VELOCITY PROFILES OF INTERPLANETARY SHOCKS

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ABSTRACT

The type II radio burst has long been identified as being generated by a shock propagating through the solar corona. Only recently has it been possible to observe radio emission from shocks travelling through the interplanetary (IP) medium. Using the drift rates of IP type II bursts the velocity characteristics of eleven shocks have been investigated. The analysis indicates that shocks in the IP medium undergo acceleration before decelerating. The slower shocks take longer to attain their maximum velocity. Inconsistencies arise when the analysis is extended to the higher frequency (>500 kHz) data.

Introduction

At the time of the first description of the type II phenomenon (Wild and McCready, 1950) it was realized that the responsible disturbances propagated at speeds greater than 500 km/sec (Wild, 1950). Such speeds are well in excess of the speed of sound in the corona. The coincidence between the detection of a sudden commencement geomagnetic storm, initiated by a shock, and the observation of a type II burst at the sun a few days beforehand (Roberts, 1959) led to the acceptance of the theory that type II bursts are generated by shocks. The presence of two emission bands separated in frequency by about a factor of two indicated that fundamental and first harmonic electron plasma emission was being observed. Assuming a coronal density model the rate at which the burst drifted through the frequency range was then related to the shock's velocity. With the availability of 2-D spectro-heliographs it was determined that the assumed density models were consistent with the observed source positions (Wild, 1970). It should be noted though, that the deduced coronal electron densities are about a factor of 10 greater than values determined from white light measurements of the quiet corona (Stewart, 1976).

The propagation of shocks through the corona and IP medium is of considerable interest. Shocks play an important role in the energetics of the solar corona and in particle acceleration, both at the sun and in the IP medium. In situ measurements of shocks have been made for more than fifteen years and much progress has been made in understanding shock structure. However, the majority of the spacecraft used for these studies have been in earth orbit providing information at only one heliocentric distance. Thus not much is known about the evolution of shocks. One property that is known, and was first pointed out by Gosling et al.(1968), is that most shocks decelerate during their transit from the sun. Shock speeds at 1 AU are less than the transit speeds. The deceleration is presumed to be as a result of expansion of the wave and energy transfer to the ambient solar wind.

The technique of 'tracking' a shock via its radio emission provides information about the same shock over a large range of heliocentric distances. However, until the ISEE-3 radio astronomy experiment only a few events had been detected. Malitson et al.(1973, 1976) reported detecting two events with an experiment on IMP-6 and Boischot et al.(1980) reported several bursts seen with experiments on the Voyager spacecraft. These observations were obtained by much less sensitive experiments and provided no information about shock velocities. Although in the literature (e.g. Dryer, 1975) the IMP-6 data have been used to show a constant shock velocity, in fact, this was assumed in the original data analysis.

Data Analysis

In Figure 1 we sketch the ground-based dynamic spectrum for a type II event observed at the Culgoora Observatory in October 1978. This event continued to low frequencies and the 2 and 1 MHz intensity-time profiles from the ISEE-3 experiment are shown. Note that ground-based observations are not usually possible below about 20 MHz, whereas the top frequency of the ISEE-3 experiment is 2 MHz. Thus a gap of about a decade in frequency exists in the frequency regime of interest.

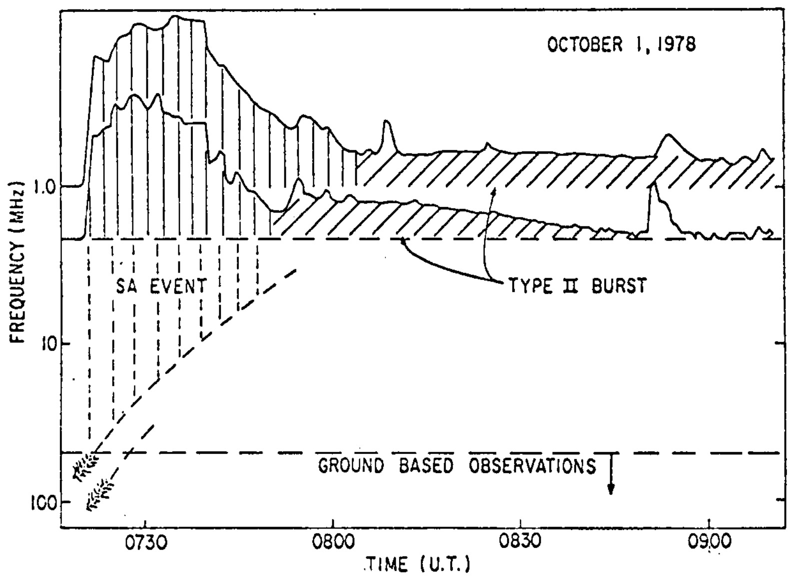

Fig. 1. This figure shows the relationship between meter wavelength phenomena and the activity detected at low frequencies. In particular the SA event is shown to precede the type II burst at 2 MHz. The dashed lines indicate what we would expect to have occurred in the unobserved region of the spectrum.

