7. RADIO OBSERVATIONS OF SOLAR FLARES

By J. P. Wild

The intense bursts of solar radio emission at the time of flares(1) are received at the earth over an enormous range of frequencies extending from about 10 Mc./sec. ($\lambda = 30$ m.) to about 30,000 Mc./sec. ($\lambda = 1$ cm.). The highest of these frequencies escape from relatively dense (chromospheric) layers of the solar atmosphere, while the lowest frequencies can escape only from the tenuous outer layers of the corona. Use of the whole available frequency range offers a potential means of exploring the solar atmosphere in great depth. Attempts to interpret the radio data(2-6) have thus far been confined mainly to the lower frequencies below about 300 Mc./sec. This account is restricted to these coronal frequencies, and will be mainly concerned with recent work at Sydney where special techniques have been used to exploit them.

During the past three years the dynamic spectrum of the Sun has been studied(5,6) in the range 40–240 Mc./sec., which explores the corona out to roughly $1 \cdot 5\ R_0$. In its most complete form, the outburst in this frequency range appears to consist of two discrete phases followed by prolonged storminess. The first phase starts near the very beginning of the optical flare and lasts for about 1 min. The second phase starts a few minutes after the beginning of the flare and lasts about 10 min. A similar time sequence is suggested by Helen Dodson's work at the McMath-Hulbert Observatory where many 200 Mc./sec. events were compared with detailed light curves(7). We find that each discrete phase exhibits a characteristic type of dynamic spectrum. More is known about the second phase which will be discussed first.

The onset of the second phase is heralded by the sudden appearance of one or more intense emission bands at a frequency of the order of 100 Mc./sec. These bands, which are sometimes superposed on a diffuse background continuum, may be accompanied by their harmonics at double the frequency. With the passage of time they gradually drift in unison towards the lower frequencies—the 'type II' dynamic spectrum (see Fig. 2). We believe this drift to be due to the outward motion of a disturbance (presumably a cloud of ionized matter) exciting plasma oscillations of decreasing frequency as it passes through successively more rarefied layers of the corona. Plasma oscillations are inherently non-linear, and the observation of harmonics strongly supports this interpretation. Also, if due to plasma oscillations, the fundamental band should exhibit pronounced absorption in its low-frequency skirt; this absorption is, in fact, observed.

The approximate heights of different plasma levels are known from optical eclipse values of coronal electron densities; hence the outward radial component of velocity can be estimated from the frequency drift. In typical cases this velocity is about 500 km./sec. Convincing corroboration of this result is provided by the work of Payne-Scott and Little(4) who followed the position of outburst sources across the solar disk; they found the source to appear initially close to the flare and subsequently move at a rate consistent with an outward radial motion of the order of 1000 km./sec.

Turning now to the first phase, we find the dynamic spectrum to consist of a rapid succession of short-lived 'type III' bursts, often superposed on a diffuse background continuum (Fig. 3). Such bursts, which are also observed intermittently at times other than flares, consist of an emission band which sweeps across the spectrum some hundred times faster than the drift rate of type II bursts. Similar harmonic characteristics are observed, suggesting again the outward motion of ionized streams exciting the plasma frequencies. In this case the velocities are very high—3×10^4 to 10^5 km./sec.

When both first and second phases of an outburst are present (Fig. 4), the whole phenomenon can be simply explained in terms of the ejection of corpuscular streams at the two very different velocities from a common 'explosion' near the base of the corona. The slower of the two velocities lies in the low supersonic range and could possibly be associated with a shock wave emanating from the explosion. This explosion would occur right at the start of the flare and may well be its initiating event.

The possible correspondence between these two classes of ejection and those inferred

