SOLAR RADIO BURSTS OF SPECTRAL TYPE II, CORONAL SHOCKS, AND OPTICAL CORONAL TRANSIENTS

ALAN MAXWELL

Harvard-Smithsonian Center for Astrophysics, Cambridge, Mass. 02138, U.S.A.

and

MURRAY DRYER

NOAA Environmental Research Laboratories, Boulder, Colo. 80303, U.S.A.

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Abstract. The association of solar radio bursts of spectral type II and coronal shocks with solar flare ejecta observed in Hα, the green coronal line, and white-light coronagraphs is examined. Rather than identifying fast-moving optical coronal transients with outward-travelling shock waves that generate type II radio bursts, as has been suggested in some earlier papers, we suggest that, for the most part, such transients should probably be identified with piston-type phenomena well behind the shock. We then discuss a general model, consisting of three main velocity regimes, in which we relate type II radio bursts and coronal shocks to optically-observed ejecta.

1. Introduction

1.1. General

Solar radio bursts of spectral type II represent a prime diagnostic for the outward passage through the solar corona of fast-mode MHD shocks generated by the more intense solar flares. It is generally believed the shocks expand in a quasi-hemispherical manner and, on rare occasions, the skirt of a shock can be discerned optically, in the form of a 'Moreton' wave, as it spreads across the interface between the chromosphere and corona. By contrast, direct optical evidence for the passage of the shocks through the corona is exceedingly tenuous.

Over the past 20 years, many authors have discussed the 'association' of coronal shocks and type II solar radio bursts with optical coronal phenomena such as Hα surges, sprays, eruptive prominences, green-line (λ 5303 Å) transients, white-light transients, and so on. In most cases, however, the association between the type II bursts and the exciter shocks on the one hand, and the optical phenomena on the other, is essentially that of two separate phenomena that merely originate in a common source: a large solar flare. Thus the velocities of the shocks and of the optical phenomena generally fall into two separate velocity regimes, the shocks moving with velocities of the order 1000–2000 km s^{-1} and the optical ejecta moving with velocities in the range 300–1000 km s^{-1}. In some cases, however, it has been suggested that fastmoving optical ejecta may be physically identified, in space and time, with the coronal shocks.

In this paper, we propose to discuss some of these matters in more detail.

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1.2. Solar Radio Bursts of Spectral Type II

The characteristics of solar radio bursts of spectral type II have been summarized most recently by Wild and Smerd (1972), McLean (1974), and Švestka (1976). It is generally agreed that the bursts are generated by the passage outward through the solar corona of fast-mode MHD shock waves which originate in relatively intense solar flares and which, at any given height in the corona, excite radio emission of the appropriate plasma frequency. The radiation is generally confined to a narrow band of radio frequencies, is often seen at both the fundamental and the second harmonic, and is randomly polarized. The fundamental emission is generally first observed at frequencies $\lesssim 150$ MHz, about 6 min after the explosive phase of a flare, and takes approximately 15 min to drift from 150 to 25 MHz, say. Observations made with the Culgoora radio-heliograph show that the type II emission regions may be distributed over as much as 180 arc deg (Smerd, 1970).

Estimates of the velocities of the shocks, made from the frequency drift-rate of the type II bursts, as recorded on radiospectrographs, in conjunction with appropriate models for the electron density above active areas on the Sun, generally give velocities in the range 1000 to 2000 km s^{-1} (Maxwell and Thompson, 1962; Weiss, 1963; and numerous subsequent authors). Estimates of the velocities of the shocks determined from positional and temporal data taken by the Culgoora radio-heliograph, while operating at two or three radio frequencies, give velocities of the same order (Nelson and Robinson, 1975; Nelson, 1977; Stewart, 1977).

There is considerable evidence to indicate that the exciter shocks generating type II radio bursts are formed in the region where the magnetic field lines extend approximately radially out from the centre of a flare (Newkirk, 1971; Dulk *et al.*, 1971; McCabe, 1971; Uchida, 1974). Such a model for the field lines was used by Dryer and Maxwell (1979) for computer simulations of the shocks generating type II bursts.

In some cases, type II radio bursts may be generated by blast waves. Uchida (1974) has shown by linear, three-dimensional computer simulations, that fast-mode MHD waves tend to refract into regions of low Alfvén velocity in the corona, where the waves *implicitly* strengthen into shocks and thus give rise to localized type II emission sources of the sort recorded by the Culgoora radioheliograph. In other cases there is evidence to suggest that type II bursts may be generated by 'piston-driven' shocks. Nakagawa *et al.* (1978), Wu *et al.* (1978), Steinolfson *et al.* (1978), and Dryer *et al.* (1979) have developed non-linear, two-dimensional computer simulations for the propagation of such shocks through the solar corona and interplanetary plasma. The non-linear models *explicitly* examine the development of the shocks and associated global response of the corona.

The processes by which particles can be accelerated to high energies in an outward-travelling shock which is carrying magnetic field with it have been examined by a number of investigators (see Švestka, 1976, and references therein). The shocks have repeatedly been identified as a possible source of many of the high-energy particles that pervade the interplanetary plasma after major solar flares.

1.3. Solar Radio Bursts of Moving Type IV

About 30% of the type II solar radio bursts are associated with bursts of spectral type IV in the meter and dekameter bands, and in these bands the type IV bursts are observed as two main species: *moving* and *stationary* (see Švestka, 1976, for a recent review).