A characteristic of the October 1978 event, and other energetic events, is the occurrence of fast drift elements emerging from the 'backbone' of the type II burst observed from the ground. The 'herring-bones', as these elements are called, have been attributed to streams of relativistic electrons accelerated by the shock (Wild et al., 1963). In very energetic events these electrons propagate to 1 AU causing intense emission at low frequencies. We presume that the release and/or acceleration of these electrons ceases above approximately the 5 MHz plasma level because at 2 MHz the observed activity ceases after about 25 minutes (see figure 1 for clarification). The intense low frequency outburst has been called a shock accelerated (SA) event (Cane et al., 1981). Type II bursts observed by ISEE-3 (which we call IP type II bursts) are preceeded by SA events. Since the SA event at 2 MHz begins within a minute or so of the type II burst observed at about 20 MHz, associations between ground and ISEE-3 type II events can be made unambiguously despite the lack of coverage in the regime between about 20 MHz and 2 MHz.

Figure 1 shows ISEE-3 intensities on a logarithmic scale and it is clear that the type II emission is much weaker than the SA event. The 2 and 1 MHz type II emission appears to be very weak but this is only because it is competing with the intense background emission from our Galaxy. We have detected type II emission at 2 and 1 MHz in only about 50% of the IP type II events. At lower frequencies the Galaxy decreases in intensity and the type II bursts are more easily discerned - provided other solar activity is at a minimum.

The characteristics of a type II burst at lower frequencies are shown in Figure 2. In the figure we show intensities as a function of time for eight frequencies for an event on May 16, 1981 and in this figure we use a linear

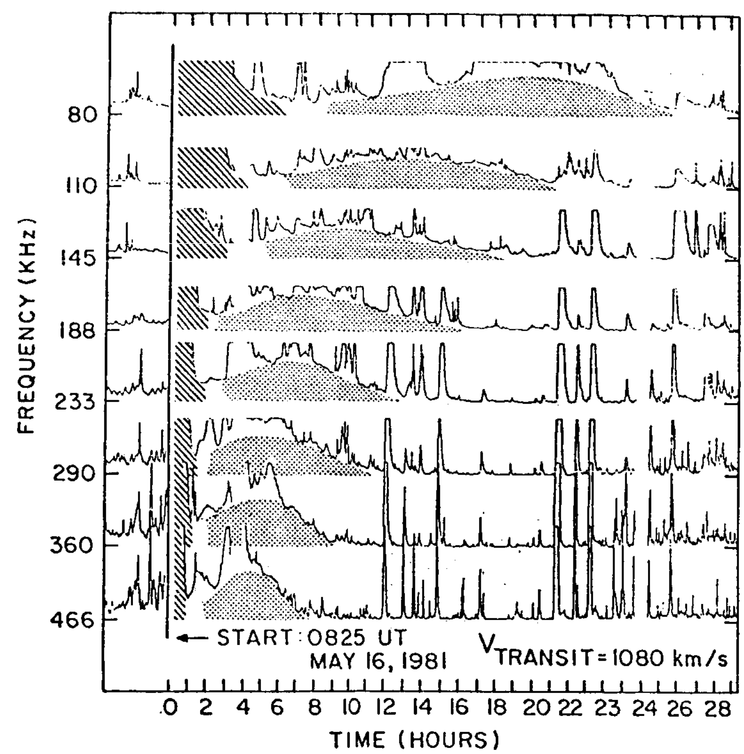

Fig. 2. Intensity versus time profiles for eight of the ISEE-3 observing frequencies. The type II emission is indicated by the stippling and the SA event by hatching.

scale. The strong type III bursts (flat-topped intensifications seen on all frequencies essentially simultaneously) have been chopped above a certain intensity to enhance the much weaker type II emission. The SA event is indicated by diagonal hatching. The type II event, indicated by stippling, is seen to drift through this frequency range (466 - 80 kHz) in about 25 hours. For this event the transit velocity, i.e. the velocity determined from the time interval between the start of the event at the sun and the sudden commencement, was about 1000 km/sec.

Figure 3 shows the profiles for another event whose transit velocity was about 800 km/sec and it is seen that this event drifts through the same frequency range more slowly. The drift rates of all the bursts studied show this consistency with the derived transit velocities. This result substantiates our identification of the flare associated with a particular sudden commencement. Apart from a few isolated cases the transit velocities of the shock studied are basically independent of flare longitude. This means that to a first approximation the shocks expand isotropically.