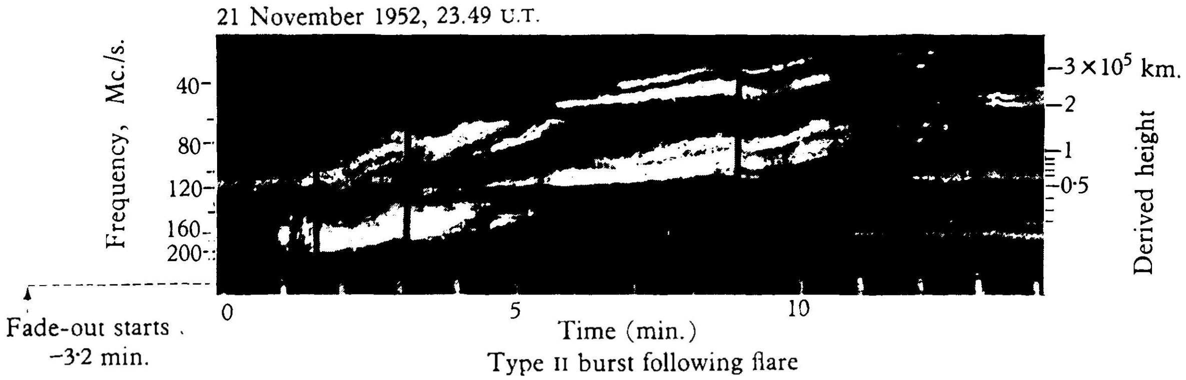

Fig. 2. The dynamic spectrum of the second phase of an outburst (the first phase was absent in this event) showing complex, drifting emission bands at both fundamental and second-harmonic frequencies.

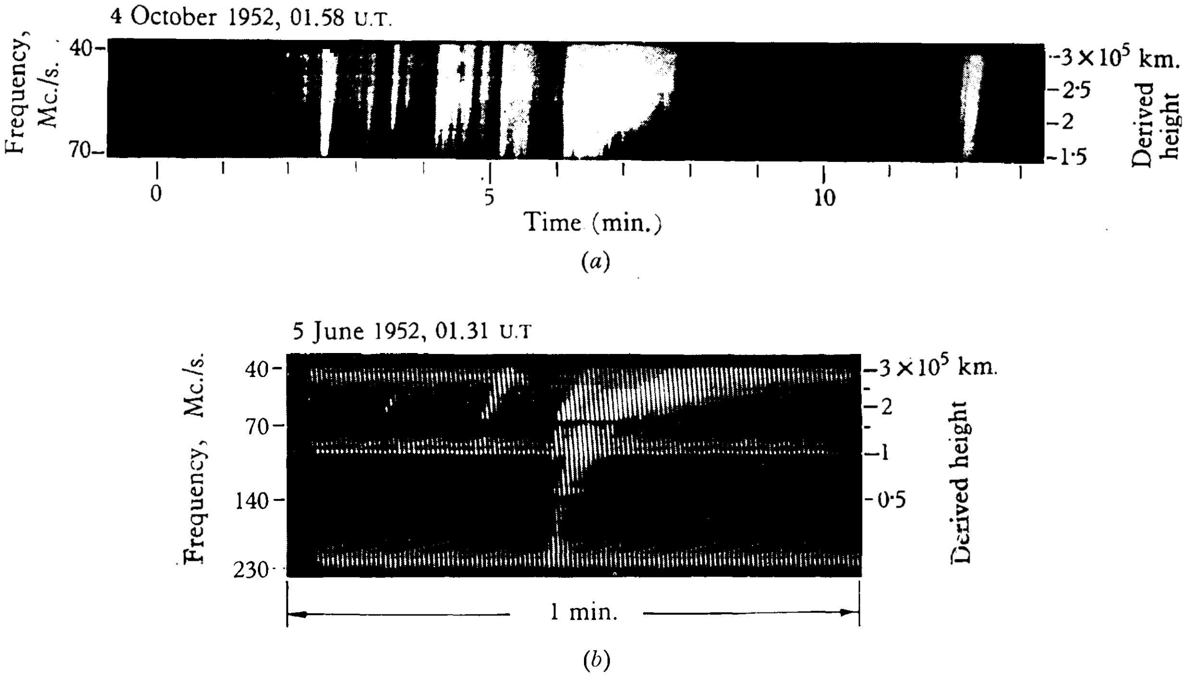

Fig. 3. (*a*) The dynamic spectrum of an outburst in which only the first phase was received (type III bursts); (*b*) Type III bursts on an expanded time-scale, showing their finite frequency drift and (in one case) the presence of a second harmonic.

