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A shock associated (SA) radio event and related phenomena observed from the base of the solar corona to 1 AU

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Abstract. We present for the first time an almost complete frequency coverage of a Shock Associated (SA) radio event and related phenomena observed on May 6, 1996 at 9:27 UT. It is observed from the base of the solar corona up to almost 1 Astronomical Unit (AU) from the Sun by the following radio astronomical instruments: the Ondřejov spectrometer operating between 4.5 GHz and 1 GHz (radiation produced near the chromosphere); the Thermopyles Artemis-IV spectrograph operating between 600 MHz and 110 MHz (distance range about 1.1-1.4 $R_\odot$ from sun center); the Nançay Decameter Array operating between 75 and 25 MHz (distance range about 1.4-2 $R_\odot$); and the RAD2 and RAD1 radio receivers on the WIND spacecraft covering the range from 14 MHz to about 20 kHz (distance range between 3 $R_\odot$ and about 1 AU). Observations at the Nançay Decameter Array clearly show that the SA event starts from a coronal type II radio burst which traces the progression of a shock wave through the corona above 1.8 $R_\odot$-2 $R_\odot$ from the sun center. This SA event has no associated radio emission in the decimetric-metric range, thus there is no evidence for electron injection in the low/middle corona.

The SA event enigma: What does SA stand for?

Type II and type III solar radio bursts result from the interaction of a disturbing agent –a beam of energetic electrons or a shock wave– with the ambient plasma [Wild and Smerd, 1972]. Radiation is produced near the fundamental of the local plasma frequency f_p (kHz) = $9n_e^{1/2}$ (cm^{-3}) and/or its second harmonic through various plasma mechanisms [see e.g. Robinson, 1997]. The observed frequency can be converted into an altitude in the corona, assuming a density model and the radiated mode. Different frequency drifts reflect different velocities along the density gradient in the corona and interplanetary medium, helping us to characterize the nature of the exciter: 0.05-0.3 c electron beam for the fast-drift, flare-associated type III bursts; 200-2000 km/s for the slow drift type II bursts (due to shock wave).

A class of intense interplanetary type III bursts closely associated to meter-wave (coronal) type II bursts was proposed by Cane et al. [1981] to be produced by electrons accelerated by shock waves in the solar corona, defining henceforth the acronym SA as *Shock Accelerated.* Some events appeared to be the extension of "herringbone structures" which are generally accepted to show evidence for shock acceleration [Nelson and Melrose, 1985; Cairns and Robinson, 1987]. In all cases, the radio signature began at distances larger than about 2 $R_\odot$ from the sun center (or frequencies below about 50 MHz), which made their observation difficult or impossible (the ionospheric cutoff frequency can be as high as 20 MHz by day). All observations were hampered by a dramatic frequency gap or distance gap [see e.g. Kahler et al., 1989, Fig. 1]. It was found that the SA events are well correlated with major proton events [Kahler et al., 1986] which are known to be mostly associated with interplanetary shocks [Reames, 1997] (for a review see Cane [1997]).

This interpretation was challenged by some authors [Kundu et al., 1984, 1990; Trottet, 1986; Klein, 1992; Klein and Trottet, 1994; Klein, 1995] who argued that, in many cases, the good correlation between the SA time profiles and the concurrent microwave burst and/or hard X-ray burst strongly suggested that the SA events were caused by electrons accelerated in or near the microwave or X-ray source region, i.e. near the chromosphere, rather than in coronal shock waves. Shock waves are considered by Klein and Trottet [1994] to be inefficient accelerators of electrons. It turns out that, following their initial [1981] paper, Cane and coworkers, and all other subsequent authors, translated SA as *Shock Associated.* This expresses an uncertainty on the origin of the electrons responsible for the SA events.

The WAVES investigation on the WIND spacecraft [Bougeret et al., 1995] includes the "RAD2" receiver whose role is precisely to cover the critical frequency range from 13.825 MHz or about 3 $R_\odot$ (1 $R_\odot$ = 1 solar radius = 696,000 km) to 1.075 MHz or about 20 $R_\odot$. It is complemented by the RAD1 receiver (frequency range 1040-20 kHz) which allows us to track the evolution of the radio sources to 1 AU.

Thus, for the first time, provided we also use ground-based radio instruments covering the high frequency counterpart of the event (corona and lower corona) and include the X-ray observations, we can study all different aspects of phenomena believed to trace the injection of energetic electrons. The object of this paper is to thoroughly discuss a particular, but representative, event which shows an SA signature and for which we have a unique and complete data set.