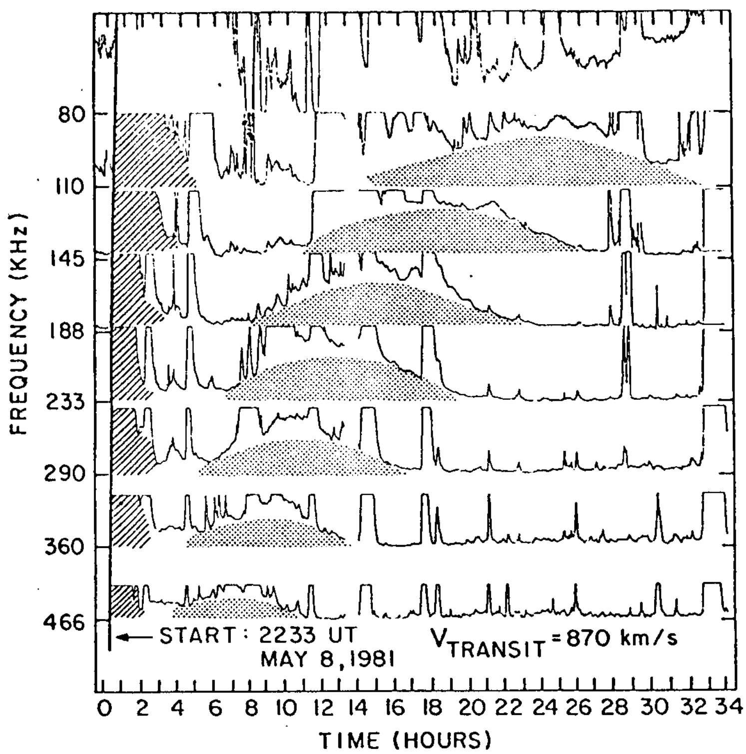

Fig. 3. Intensity profiles for another event. This event has been attributed to a slower shock than that associated with the event in fig.2 and has a slower drift rate.

We have determined the height of a number of shocks as a function of time by using an appropriate density model and assuming that the maximum of the burst at each frequency is the time when the shock was at the appropriate plasma level, i.e. coronal height. The occurrence of SA events before IP type II bursts provides unambiguous identification of the start of the event at the sun. The initial height of the shock at the commencement of the SA event is essentially the height at which shocks produce meter wavelength type II emission. This height is in the range 1.5 - 3 solar radii heliocentric distance. The density model comprised a constant R^{-6} term and a variable R^{-2}

term. The R^{-6} term is negligible beyond about 10 solar radii. The amplitude of the R^{-2} term was varied for different events so that a smooth height-time curve was obtained, with the end points anchored by the start of the event at the sun at 2 solar radii and the SC at the earth at 215 solar radii. Small variations in the amplitude make little difference to the basic shapes of the velocity curves, and thus for most events the same density scale was used. Figure 4 shows data for the event of May 16 of 1981. We note that a data gap at the beginning of the event covered the time interval when we expected to detect the event at 1 and 2 MHz. The smooth curve is the spline function of least curvature fitted to the data taking into account the accuracy to which the maximum of the burst at each frequency can be estimated.

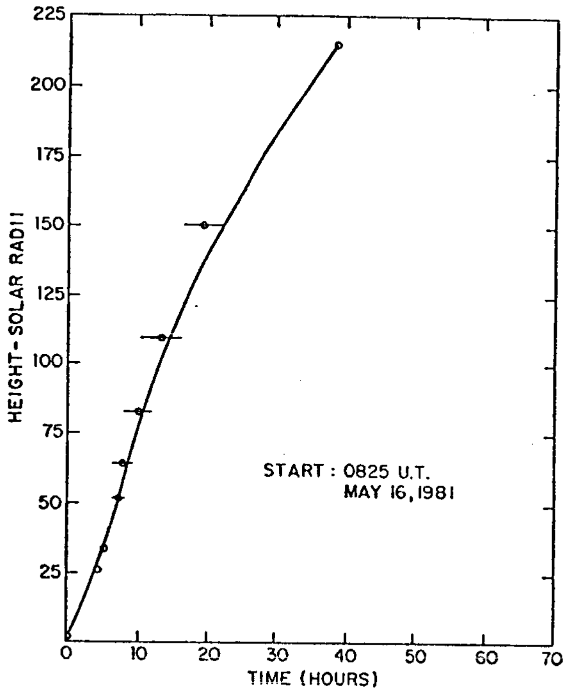

Fig. 4. Deduced height versus time profile for an event. The smooth curve is the spline function of least curvature fitted to the data.