In this paper, we shall be mainly concerned with moving type IV bursts. Smerd and Dulk (1971) distinguished three categories of these bursts and their properties have also been discussed by Schmahl (1972), Robinson (1978), and Kai (1979). The categories are as follows. (i) *Expanding magnetic arch*: This type is rarely observed; the expansion velocity is of the order of 300 km s^{-1}; the radio emission is unpolarized at the top of the arch and circularly polarized at its footpoints. (ii) *Isolated source (ejected plasmoid)*: Here the velocities generally fall within the range 200–800 km s^{-1}; the radiation is highly circularly polarized; the emission is usually not associated with a type II burst or, if it is, the type IV plasma blob may sometimes propagate in a different direction from the type II burst. (iii) *Advancing front*: In this variety, a wide irregular arc of emission is discerned on radio-heliograph records a few minutes after the passage of a type II source (the delay in the appearance of the type IV radiation is interpreted in terms of Razin–Tsytovich suppression of gyro-synchrotron radiation from the source by the intervening medium); the outward velocity of the arc is of the order of 1000 km s^{-1}; the radio emission shows little or no polarization.

For many years it was believed that moving type IV radio bursts resulted mainly from gyro-synchrotron emission at low harmonics generated by mildly relativistic electrons (energies <0.5 MeV) moving in magnetic fields of a few Gauss. Recently, however, it has been shown that plasma radiation at the second harmonic must also be taken into account as a possible radiation mechanism. Type IV radio emission is, of course, also subject to a suppression at lower frequencies by the Razin–Tsytovich effect. (See Švestka, 1976, and references therein, for a review of these matters.)

1.4. Fast-Moving Optical Coronal Transients

Ground-based Hα cameras and coronagraphs provide data on fast-moving transient phenomena in the inner corona, over a height range of approximately 1 to $2R_\odot$ (see Bruzek, 1974; and Švestka, 1976, for reviews). In most cases the Hα ejecta have velocities that are much lower than the shock exciters of type II radio bursts. Thus surges have velocities of only 100–200 km s^{-1} and eruptive prominences have velocities of several hundred km s^{-1}. However, flare sprays may have velocities of the order of 700–1000 km s^{-1}, and these velocities are close to the low end of the velocity range for coronal shocks.

Coronal transients observed in emission in the green coronal line (λ 5303 Å) have been discussed by Dunn (1971) and by DeMastus *et al.* (1973). The method of data acquisition did not permit recording of phenomena with velocities greater than 500 km s^{-1}; the observations covered the height range 1.04–1.20$R_\odot$. Of some 20 observed fast events (velocities >300 km s^{-1}) five were associated with flares that generated type II bursts. The delays between the observation of type II bursts and observations of fast-moving green-line transients were respectively 39, 56, (uncertain), 25, and 21 min. DeMastus *et al.* (1973) noted that slow-drift (type II) bursts seem to depend on either the sweeping open of the coronal region in a re-alignment type event, or the whip-like action of coronal structure in an accelerated expansion.

Farther out in the corona, in the height range 2 to $10R_\odot$, fast-moving transients have been observed with white-light coronagraphs on board the OSO-7, Skylab-ATM, and P78-1 satellites. Munro *et al.* (1979), in reviewing transients observed with the white light coronagraphs on board Skylab-ATM, found that about 40% of the white light transients were associated with flares, about 50% were associated with eruptive prominences solely (without flares), and about 70% were associated with eruptive prominences or filament disappearances (with or without flares). Gosling *et al.* (1976) noted that the velocities of the leading edge of the transients averaged about 330 km s^{-1} for transients associated with eruptive prominences and about 475 km s^{-1} for transients associated with flares; transients with velocities greater than 500 km s^{-1} were generally associated with type II and/or type IV solar radio bursts.

2. Fast-Mode MHD Shocks, Type II Solar Radio Bursts, and Fast Optical Ejecta: Individual Cases

We now proceed to summarize 10 individual cases in which investigators have examined the relation of fast-moving optical coronal phenomena (velocity $\gtrsim 750$ km s^{-1}) to type II radio bursts and fast-mode MHD shocks. In some cases, interplanetary 'signatures' of the shocks and ejecta were also examined. The appropriate data are summarized in chronological order in Table I and we now discuss the individual cases in turn.

(1) McCabe (1971) has discussed the relation of high velocity Hα ejecta, generated by a class 2B solar flare on 1969 March 12, 17:38 UT, to associated type II and type IV radio bursts. A spray, recorded on a sequence of Hα coronagraph photographs, was tracked to a distance of $2R_\odot$. One set of spray fragments had velocities in the range 770 to 980 km s^{-1}, a second set in the range 500–820 km s^{-1}, and a third set in the range 320 to 520 km s^{-1}. McCabe noted that the region producing the flare and subsequent events was at the base of an open field structure and also noted that 'if the type II event and the prominence ejection had simultaneous origins, the rate of ascent of the radio source was greater than that of the visible Hα material'. The dynamic spectrum of the type II burst, recorded at the Harvard Radio Astronomy Station, Fort Davis, Texas, is shown in Figure 1(a).

(2) Brueckner (1974) examined white-light coronagraph data, taken from OSO-7, and radio bursts associated with a flare that occurred on 1971 December 14, 02:36 UT. The white light data showed plasma clouds moving outward from the Sun, between 3 and 10 $R_\odot$; their estimated velocities close to the surface of the Sun were