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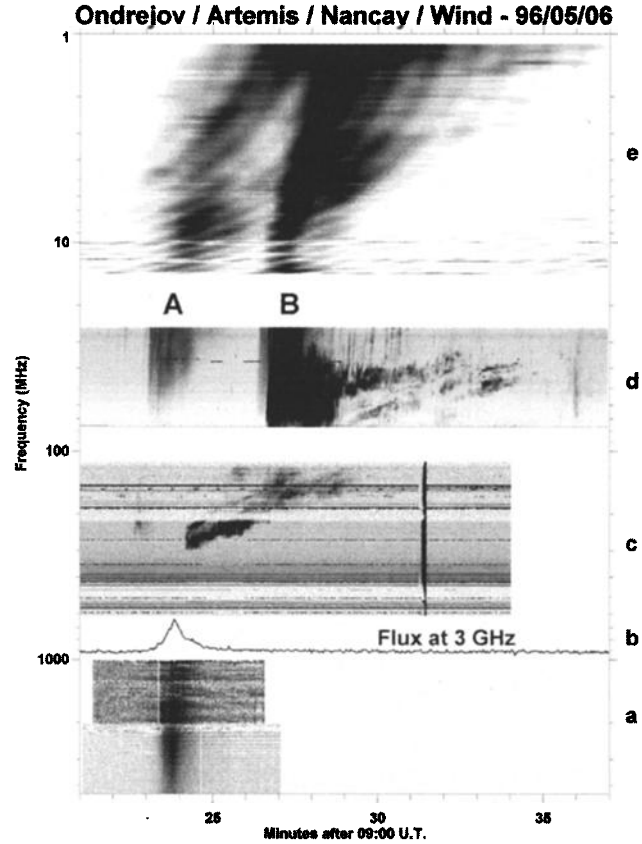

Figure 1. Global dynamic spectrum of the May 6, 1996 event, from 4.2 GHz down to 1 MHz. The frequency scale is logarithmic. From the bottom (chromospheric levels) to the top (about 20 $R_\odot$): (a) Ondřejov dynamic spectrum of the micro-wave burst associated with the (A) component. Horizontal and slightly slanted enhancements are artefacts created by the antenna response; (b) Ondřejov global flux at 3 GHz; (c) Artemis-IV Thermopyles (horizontal lines are created by local interferences, the vertical line near 9:32:40 UT is a calibration); (d) Nançay Decameter Array: the type II stops at about 09:35 UT and does not extend to frequencies below 35 MHz; (e) Wind/Waves/RAD2. The modulation is produced by a beat between the spacecraft spin and the linear sweep of the 256 frequencies. It appears to be curved because of the logarithmic frequency scale. These radio emissions trace the presence of energetic electrons.

The May 6, 1996 event: an epitome for the SA event enigma

On May 6, 1996 the configuration of the Sun was relatively simple, and characteristic of a period of solar minimum. A B4.2 class flare was reported in the GOES event listing, from 9:20 UT to 10:10 UT, with a peak at 9:37 UT. The profile is characteristic of heating and dissipation, clearly associated with the injection of energetic electrons in the lower corona. We could not find any evidence for a hard X-ray burst (the BATSE/CGRO instrument was not observing), but it is known that 4 GHz bursts typically have a profile similar to that of hard X-rays, and may indicate beams of electrons. In the following, we describe the set of radio observations, from high frequencies that are emitted near the chromosphere, to lower and lower frequencies emitted at increasing distances from the sun, up to 1 AU. Figure 1 summarizes the radio observations discussed in this paper, using a common logarithmic frequency scale.

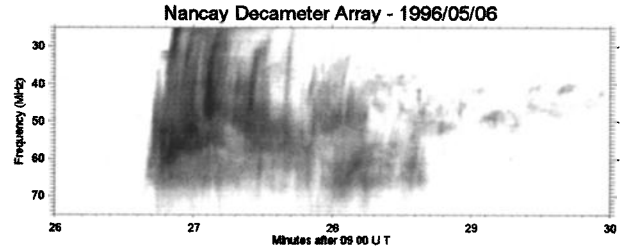

Figure 2. Nançay Decameter Array data shown with a low contrast in order to demonstrate the herringbone structure of the event

Ondřejov spectrometer (Figure 1a-b): During the impulsive phase of the flare the Ondřejov radiospectrograph [Jiřička et al., 1993] recorded faint fast-drift bursts in the 1–4.5 GHz frequency range at 9:23–9:25 UT. The bursts indicate weak acceleration and non-thermal radiation processes at this phase in deep layers of the solar atmosphere. The single frequency time profile at 3 GHz (Fig. 1b), which is more reliable than the dynamic spectra to detect faint events, does not show any other increase during the whole coronal and interplanetary event.

