culgoora radioheliograms for the event of 1970 April 29. The flare position is shown by a cross. Dashed and full lines refer to RH and LH circular polarization respectively, both normalized to the brightest point in the LH image. The symbols II, III, IVM, FC and SC denote the types of bursts: type II, type III, moving type IV, flare continuum and storm continuum respectively. (From Dulk and Altschuler, 1971.)

shows the path of the moving type IV source and also the slight motion of the storm continuum source. Figure 11 shows the variation with time of the flux density and the degree of circular polarization of the main sources. These curves are characteristic of this type of burst, particularly the rapid fading of the type IV burst (in this case three decades in 12 min) and the progressive increase of the degree of polarization up to a maximum of about 80%. The rapid fading limits our ability to follow these sources to great distances from the Sun, but generally there is no indication of slowing down

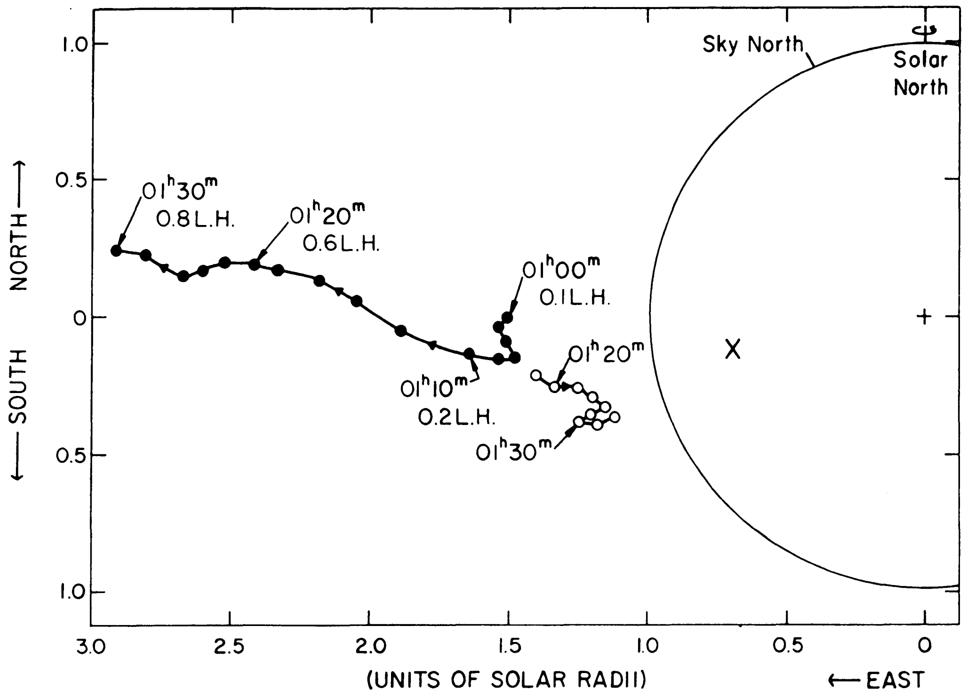


Fig. 10. The path of the centroid of the moving type IV bursts (filled circles) and of the continuum (open circles) for the event of Figure 9. The flare position is marked by a cross. (From Dulk and Altschuler, 1971.)

of the sources as they fade. The appearance of the storm continuum source late in the event is also typical, although the short life of this particular continuum source is atypical – several hours' duration is more normal.

One point of conflict with Boischot's (1958) original observations should be noted. He described sources as moving out and then falling back to a position close to the Sun. From the observations just described and a number like them it seems possible that Boischot really observed a moving source which kept moving out but faded rapidly, and a stationary source which appeared at about the same time as the moving source faded. With one position every 4 min in one dimension only it might be difficult to distinguish between these two possible interpretations.