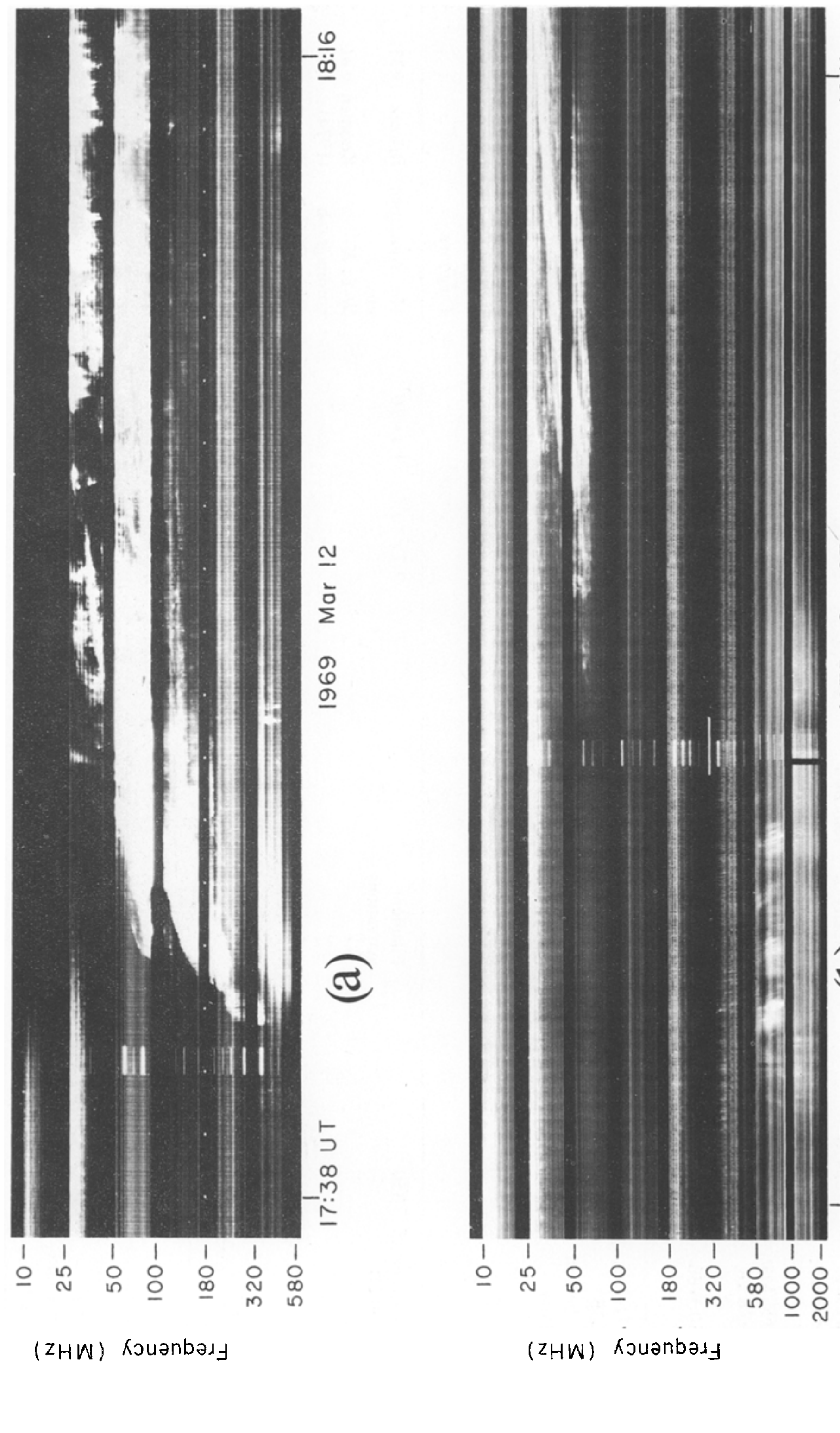

Fig. 1. (a) Spectrum of solar radio bursts, over the frequency range 10–580 MHz, recorded at the Harvard Radio Astronomy Station on 1969, March 12, commencing at approximately 17:40 UT. (b) Spectrum of solar radio bursts, over the frequency range 10–2000 MHz, recorded at the Harvard Station at the time of the solar flare of 1973, October 27, commencing approximately 15:54 UT. A white-light coronal transient associated with this flare is shown in Figure 2.

TABLE I

Data on optical ejecta and radio bursts of types II and IV generated by solar flares

	Flare: Date, time (UT), intensity, position	White-light transient velocity (km s^{-1})	Hα ejecta velocity (km s^{-1})	Type II (shock) velocity (km s^{-1})	Moving type IV velocity (km s^{-1})	Mass ejected (g)	Energy of ejected mass (erg)	Remarks	References
1	1969, Mar. 12 17:38 2B N10 W80		Spray 320–980	1600[a]	Quasi-stationary			Hα: Haleakala Radio IV: Clark Lake Radio II: Fort Davis	McCabe (1971) This paper
2	1971, Dec. 14 02:36 30° behind E limb	700 (diffuse cloud) 1000 (compact clouds)	Spray 250		1000	4×10^{16}	10^{32}	W-L: OSO-7 Hα: Mitaka Radio IV: Nobeyama	Kosugi (1976)
		950–1400 (clouds)		1600			$>10^{32}$	W-L: OSO-7 Radio II: Culgoora	Brueckner (1974)
3	1972, June 15 09:50 2B S12 E10	350[b]	Filament activations	[c]		7.7×10^{15}	1.4×10^{31}	Hα: Anacapri, etc. W-L: *K* coronagraph W-L: OSO-7 IPS data on shock Data at 1.6 AU from Pioneer 10	Bruzek (1975) Koomen *et al.* (1974) Tousey and Koomen (1974) Ward (1975a, b) Wu *et al.* (1976)
4	1972, Aug. 12 20:10 17° behind W limb		Surge and spray 500		400			Hα: Mauna Loa. Radio IV: Nederland, Clark Lake	Riddle *et al.* (1974)