Artemis-IV spectrograph (Figure 1c): This event is the first type II burst recorded by the new Artemis-IV spectrograph operated by the University of Athens in Thermopyles [Maroulis et al., 1997]. The dynamic spectrum ranges from 110 MHz to 600 MHz. A faint type III burst-like signature is seen near 9:22:40, between 150 MHz and 240 MHz. The type II burst starts rather abruptly near 9:24:30 UT in the 225-300 MHz range and is consistent with radiation at $2f_p$, with some evidence for a split band [see e.g. Nelson and Melrose, 1985]. The fundamental is more diffuse and starts near 9:25:30 UT in the 110-125 MHz range. We verified on single frequency plots that no other activity was observed in association with this event.

Nançay Decametric Array (Figure 1d): The Nançay decametric spectrometer [Boischot et al., 1980] was observing in the 25-75 MHz range. The progression of the harmonic band of the type II burst is clearly seen until 9:34:30 UT. It presents an irregular, patchy structure that again suggests band-splitting. The fundamental is more difficult to detect because it is masked between 9:26:30 to 9:28:50 by intense herringbone structures [Nelson and Melrose, 1985]. The latter saturate the grey-scale chosen in Figure 1d, but not the receiver, as can be seen on Figure 2 which uses a grey-scale with less contrast. After 9:28:50 UT, fundamental emission is seen around 50 MHz. Using the Saito et al. [1977] density model, we estimate the shock velocity to be roughly 500 km/s (+300, -100 km/s). The herringbone structures are believed to be direct evidence for the acceleration of electron beams at the shock front, both upstream and downstream of the shock. The herringbone structure is better seen on Figure 2. It emerges from the type II burst backbone, going both towards higher and lower frequencies. The intensity of the herringbones decreases rapidly towards higher frequencies (i.e. towards the sun), while the intensity remains at a high level and slightly increases below 30 MHz. Another conspicuous feature is a type III burst (labelled (A) on Fig. 1d) starting near 9:23 UT, barely detectable at 75

MHz, rising sharply in intensity below 50 MHz and lasting about 2 minutes at 25 MHz.

Wind/Waves investigation (Figure 1e): The RAD2 receiver [Bougeret et al., 1995] was covering the 1.075-13.825 MHz range with 256 frequencies in a linear sweep mode. Two interplanetary type III radio bursts are identifiable on Figure 1e: the first one (burst A) corresponds to the type III burst seen by the Nançay Decametric Array near 9:23 UT, the second one (burst B) is associated with the intense herringbone structure mentioned above. Further out in the interplanetary medium, the two components (A) and (B) merge together and are tracked by the RAD1 receiver down to about 50 kHz, which is close to the local plasma frequency (not shown on Fig. 1).

Discussion: Shock acceleration or turning-on of radio emission by the shock?

The May 6, 1996 event just described epitomizes the controversy mentioned in the first Section. Two components (A) and (B) started in the 60-50 MHz range ($\simeq 2\ R_\odot$ from the center of the Sun). On the one hand, component (B) appears to start from the type II shock (near 09:26:40, when the fundamental is at about 60 MHz), with positively no associated radio signature at higher frequencies, that is in the lower corona (no microwave burst, no flare continuum, etc.); it coincides with the herringbone structure and can be considered as a typical SA as described by Cane et al. [1981]. On the other hand, component (A) starts progressively near 50 MHz and it is likely that the energetic electrons come from the lower corona: the peak time of the 1-4.5 GHz burst almost coincides with that of component (A) at 25 MHz, and we mentioned a faint type III burst-like event near 9:22:40 and 220 MHz in the ARTEMIS data. The microwave event indicates on-going heating and dissipation near the chromosphere, but it does not demonstrate that electrons are injected up into the corona, since no other radio signature is seen. This last assertion, however, has to be taken cautiously: propagation of radio waves near the chromosphere is poorly understood and the absence of a signature above a certain observational threshold does not mean that energetic particles are not present. This remark also applies to component (B) whose electrons may come from the lower corona. The possible interpretations are summarized on Figure 3.