Although the essentially linear motion of the two examples I have chosen is

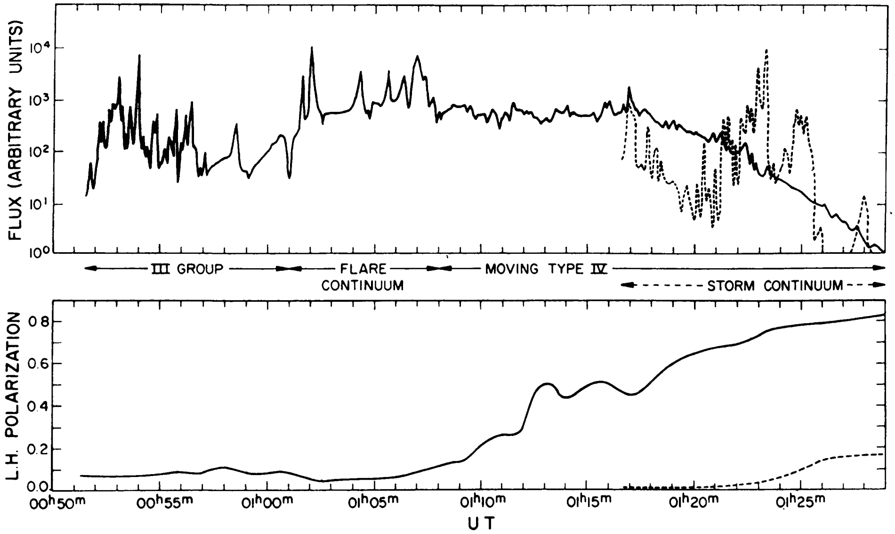


Fig. 11. Flux density and polarization of the sources of Figures 9 and 10, recorded at 80 MHz with the Culgoora radioheliograph. The dashed curves refer to the storm continuum. The other burst types are as indicated. (From Dulk and Altschuler, 1971.)

typical of most 'isolated-source' bursts there have been cases where the trajectories showed significant curvature (e.g. Smerd, 1971) or even where the movement was largely around the limb rather than radially outward (Dulk *et al.*, 1971b).

3.4.1. *The French Burst*

Although four categories seem adequate for the observations made at 80 MHz with the Culgoora instrument, there is one observation, made at Nançay at both 169 and 408 MHz, which appears to merit separate consideration. The special features of this burst (Boischot and Clavelier, 1968) are that it started suddenly and simultaneously at both observing frequencies at a great height above the photosphere (1 $R_\odot$). Both frequencies were emitted from the same source, which moved to a height of 2 $R_\odot$ above the photosphere. The spectrum of the burst had very sharp cut-offs on both the high-and low-frequency edges.

The interpretation of these features given by Boischot and Daigne (1968) and Lacombe and Mangeney (1969) is as follows. The common position for the two frequencies is consistent with the normal synchrotron interpretation, although the sharp low frequency cut-off is taken to indicate that the plasma inside the source had suppressed the low frequencies (Razin-Tsytovich effect). The sudden start at a great height is interpreted as indicating that the electrons were accelerated in situ at this height. Lacombe and Mangeney (1969) developed a shock wave model to explain this. In their model the shock wave was capable of accelerating electrons to MeV energies for only a critical range of Mach numbers, which only occurred between the heights of 1 and 2 $R_\odot$. However, Smith (1971) has criticized this model. He finds that general heating of the electron gas will occur, rather than acceleration of a select few electrons. Mangeney (1974) has since developed another theory for accelerating relativistic electrons, this time in a parallel shock, which avoids this criticism.

3.4.2. *Interpretation*

Smerd and Dulk (1971) found that it is not always possible to decide the classification of a particular event with certainty. Nonetheless the four classes just described appear to be adequate to cover all the bursts so far observed at Culgoora. (I have added the jet to the three classes considered by Smerd and Dulk; the classification of the French event as an advancing front relies on rather uncertain theoretical considerations, as discussed above.)

Since these very different phenomena all represent some sort of disturbance moving out through the corona it should be instructive to examine the similarities and differences. Since all have sources which move out to a considerable distance from the Sun – well above the 80 MHz plasma level – it has generally been accepted since Boischot and Denisse (1957) that the only possible emission mechanism is synchrotron emission from energetic electrons spiralling in a magnetic field. However, as first pointed out by Kai (1969b), the very strong circular polarization observed in the late stages of many isolated sources is a difficulty with this interpretation.

A relativistic electron, velocity βc, radiates most strongly in about the γ^3-th harmonic of its frequency of gyration, f_g/γ, where the Lorentz factor γ is $(1-\beta^2)^{-1/2}$ and f_g is the gyro frequency for non-relativistic electrons ($f_g(\text{MHz}) = 2.8B$ (gauss)). But radiation in high harmonics is generally linearly polarized whereas low harmonic radiation appears strongly circularly polarized if viewed approximately along the magnetic field. Hence for strong polarization we must assume subrelativistic electrons, i.e. electrons with $\gamma \lesssim 2$. But this leads to a major difficulty; these electrons will not radiate much at frequencies above $4f_g$, and so to explain observation at 80 MHz we must suppose that $f_g \gtrsim 20$ MHz or $B \gtrsim 6$ G inside the source. Particularly at the extreme distance of 6 $R_\odot$ for the record holder (Sheridan, 1970), this field is well above all the best estimates of coronal magnetic field strength (e.g. Newkirk, 1971).

Hence there seems little choice. Until someone can propose a reasonable alternative to synchrotron emission of the radiation it seems that the moving sources must carry their own strong magnetic field with them. Of course, there is no suggestion that this structure should be stable. On the contrary, a number of authors have studied the evolution of expanding sources (e.g. Dulk, 1970b, 1973; Schmahl, 1972) and I believe Dr Dulk will be presenting a recent model of this type which successfully explains many of the observed characteristics, particularly the rapid fading and the simultaneous rise in polarization.