5	1973, Jan. 11 00:36, 1B N14 W80	430 (max. brightness) 620 (leading edge)	Spray 300–600	800–1200	600–700	1.7×10^{16}	10^{31}	W-L: OSO-7 Hα: Haleakala, Mauna Loa Radio II, IV: Culgoora	Stewart *et al.* (1974b)
6	1973, Jan. 11 18:01-N N14 W80	230 (max, brightness) 750 (leading edge)	Spray 230–450	800–1200	700	(4×10^{39} electrons)		W-L: OSO-7 Hα: Haleakala, Mauna Loa Radio II, IV: Clark Lake	Stewart *et al.* (1974a)
7	1973, June 10 08:15 1N N21 E85	500 (leading edge)	Eruptive prominence 500	660		5.4×10^{15}	p.e. $>7\times10^{30}$ k.e. 1.7×10^{30}	W-L: Skylab Radio II: Weissenau, Úpice	Hildner *et al.* (1975)
8	1973, Sep. 7 11:41, 2B S18 W46	>960 (leading edge)	Dark surge on disk	[d]	[e]	2.4×10^{16}	1.1×10^{32}	W-L: Skylab Data at 1 AU from Pioneer 9	Gosling *et al.* (1975)
9	1973, Sep. 14 23:00 approx. 26° behind W limb	720 (expanding loop)			Stationary	3×10^{15}	t.e. 3×10^{29} p.e. 3.6×10^{30} k.e. $>1.7\times10^{3}$	W-L: Skylab Radio IV: Culgoora	Dulk *et al.* (1976)
10	1973, Oct. 27 15:43 2B N18 E55	620 (leading edge)	Eruptive filament	1200[f]				W-L: Skylab Radio II: Fort Davis	Gosling *et al.* (1976) Munro *et al.* (1979) This paper

(a) Velocity estimate from dynamic spectrum recorded at Fort Davis (Figure 1a), with assumption of electron density distribution of 10 times quiet Sun level.
(b) Velocity derived by authors from W-L data published by Koomen *et al.* (1974), corrected for projection effect for flare at E10.
(c) Radio II burst recorded at Weissenau.
(d) Radio II burst recorded at Sagamore Hill and Weissenau.
(e) Radio IV burst recorded at Boulder and Sagamore Hill.
(f) Velocity estimate from dynamic spectrum recorded at Fort Davis (Figure 1b), with assumption of electron density distribution of 10 times quiet Sun level.

about 1400 km s^{-1}. By tracing their trajectories back in time to the lower s
corona, he found that the plasma clouds appeared to coincide with discrete typ
radio outbursts, observed between 02:41 and 02:56 with the Culgoora ra
heliograph. The velocity of the exciter of the radio bursts was estimated to
1600 km s^{-1}. The energy in the total coronal blast was estimated at $>10^{32}$ erg.
the previous day, December 13, a bright coronal streamer had been observed in
region of the subsequent eruption; on the following day, December 15, only a w
remnant of the original streamer could be found. Brueckner suggested, theref
that the mass in the coronal blast be determined by emptying the preflare strea
configuration. Kosugi (1976) also examined Hα, radio, and white-light coronal
(from OSO-7) associated with the same flare. He interpreted the white-light da
terms of compact plasma clouds moving outward through the corona with veloc
of the order of 1000 km s^{-1} and also of a diffuse cloud whose leading edge h
velocity of approximately 700 km s^{-1}. Kosugi noted that the frequency drift of
first group of type II bursts was so rapid that the exciter might have been a blast-
shock with no direct physical connection to the subsequent mass ejection proce

(3) Tousey and Koomen (1974) have discussed white-light transients, recorde
the coronagraph on OSO-7, that occurred after a class 2 solar flare on 1972 June
09:50 UT. The flare generated a type II solar radio burst. (Another class 2 f
occurred in the same region three hours later, at 12:26 UT; it was associated wi
type IV burst.) From scintillation data on cosmic radio sources, Ward (1975a
reported the detection on June 16 at 05:05 UT of a shock wave in the solar v
which appeared to have been generated by the flare on June 15 at 09:50. The sh
decelerated as it moved outward and propagated with an irregular shape. Th
observations led Wu *et al.* (1976) to apply a one-dimensional hydrodyna
time-dependent model to the observed sequence of events, including *in situ* ob
vations in the solar wind of the transient's 'signature' at 1.6 AU by Pioneer
Assuming that the shock expanded outward from the flare region over π sr, t
successfully related the model's predictions of the energy and mass of the flare ej
to the figures observed at 1 AU: 1.4×10^{31} erg and 7.7×10^{15} g. Wu *et al.*
suggested that the white-light transient detected by OSO-7 might have been c
dense plasma within the shocked corona, observed far from the Sun against the p
of the sky. This shocked plasma would have lagged behind the shock wave obse
by Ward. A similar event, with data recorded by Skylab and Pioneer 9 (Gosling *e*
1975), is discussed below in case No. 8.

(4) Riddle *et al.* (1974) examined the case of a coronal disturbance initiated
flare on 1972 August 12, approx. 20:10 UT. The flare itself was estimated to be
behind the west limb and it was associated with an Hα spray, which was first obse
at the limb at 20:20 UT and which had an outward velocity of 510 km s^{-1}. Ob
vations of coronal electrons taken with a ground-based K-coronameter, indicat
depletion of the coronal electrons after the flare event. The flare also gave rise
radio type IV burst, velocity approximately 400 km s^{-1}, which was tracked out
distance of $5.5R_{\odot}$ with swept-frequency interferometers at Nederland (Universi

Colorado) and Clark Lake (University of Maryland), and which moved in the same direction as the faster moving Hα material. No type II burst was observed, presumably because the flare site was too far behind the west limb. Riddle *et al.* suggested that the moving type IV burst may have resulted from synchrotron radiation from electrons within an outward moving shock front. (To the present writers, however, the velocity of the moving type IV burst, 400 km s^{-1}, seems rather too low for it to be identified with a shock front; it would seem more likely, therefore, that the observed type IV burst may have been of the 'ejected plasmoid' variety.)