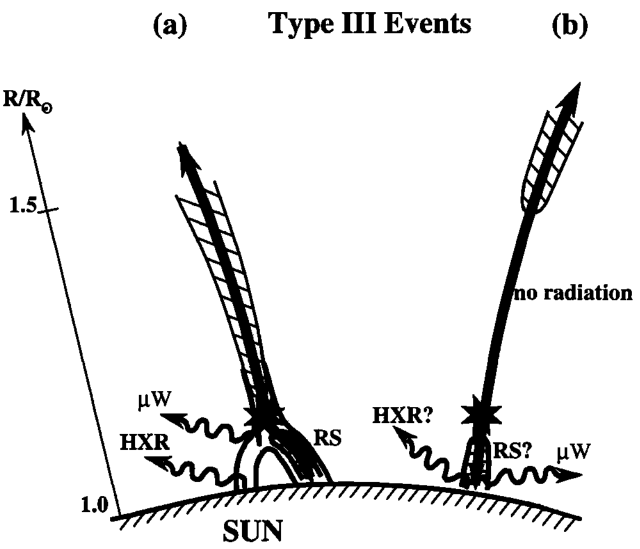

Figure 3. Discussion suggested by the May 6, 1996 event: star = source of acceleration of the electrons; thick line = path of the energetic electrons; hatched area = radio source which can be remotely tracked; HXR = hard X-ray; μW = microwave burst; RS = reverse-slope type III burst; HB = herringbone structures. Top: the radio radiation from the electron beam may start close to the site of acceleration, as in (a) or much further out, as in (b), when conditions for the beam-plasma instability take some distance or time to be met. The situation sketched in (a) is supported by extensive analyses [Aschwanden et al., 1995; Aschwanden and Benz, 1997]; the top of the loop, site of the acceleration is below 1.1 $R_\odot$ from the sun center. Sketch (b) could depict burst (A) in Figure 1. Bottom: in the presence of a shock, either the electrons are accelerated at the shock, as in (c), and SA means Shock Accelerated; or the beam of electrons is generated at low coronal levels, follows a scenario similar to case (b), but is disturbed when it crosses the shock wave, which causes the radio emission to turn on abruptly, as sketched in (d) and SA means Shock Associated.

The common association of oppositely drifting pairs of type III radio bursts, one with normal drift indicating electrons beamed upwards, and one with a reverse-slope (RS) indicating electrons beamed downwards, suggests a flare scenario in which bidirectional streams of electrons are accelerated near the top of flare loops, or in the cusp [Aschwanden et al., 1995]. A statistical analysis of the frequency of the separatrix between upward-accelerated and downward-accelerated electron beams has shown that the height of the acceleration site is located in regions where the electron density is in the range $n_e = (0.6-10) \times 10^9 cm^{-3}$ [Aschwanden and Benz, 1997], about an order of magnitude lower than the electron density found in the associated soft X-ray flare loops. Still, this puts the site of acceleration at an altitude of a few times 10,000 km, at most 50,000 km (that is below 1.1 $R_\odot$ from the sun center). This is the situation depicted in Figure 3a, 3b, and 3d. Figure 3c puts the site of the acceleration at the shock front. Reverse-drift herringbones are actually seen, but do not extend downward very far; the precipitating electrons may be thermalized or magnetically mirrored, thus preventing any signature in the lower corona.

Conclusion: A new definition of SA events and potential observational tests

Considering the discussion in the first Section, we believe that the remote sensing of shock acceleration by radio means is a critical issue and requires extraordinary evidence in order to provide a definite interpretation of such events. Now that we have continuous coverage, we can confirm the definition expressed by Cane et al. [1981], who suggested that SAs were the extension of herringbones.

We propose to unequivocally define a SA (Shock Associated) event as:

(i) a type III-like burst that is observed to start from a type II shock, AND

(ii) extends through the interplanetary medium.

We note that:

- criterion (i) is verified for herringbones, not (ii).

- criterion (i) means that there is no radio signature of upward streaming electrons (normal-slope type IIIs) behind the shock, a proxy that has been used in the past [see e.g. MacDowall et al., 1987].

- SA means Shock Associated, in the sense that the radio emission appears to start from the shock. It does not make any assumption on the origin of the electrons. Hence SA can also be used in the presence of flare continuum, type IV, etc.

- receivers like WIND/RAD2 are essential in order to bridge the corona to the interplanetary medium, but the decameter range –observable from the ground– has also an essential, critical role (it covers the range where the basic phenomenon takes place –either acceleration or radio turning-on).

Our discussion brings forward possible tests for SA events.

If the SA electrons are accelerated in the corona above 2 $R_\odot$ from the center of the sun, the spectrum of the electrons should extend to low energies, as discussed by Lin [1985] for a class of solar electron events not associated with $H\alpha$ flares. This could be directly tested when the electron beams can be measured in situ. (The electron beam associated with the event discussed in this paper did not intersect the Wind spacecraft).

We propose a model where the SA event is accelerated near the cusp of a helmet streamer, where the passage of the shock wave could trigger violent magnetic field reconnections and the acceleration of electrons. This could be tested by an analysis of the starting frequencies of the SA events and the comparison with existing coronal structures.

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