However, a second problem still remains to be faced: for the very high degrees of circular polarization recorded the source must be viewed along the magnetic field to within say 45°. This is a statistically unlikely orientation which should only occur in about 30% of cases, yet polarization degrees higher than 70% are reported for well over half the isolated sources so far recorded. This orientation is even more unlikely if we consider that the synchrotron emissivity of a source containing an isotropic distribution of electrons is peaked in the plane normal to the magnetic field. An anisotropic electron distribution would shift the emission peak away from the direction where the polarization is least, but it is believed that such distributions are unstable to whistler emission. Even stronger magnetic fields (and less energetic electrons) could be invoked, but the field strengths are already embarrassingly high.

Of course the problem of explaining the frequent observation of very high degrees of circular polarization would probably apply equally to any other emission mechanism which might be proposed as an alternative to synchrotron emission. Taken in isolation it seems to require a peak of emission along the direction of the magnetic field.

In the case of the magnetic arch, it seems obvious to follow Wild (1969c) and assume a different emission mechanism for the polarized feet of the arch, which appear near the plasma level and the unpolarized apex.

Similarly the shock wave character of Kai's (1970) expanding arch seems obvious both from its large extent at right angles to the direction of motion (Figure 5) and its continuity with the type II burst. Nonetheless the great height reached by the longest-lived part of the arch seems to rule out any mechanism other than synchrotron emission.

There is no mystery about the end of type IV bursts. As mentioned already, their rapid fading makes them impossible to follow further, although there is generally no indication of deceleration as they fade. The current idea is that the fading is a consequence of the expansion of the source. However, the breaking up into a number of separate sources of the same (e.g. Sheridan, 1970; Smerd, 1971) or opposite (e.g. Riddle, 1970b) senses of polarization is an interesting complication which has not yet received much attention.

3.4.1. *A Link With Type I Storms*

I should like now to present briefly a recent observation made at Culgoora with the radioheliograph observing at both 80 and 160 MHz. This event, described by McLean (1973) has a number of interesting features which can be summarized as follows (see Figure 12).

(a) The event was initiated by a prominence which was observed to rise above the limb.

(b) The first phase of the radio event was a type I storm observed with the Culgoora spectrograph. As the prominence rose higher in the corona the type I storm spread to lower frequencies. The 80 and 160 MHz emission during the type I storm came from different heights above the limb, presumably determined by the plasma levels.

(c) The storm moved some distance around the limb, then faded. As it faded a faint moving type IV source appeared, with both frequencies coming from near the last observed position of the 80 MHz storm.

(d) The moving type IV source moved out along a radial path. The sources at the two frequencies did not coincide exactly.

I have brought this observation in at this stage to show that type I emission may