(5) Stewart *et al.* (1974b) discussed the relation of solar radio bursts of spectral types II and IV to Hα, K-coronameter and white-light coronagraph observations of a flare that occurred on 1973 January 11, 00:36 UT. The white-light observations were taken with a coronagraph on OSO-7 and with a K-coronameter at the Mauna Loa Observatory, Hawaii. Projected radial velocities for an outward-moving white-light cloud were estimated at 430 km s^{-1} for the centre of maximum brightness, and 620 km s^{-1} for the leading edge. The cloud was tracked to $9R_\odot$. Radio data, taken with the Culgoora radioheliograph, showed a type IV burst moving outward from 1.8 to $2.6R_\odot$ with a velocity of approximately 600–700 km s^{-1}. The velocity of the type II shock was estimated to be in the range 800 to 1200 km s^{-1}. The authors interpreted the various ejecta from the flare as forming a piston driving a shock but were unable to determine 'whether the leading edge of the white-edge cloud [was] the piston or the compressed gas immediately behind the shock front'. The cloud of coronal gas was estimated to contain $\sim 2 \times 10^{39}$ electrons and the energy in the magnetic field of the type IV plasmoid was estimated to be $\sim 10^{30}$ to 10^{31} erg.

(6) Stewart *et al.* (1974a) also investigated radio and white-light phenomena associated with a second flare on 1973 January 11, at 18:01 UT. The second flare was considered to be homologous with the earlier flare from the same region. A coronal cloud, observed in white light with equipment on OSO-7, exhibited a leading edge that was moving outward with a velocity of 750 km s^{-1}. However, the region of maximum brightness in the cloud was moving with a velocity of only 230 km s^{-1}. The white-light cloud was regarded as constituting the piston behind a shock which gave rise to a type II radio burst recorded at the Clark Lake Observatory; the shock was estimated to have a velocity of the order of 800 to 1200 km s^{-1}. A moving type IV radio burst, associated with the white-light cloud, had an outward velocity of approximately 700 km s^{-1}. The coronal cloud was estimated to contain $\sim 4 \times 10^{39}$ electrons.

(7) Hildner *et al.* (1975) examined Hα, radio, X-ray and white-light coronal data (from Skylab-ATM) on a solar flare of 1973 June 10, 08:15 UT. They reported observations of a white-light transient which had a leading edge that moved outward with a velocity of approximately 500 km s^{-1}, over the height range 3.6 to $5.0R_\odot$. They also suggested that a type II radio burst associated with the flare was generated by a shock with a velocity of 660 km s^{-1}. The type II burst was observed over the period 08:45–08:55, and the authors linked the type II shock directly with the leading edge of the white-light coronal transient, velocity approximately 500 km s^{-1},

which was observed during the period 09:30 to 10:00. (To the present writers, the suggested velocity, 660 km s^{-1}, of the exciter shock seems rather low. In any event, as the observed velocity of the white-light transient was less than that of the shock, the optical transient presumably constituted part of a piston driving the shock.)

(8) Gosling *et al.* (1975) compared Hα, radio, and white-light coronagraph data taken with Skylab-ATM on a flare that occurred on 1973 September 7, 11:41 UT with data on a shock wave and solar ejecta subsequently detected by the satellite Pioneer 9 in the vicinity of 1 AU. They estimated the average velocity of the leading edge of the outward-travelling white-light transient to be >960 km s^{-1}, over the height range 1 to 8.4$R_{\odot}$. They did not, however, give estimates of the velocities of the exciters of type II and type IV radio bursts recorded at the time. The measured speeds at 1 AU for the shock and for the presumed solar ejecta were respectively 722 and 600 km s^{-1}, and the overall decreases in the velocities of the shock and flare ejecta between the Sun and the Earth were estimated as 0.76 and 0.68, respectively. (Decelerations of this order, for both shocks and flare ejecta, have been predicted by a theoretical one-dimensional, time-dependent MHD model developed by Dryer (1975) and by Dryer and Steinolfson (1976). The model also predicts that deceleration is strongest between the Sun and 1 AU.)

(9) Dulk *et al.* (1976) compared white-light coronagraph data from Skylab ATM and radio data on a solar flare that apparently occurred in an active region 26° behind the West limb, on 1973 September 14, at about 23:00 UT. The white-light transient took the form of a loop, moving out with a velocity of 720 km s^{-1}; ahead of the loop was a region of compressed material headed by a bow wave. Following the loop was a massive flow of slower-moving coronal material. The radio emission took the form of intense type IV emission with the radiation originating at a fixed height for a given wavelength (i.e., *stationary* type IV emission); the radio burst also appeared at greater heights, and at later times, with increasing wavelength. A type II radio burst was not observed, possibly because the flare was so far behind the limb. The authors interpreted the bow-wave-like front as an MHD shock, of Alfvén Mach number ≤ 2, which was accelerating electrons that gave rise to the type IV emission. The ratio of thermal energy density to magnetic energy density ($\beta = 8\pi nkT/B^2$; where n = particle density, k = Boltzmann's constant, B = magnetic field strength) was estimated to be 0.035 in the compression region and 0.007 in the loop.

(10) Gosling *et al.* (1976) discussed a white-light transient, observed with equipment on Skylab-ATM, generated by a flare that occurred on 1973 October 27, 15:43 UT. Munro *et al.* (1979) estimated the velocity of the leading edge of the transient to be 620 km s^{-1} at 16:59 UT. Radio spectral data for this flare, recorded at the Harvard Radio Astronomy Station, Fort Davis, Texas, are shown in Figure 1(b) and the white light transient is displayed in Figure 2. In Figure 1(b), impulsive bursts (some with reverse drifts) are seen in the frequency band 500–2000 MHz from 15:54:30 until 15:59; type IV emission was also recorded in this band from 15:54 until 18:30. A type II burst, commencing at 16:01:30, is visible at the second harmonic at 75 MHz; fundamental emission at approximately 40 MHz can just be