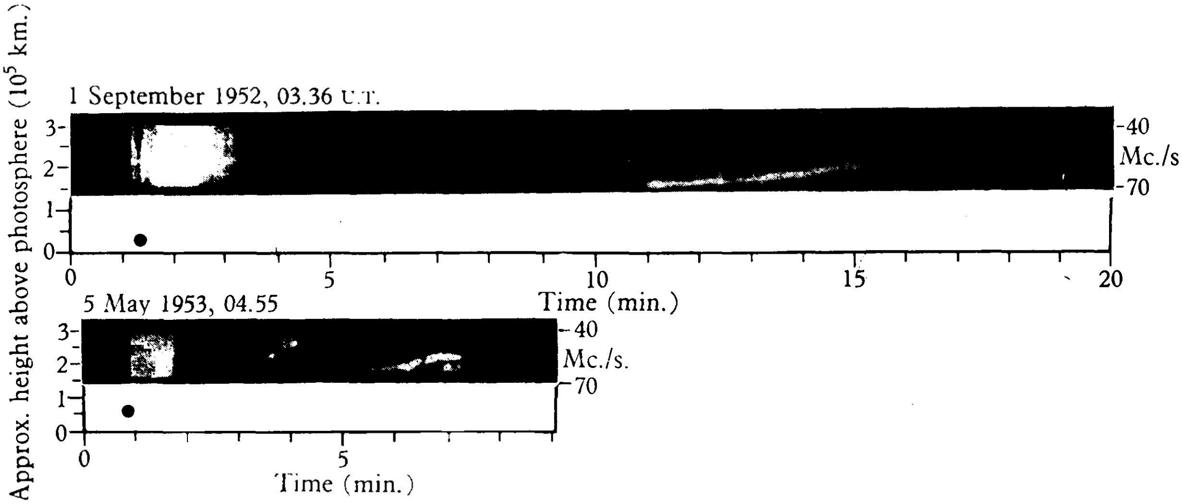

Fig. 4. Outbursts containing both first and second phases. In each case, the black dot locates the time and approximate height of a hypothetical initiating event ('explosion') from which the two phases could have originated.

from other kinds of solar and terrestrial data is somewhat speculative, but offers interesting possibilities (Fig. 5). The type II velocities ($\sim$500 km./sec.) are similar to the fastest velocities found by Dodson for Hα ejections at the start of flares; they also appear to be consistent with velocities of the geomagnetic and auroral particles (being rather slower than the storm particles ejected from the great (3^+) flares). The type III velocities ($\sim$50,000 km./sec.) correspond to no known optical phenomenon, but lie in just the range required to account for the observed time delays ($\sim$1 hour) between flares and increases in cosmic rays at the Earth.

The inference that ejections at up to one-third the velocity of light are being observed from a relatively quiescent star may provide a vital link in the wider problem of the origin of cosmic rays. For if the ejected particles were protons, their energy (approaching 100 MeV.) might well be sufficient to permit their acceleration to enormous energies by Fermi's process of successive collisions with interstellar magnetic fields.

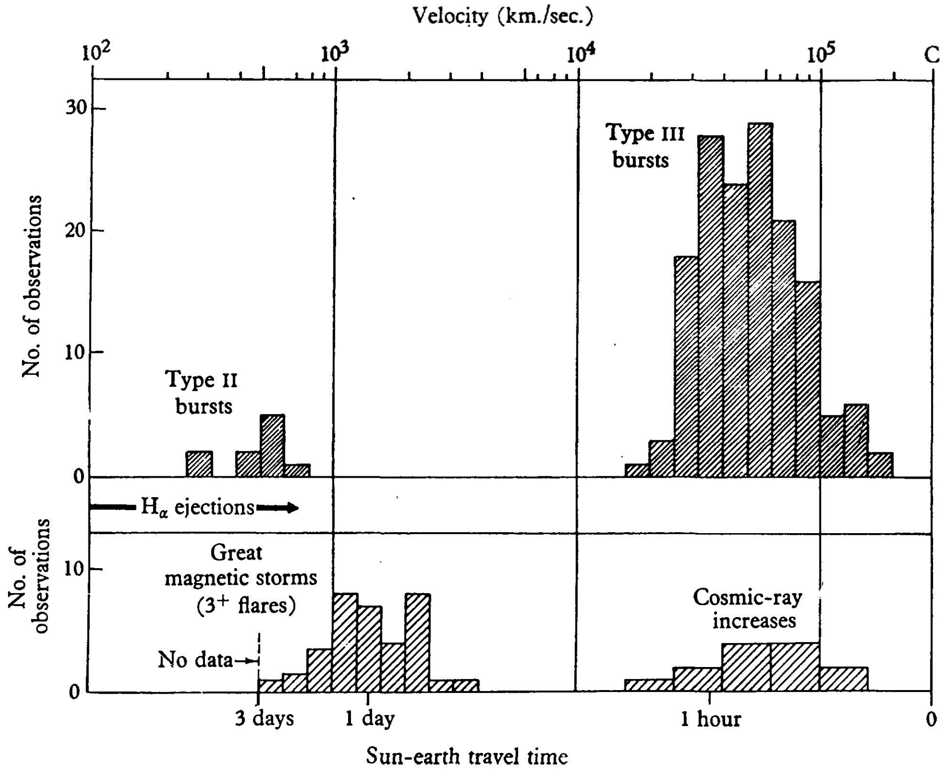

Fig. 5. Histograms comparing the derived velocities of type II and type III ejections with those required to account for time delays of corpuscles reaching the earth after large flares. Data on great magnetic storms (due to H. W. Newton) correspond to great flares (3^+), while data on type II bursts correspond to smaller flares.