This technique has been applied to a number of events. Shock velocities as a function of heliocentric distance were obtained by taking the first derivative of the spline function fitted to the height-time data.

Results and Discussion

Figure 5 shows the velocity curves for four events. The events have been organized as a function of transit velocity. The fastest event is at the top left and the slowest event is bottom right. Ignoring for the moment the profiles below about 20 solar radii one can see that for these events the shocks accelerate over a distance ranging from about 60 to 100 solar radii. The other events that have been analyzed have similar profiles. If the shocks are being driven over the distances indicated by the acceleration region then the data suggest that the slower shocks are driven further than the fast shocks.

The upper right profile shows a large peak below 20 solar radii and this was obtained from the 1 and 2 MHz data. Note that had 2 and 1 MHz data points been available we expect, based on our results for other events, that the upper left event would also have had a sharp impulsive peak. Other events show this peak. Thus velocities obtained from the high frequency data seem to be inconsistent with the low frequency results. However, they are not inconsistent with analyses of ground-based events which give typical velocities of the order of 1000 to 1500 km/sec (Maxwell and Thompson, 1962). For some events even greater velocities have been derived (Gergely, 1982). Our

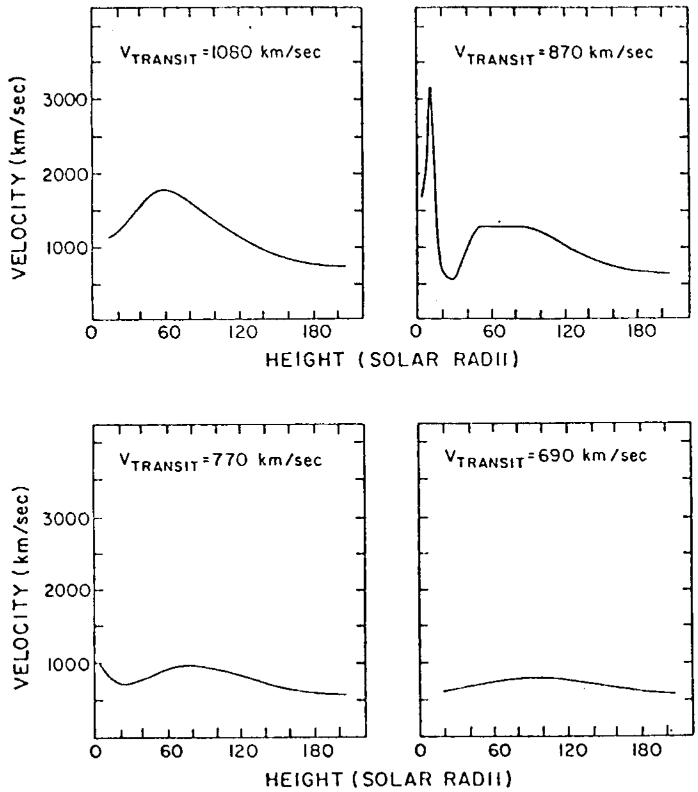

Fig. 5. Velocities as a function of heliocentric distance for four events. The top figures (L-R) are for events commencing May 16 and May 8 1981. The bottom figures (L-R) are for events commencing December 11, 1978 and August 26, 1979.

analysis assumes that the density scale derived for the low frequency (<1 MHz) data could be extended smoothly to the high frequency (1 and 2 MHz) data and that the same mode of emission was occurring. If these assumptions are incorrect certain conditions could result in the high frequency plasma levels being placed too high in the corona and this would lead to high velocities. Another explanation for our results is that the type II emission profile is being incorrectly interpreted. However, the differences in appearance of the type II emission in the two regimes suggests an interesting alternative which is that there are two shocks. The shock responsible for the high frequency emission could be a blast wave which dissipates in the low corona. The increase in velocity deduced from the low frequency data implies a driven shock. The driver would presumably be a mass ejection detectable as a white light coronal transient. From the preliminary analysis to date there is a good correlation between IP type II events and fast mass ejections as observed by the P78-1 coronagraph. Whatever the answer is it is clear that there are differences between the low corona and the interplanetary medium as probed by radio emission from shocks.

In summary, interplanetary shocks produce radio bursts with frequency drift rates dependent on the shock velocities. Analyses of these drift rates indicate that the shocks accelerate out to some distance (of the order of 80 solar radii) and then decelerate. Some change in the properties of the corona or the type II emission occurs below 20 solar radii which remains to be explained.

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