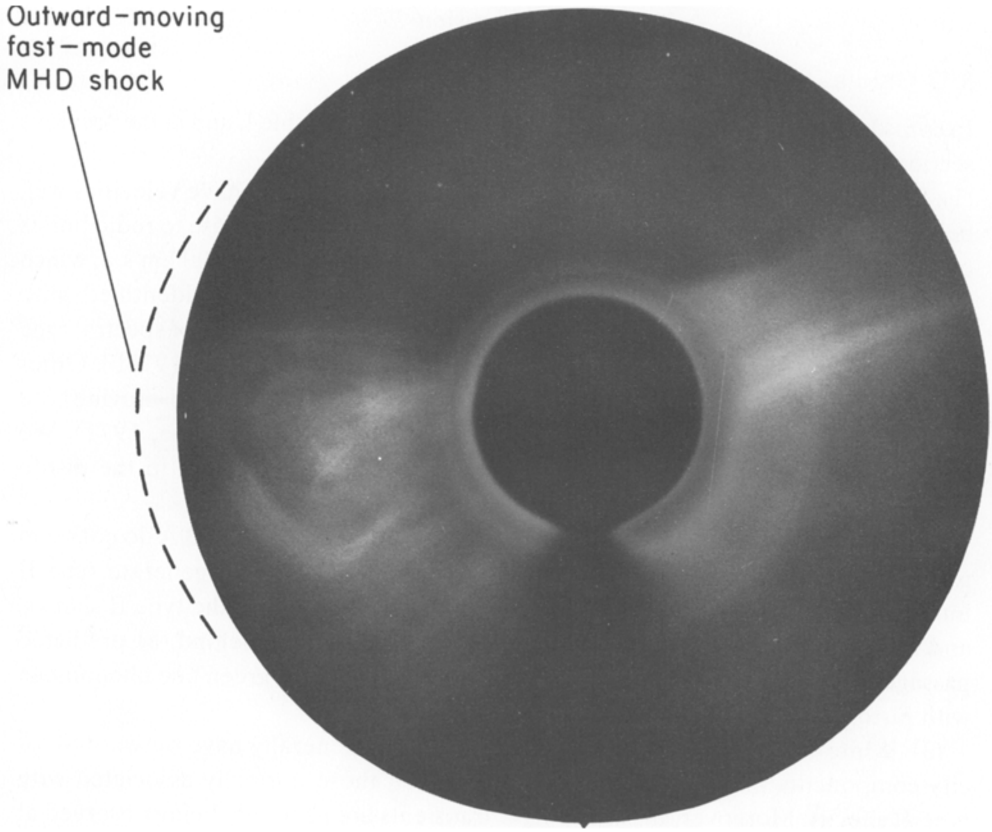

Fig. 2. White-light coronal transient photographed on 1973, October 27, 16:59 UT with equipment on Skylab (Gosling *et al.*, 1976). The flare that generated the transient commenced at 15:43 and was located at N 20 E 55. In the photograph, north is at the top and east to the left; the field of view is 6 solar diameters; the occulting disk is 1.5 solar diameters. The location of a shock wave, moving at 1200 km s^{-1}, that originated in the flare at the time of the explosive phase, is indicated by the dashed line at $6.5R_{\odot}$.

discerned. From the spectral records, and with the assumption of an electron density distribution of 10 times the quiet Sun level, the present writers estimated the velocity of the shock wave giving rise to the type burst to be approximately 1200 km s^{-1}. The shock was assumed to have originated in the explosive phase of the flare at 15:54 (the commencement of the impulsive microwave bursts). Gergely *et al.* (1977), using data on the radio burst recorded with a one-dimensional swept-frequency interferometer, covering the band 20–120 MHz, at Clark Lake, California, stated that the radio event, 'possibly a type II–IV burst, was very complex', that 'the plane-of-the-sky velocity of the burst source was about 7000 km s^{-1}', and that 'the white-light loop exhibited a conspicuous bulge in the region where the large motion of the radio source was observed'. (To the present writers, a velocity of 7000 km s^{-1} for the exciter of type II or type IV radio bursts seems very high – nearly twice as high as any previously reported velocity for such exciters.)

3. Discussion

3.1. General points

In considering the data from the 10 events summarized in Table I, and in the previo sections, we note the following points:

(1) Surges and eruptive prominences observed in Hα generally have velocities w below those associated with the fast-mode MHD shocks that give rise to radio bur: of spectral type II, but flare sprays may have velocities as high as 1000 km s^{-1}, whi are comparable with shock velocities. Some sprays have been identified wi outward-moving plasma that subsequently generates radio emission of spectral ty IV, of the isolated source (ejected plasmoid) category (Stewart *et al.*, 1974b). Oth sprays seem to follow trajectories that are just behind those of outward-moving ty II bursts but appear to be moving at slightly lower velocity (McCabe, 1971). V believe, therefore, that flare sprays may well be identified material in the pist section of piston-driven shocks, rather than with the shock itself.

(2) Coronal transients observed so far in the emission line at λ 5303 Å do not see to be directly associated in space and time with the shocks that generate type bursts. The transients generally have velocities much lower than the type II shocl and they are also generally observed at times and places well behind the predict passage of a shock from a solar flare. Again, we identify these green line phenome with piston-type phenomena well behind a shock.

(3) White-light coronal transients observed so far generally have outward-vel city components that are substantially lower than those normally associated wi type II shocks. Moreover, the white-light transients are generally being observed height ranges of 1.5 to $6R_\odot$, say, at times when a shock, travelling at 1000 km s and originating in the explosive phase of an associated flare, would already traversing heights $>6R_\odot$ (see Figure 2). We suggest, however, that transients wi velocities of the order 750 to 1000 km s^{-1} might, in some cases, be closely related the contact surface (that is, the front of the piston) driving a shock.