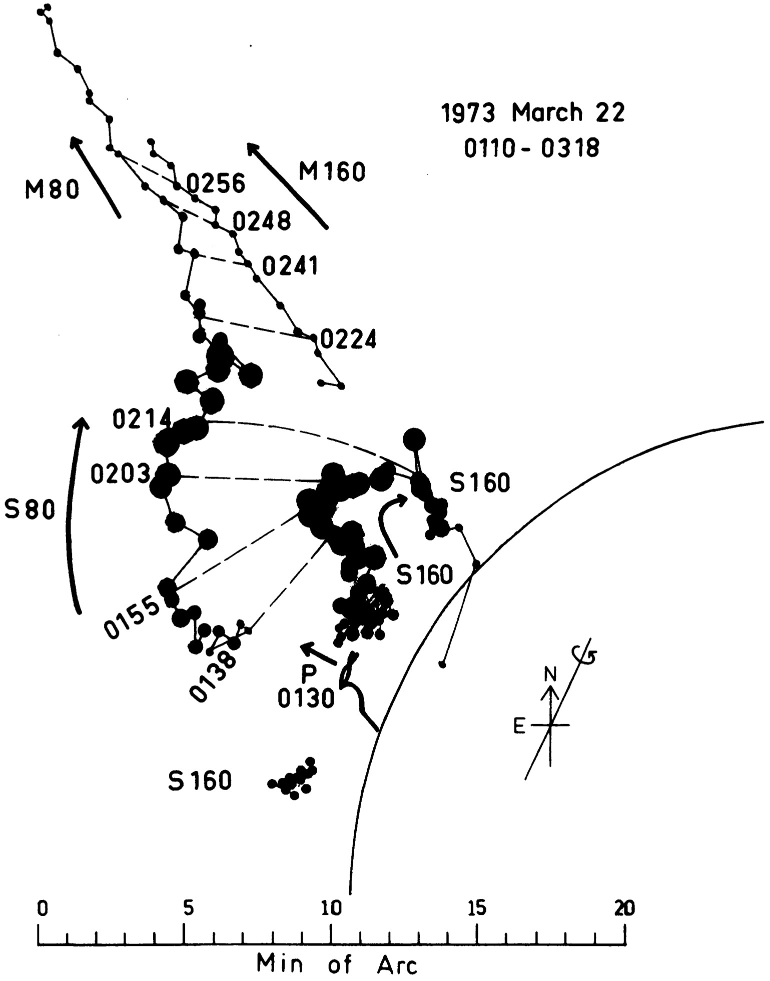


Fig. 12. Paths of the centroids of sources observed during the event of 1973 March 22. Each dot represents the position of the centroid of a radio source; the area of the dot is proportional to the flux density. S80 and S160 are the 80 and 160 MHz components of the first, storm part of the event, and M80 and M160 the components of the moving source. The appearance of the ascending prominence at 01^h30^m UT has also been shown (labelled P). Some of the almost simultaneous observations at the two frequencies have been joined by broken lines and the time of these observations are indicated. Successive positions at each frequency have been joined by full lines, and the direction of motion indicated by heavy arrows. To avoid confusion only one record in 56 has been used for this figure (i.e. the dots are at intervals of 56 s). (From McLean, 1973.)

also be associated with the ejection of matter from the Sun. We have had other, less direct evidence of this for some time. Le Squeren (1963) found that noise storms started or increased in activity about 1 h after a flare. So called stationary type IV bursts are probably just examples of this result. In addition, Wild and Zirin (1956) observed another probable type I event associated with a rising prominence. However, this aspect of the observations does not appear to have been included in any theoretical work.

4. Conclusion

Radio observations of the Sun reveal two main phenomena indicative of ejection from solar flares: type II and moving type IV bursts. Although the broad outlines of the interpretation of these phenomena are well established we have much to learn before we can really claim to understand them.

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DISCUSSION

Sturrock: A simple interpretation of the blast-wave theory of type II bursts leads one to expect radiation over a wide range of frequency, namely the range of plasma frequency corresponding to the wide range of height covered at any one instant by the blast wave. This is very different from the typically narrow frequency band of a type II burst.

McLean: Emission occurs preferentially where the shock front is parallel to the electron density contours. Also, as Uchida has shown, the emission is not really a spherical wave but occurs predominantly in regions where Alfvén velocity is low.

Smith: Also, on this point, it is not inconsistent that we start out with a blast wave because we only get type II emission when special conditions are satisfied, such as the Mach number being high enough.

On another matter, an alternative explanation for 'winking' phenomena in type II bursts is that special conditions are required for emission such as the angle between the plane of the shock and the magnetic field lying in a narrow range. Is there any observational evidence to favor the hypothesis that 'winking' is related to 'herring-bone' over the above explanation?

McLean: As far as I know, no.

Kai: I would like to comment on some points in the shock wave – moving IV relation. I have reached the following conclusion from a statistical study of about 30 IV(M) which were observed at Culgoora. There are at least two kinds of IV(M): high velocity ($\gtrsim 1000$ km s^{-1}) ones, which are unpolarized and rarely observed and have close association with shock waves, and the low-velocity (~ 400 km s^{-1}) type IV's, which are strongly polarized and have no direct association with shock waves. The majority of IV(M) fall into this second class. I suggest, therefore, (and this is supported by other observational evidence) that most IV(M) are caused by low-velocity material which possibly moves along open magnetic field lines above a closed helmet structure of magnetic fields. Secondly, IV(M) are not as energetic events as we previously thought. Even minor sub-flares can often produce IV(M) bursts, IV(M) are hardly associated with the proton events measured in interplanetary space.

Maxwell: Can you clarify something about the March 30, 1969 burst? The original emission was over 180°. Was the burst due to type IIIs or, if not, what was its origin?

Smerd: The early wide spread of the 80 MHz burst sources in the 1969 March 30 event can be explained if the radiating electrons reached the source regions along similarly widespread magnetic-field lines from an explosive center behind the west limb.

Maxwell: Was this burst unusual?

Smerd: Dulk *et al.* (1971a) showed that the large-scale coronal field (as computed from the observed photospheric field) was remarkably constant over three solar rotations – including that of March 1969 – in spite of a number of major flare events during that period. The large-scale field was characterized by an unusually widespread network from the explosive center to 'all points on the Sun'.

Uchida: I understand that the harmonic-band copies most of the structures in the fundamental. Is the herringbone structure in the fundamental also copied in the harmonic band? I think this point is pretty important in understanding the production mechanism of harmonics, whatever it may be.

Smerd: Yes.

McLean: The major features certainly occur together in both fundamental and harmonic; fine details are probably repeated too.