REFERENCES

(1) J. S. Hey, *Nature*, **157**, 47, 1946; E. V. Appleton and J. S. Hey, *Phil. Mag.* **37**, 73, 1946.
(2) R. Payne-Scott, D. E. Yabsley and J. G. Bolton, *Nature*, **160**, 256, 1947.
(3) J. P. Wild, *Aust. J. Sci. Res.* A3, 399, 1950.
(4) R. Payne-Scott and A. G. Little, *Aust. J. Sci. Res.* A5, 32, 1952.
(5) J. P. Wild, J. A. Roberts and J. D. Murray, *Nature*, **173**, 532, 1954.
(6) J. P. Wild, J. D. Murray and W. C. Rowe, *Aust. J. Phys.* **7**, 439, 1954.
(7) H. W. Dodson, E. R. Hedeman and L. Owren, *Ap. J.* **118**, 169, 1953.

DISCUSSION

W. O. ROBERTS: Can you not interpret the high velocity of type III bursts (of the order of c/5) as a far smaller velocity of the order of 500 km./sec. by considering the sweep of frequency to be that associated with a disturbance passing through the concentrated coronal emission centred at the 'limb' near the flare?

J. P. WILD: A strong argument against this is that type III bursts are observed on a frequency as low as 18 Mc./s. and for this radiation to escape from the corona the source must be about 1·8 solar radii above the flare. Since the emission of radio waves of 18 Mc./s. takes place nearly simultaneously with the commencement of the flare, the velocity of propagation for the emitting region in the corona must be great.

W. O. ROBERTS: It is, in other words, assumed that the density distribution in the corona is the same above the active region as in the undisturbed parts?

J. P. WILD: It is assumed that the density above the flare is equal to, or greater than, the undisturbed density.

J. L. PAWSEY: For the opposite possibility to be applicable, there must be a kind of hole in the corona.

W. O. ROBERTS: I would not be surprised if this were so.

R. C. JENNISON: Can you give an estimate of the relative amount of energy in fundamental and second harmonic of plasma radiation?

J. P. WILD: Regret, no. The fundamental and harmonic are often received with comparable intensity.

R. C. JENNISON: Have other harmonics been observed?

J. P. WILD: Regret, no.

R. C. JENNISON: Can the strength of the second harmonic be justified on theoretical grounds.

J. P. WILD: Yes. One would expect that the intensity of the harmonics would decrease with increasing order. But the fundamental is particularly susceptible to absorption in the region of origin, and may be reduced to the order of the second harmonic. These two frequencies would then be emitted with comparable intensity, and the higher harmonics be relatively much weaker.

R. C. JENNISON: There may also be a differential effect due to differences in the polar diagram.

M. MINNAERT: Theoretical arguments have been presented recently by Sen for stronger higher harmonics.

J. P. WILD: The theoretical premises are still oversimplified in treating non-linear plasmas.

M. E. ELLISON: Are the harmonics conclusive evidence for plasma oscillations as the source of emission?

J. P. WILD: No. But an analysis of the intensity of fundamental and second harmonic as function of frequency indicates a sharp cut-off in the low-frequency side of the fundamental. This would be expected at the plasma frequency as a result of propagation, and is the most direct evidence for plasma oscillation.

H. ALFVÉN: What is the electron density at the source of the outburst?

J. P. WILD: At 150 Mc./s. it would be about 3×10^8 cm.$^{-3}$.

A. B. SEVERNY: Is there any evidence for type II bursts to consist of short individual pips?

J. P. WILD: No. The smoothness of the profile does not suggest pips. The third phase may show pips, the so-called 'storm' bursts.

C. L. SEEGER: Fast records (paper speed 5 mm./sec., recorder bandwidth 75 c./sec.) of 200 Mc./s. flare-associated radio events show clearly that there is often an enhanced component which cannot be a summation of either type III or the 'storm' bursts associated with Wild's type I event.

M. MINNAERT: Your remark refers to intervals of the order of seconds whereas Mr Wild's diagram refers to intervals of several minutes.