(4) Outward-moving type IV radio bursts of the category designated as 'advar ing front' seem to be very closely related in space and time to type II shocks. So f: however, only three cases have actually been documented (Kai, 1979). If we acce the hypothesis of Smerd *et al.* (1974), that splitting of fundamental and harmoı components of type II bursts results from excitation of the medium just in front and just behind a shock front, we may hypothesize that the type II burst itself com from the vicinity of the shock front whilst the associated type IV radiation com from the region of compression between the contact surface and the shock froı (Note, however, that none of the type IV bursts listed in Table I has been identifi with the fast-moving advancing-front category.)

(5) Data that unequivocally permit the identification of optically observed ejec with a piston driving a coronal shock are still very tenuous. We have argued that t fastest moving sprays and the fastest white-light transients have velocities compa able with those that we would expect of a piston front or contact surface. We al

note that many expanding loops and coronal bubbles observed in white-light are accompanied by type II bursts. It therefore seems reasonable to identify such optical ejecta with piston-type phenomena. We also note that, in the interplanetary plasma, several cases have now been documented of flare-generated shocks being followed, at the theoretically predicted distance for a piston, by mass ejected from the solar corona (see, for example, cases 3 and 8 in Table I).

3.2. Three velocity regimes

We therefore suggest that there exist three main velocity regimes for shocks and ejecta originating in intense solar flares. The regimes are diagrammatically illustrated in Figures 3 and 4. Figure 3 displays trajectories of shocks and ejecta as a function of height versus time. Figure 4 shows the relative locations of shocks and ejecta in the solar atmosphere, for an assumed open field configuration, about 6 min after the explosive phase.

The commencement of the explosive phase ($t = 0$) is defined in Figure 3 by the commencement of impulsive bursts in the centimeter band, associated bursts of hard X-rays, and bursts of spectral type III in the decimeter and meter bands. The explosive phase is assumed to last for approximately 30–300 s. This phase is presumably associated with the large-scale heating in the chromosphere and lower corona that ultimately gives rise to an outward-travelling shock. For intense flares, the total energy of the ejected matter is believed to be of the order of 10^{32} erg and the mass of the order 10^{16} g (see, for example, the data of Table I).

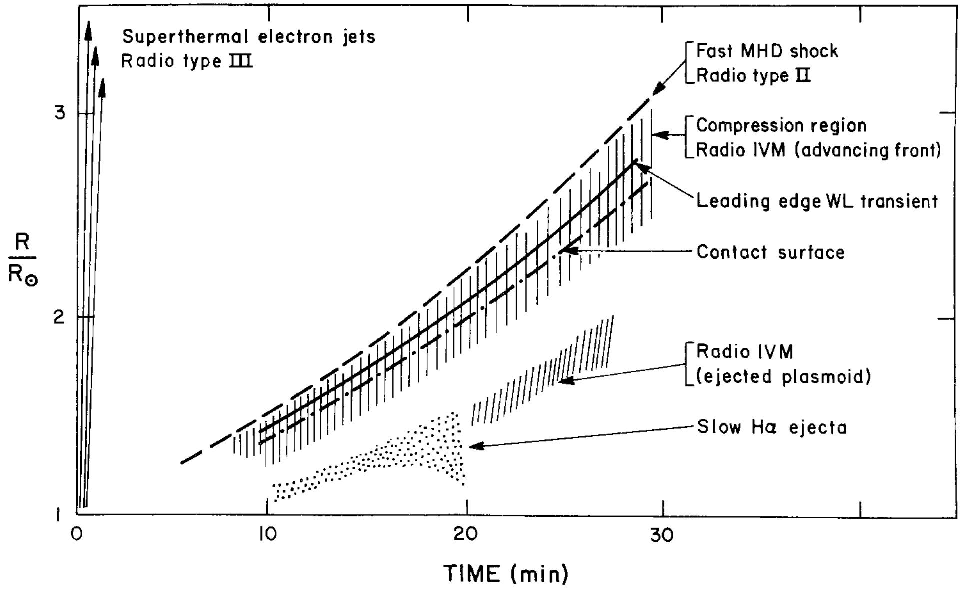

Fig. 3. Trajectories of shocks, contact surface, Hα ejecta, white-light transients, etc., generated by a solar flare. Time $t = 0$ is defined as the start of the explosive phase, as indicated by the start of hard X-ray bursts, microwave impulsive bursts, and associated type II bursts in the meter band.

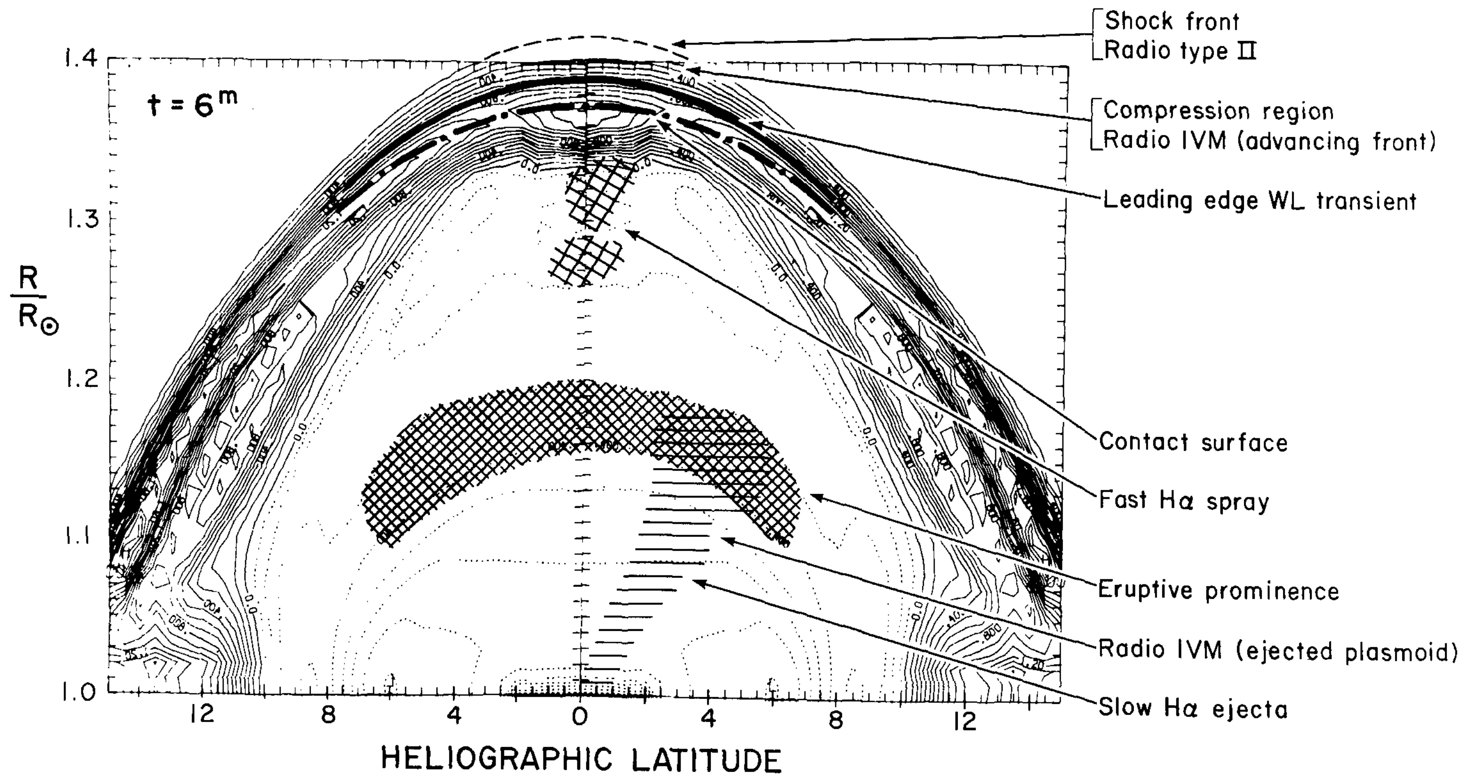

Fig. 4. Locations of shock, contact surface, and flare ejecta 6 min after the explosive phase of a flare. Solid lines represent excess density contours; in the compressed region, densities reach about five times ambient values. Dotted lines indicate rarefaction. (After Dryer and Maxwell, 1979.)

We make no attempt to specify the nature of the primary energy release in flares. (A recent review of these matters has been given by Kahler *et al.* (1980).) What we are concerned with is the secondary phase (fluid response) of the corona. We also note in passing that Syrovatskii and Somov (1980) find that the type of secondary phase we have in mind is consistent with their description of a primary, explosive phase which involves current sheet disruption triggered by tearing-mode instabilities, which themselves are followed by intense local chromospheric and coronal heating, etc. In this manner, therefore, mass within the chromosphere is heated and then ejected by the conversion of magnetic energy within the original force-free fields into thermal and kinetic forms. The latter are manifested by their appearance as a 'pressure pulse' at the coronal base. Magnetic control of the entire event is, of course, manifested during the initial phase. Subsequent motion in the secondary, coronal phase, is modulated by local magnetic topologies and plasma betas, as discussed by Nakagawa *et al.* (1978), Wu *et al.* (1978), and Steinolfson *et al.* (1980). Given sufficient energy conversion and release in the flare process, local dynamic pressures can exceed the magnetic pressures, as indicated by attainment of Alfvén Mach numbers that exceed unity. Thus temporal and spatial distribution of plasma betas and Alfvén Mach numbers must be examined in order to assess the degree of magnetic control.

The fastest velocity regime that develops after the explosive phase of a flare then corresponds to that of a quasi-hemispherical shock wave moving outward from the flare with a velocity of the order 1000 to 2000 km s^{-1} and with an Alfvén Mach number of approximately 1.5. When the shock is full developed it gives rise to type II radio bursts. The fast-moving type IV emission that is sometimes seen immediately behind the shock front is presumed to originate in the region of high compression between the contact surface and the shock front. In the compression region the plasma beta may be of the order of unity or higher. In fact, if the original pulse is taken to be caused only by emerging magnetic flux instead of by a pressure (temperature and/or density enhancement) pulse, it has been shown by Steinolfson *et al.* (1980) that $\beta < 1$ behind the contact surface and $\beta > 1$ in front of it. Thus the degree of magnetic control can be explicitly shown to be extremely strong in some portions of the disturbed plasma volume and weak in others. Certainly, the magnitude and duration of the pulse, whether it be a magnetic or pressure pulse, will determine whether matter will in fact be ejected and, if so, its ultimate mass and associated energy.

The second velocity regime corresponds essentially to the velocity of the piston driving the shock. The velocity of the contact surface, that is, the front edge of the piston, is of the order of 0.8 that of the shock itself (see Dryer, 1975 and references therein). In this regime we might identify the leading edge of the fastest white-light transients; behind the leading edge we have loops expanding outward at somewhat lower velocities. In general, we would expect the contact surfaces to be embedded within, and near the rear of the leading loop of the white-light transient. Plasma betas in this region may be ≤ 0.1. This regime might also cover higher-velocity flare sprays.

In the third regime, we place slower-moving Hα ejecta, with velocities of the order of 300–500 km s^{-1}. This regime covers the slower flare sprays, eruptive prominences, surges, moving type IV bursts of the ejected plasmoid or expanding arch varieties, and so on.

3.3. Concluding note

This paper reviews work carried out over the last 10 years that examines the relation of high-velocity optical ejecta, generated by solar flares, to coronal shocks and associated radio bursts of spectral type II. We expect that many of the present ambiguities in the interrelation of these phenomena will be clarified during the next few years by coordinated programs that will be carried out by ground-based optical and radio observatories, in conjunction with equipment on the Solar Maximum Mission, the P78–1 satellite, and on the Space Shuttle.

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