RADIO DATA AND COMPUTER SIMULATIONS FOR SHOCK WAVES GENERATED BY SOLAR FLARES

Alan Maxwell
Harvard College Observatory, Cambridge, MA 02138, USA
Murray Dryer
Environmental Research Laboratories, NOAA, Boulder, CO 80302, USA

Solar radio bursts of spectral type II provide a prime diagnostic for the passage of shock waves, generated by solar flares, through the solar corona. In this investigation we have compared radio data on the shocks with computer simulations for the propagation of fast-mode MHD shocks through the solar corona. The radio data were recorded at the Harvard Radio Astronomy Station, Fort Davis, Texas. The computer simulations were carried out at NOAA, Boulder, Colorado.

It is generally agreed that type II solar radio bursts result from the passage outward through the solar corona of fast-mode MHD shocks generated by relatively intense solar flares. The radio emission comes from plasma oscillations, is generally confined to a narrow band of radio frequencies, is often seen at both the fundamental and second harmonic, and is randomly polarized. In many cases, the fundamental emission is first observed at frequencies of approximately 150 MHz, about 5 minutes after the explosive phase of a flare (generally indicated by emission of impulsive bursts in the microwave band and associated hard X-ray bursts). The radio emission then drifts slowly downward in frequency, taking approximately 15 minutes to drift from 150 MHz to 25 MHz, say. With the assumption of an appropriate electron density model, it is possible to interpret the observed emission frequencies in terms of emission from corresponding plasma heights in the solar atmosphere: for the assumed density models, the frequency range 150 to 25 MHz then transforms to an equivalent height range of approximately 1.5 to 2.5 $R_{\odot}$. From the drift rate of the radio burst it is then possible to determine the outward radio velocity component of the shock generating the burst and this is usually of the order 1000 to 2000 km s^{-1}. Velocities of the outward-traveling shocks have also been determined from positional data, taken as a function of time, recorded by the radioheliograph at Culgoora, Australia, while operating at frequencies of 43, 80, and 160 MHz, and these data give shock velocities of the same order (Nelson 1977).

Data taken at Culgoora also show that the type II emission regions may be widely distributed, at times over as much as 180 arc deg around the solar disk (Smerd, 1970). Uchida (1974) has shown, by computer simula-

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tions, that fast-moving MHD waves tend to be refracted into regions of low Alfven velocity in the corona, where they strengthen into shocks, and in this manner give rise to type II emission sources of the sort recorded at Culgoora. Uchida's model was developed for a wave generated by a blast. In the case of large flares, however, radio evidence (in the form of type IV emission falling closely behind the type II burst both in time and position) suggests that the shock may often be driven by a piston.

Computer models for the propagation of fast-mode MHD shocks through the solar corona, and then out of the interplanetary plasma have been developed at NOAA in Boulder and the University of Alabama in Huntsville (cf. Wu et al., 1978; Steinolfson et al., 1978). The models simulate the coronal mass motions and shock waves resulting from solar flares. The model that was used for the present investigation was two-dimensional, time-dependent, and was applied to the meridional plane. The assumed magnetic topology was that of a hexapole embedded in the solar corona. An input pulse was then applied at a region where the magnetic field lines appeared to open into the interplanetary plasma. The pulse was applied over 5 degrees in heliographic latitude, and it was applied at the base of the corona where the ambient temperature was assumed to be 2×10^6 K, the magnetic field 2 Gauss, and the plasma beta was assumed to be 1. The density in the solar atmosphere was assumed to decrease in a quasi-exponential manner (the computer density model approximated the density model used for the interpretation of the radio data at heights of about 2 to 3 $R_\odot$). The computer simulation was terminated at 6 $R_\odot$.

The computer simulation provides information on the global response of the corona, after the input of a large energy pulse, in terms of density, temperature, particle velocity, and the redistribution of magnetic field. Various forms of input pulses could be applied: for example, a series of rapid pressure pulses, a square-wave pressure pulse, a magnetic pulse, etc. In the present investigation, the best simulation for the observed radio data was given by an input pulse which had the form of a square-wave pulse of duration 10 min, containing a temperature (or pressure) increase of 40 times the ambient value. It is also interesting to note that this input pulse is similar to the pressure changes observed in X-ray loops, at the time of a flare, where the pressure may increase by a factor of about 50 for a period of several minutes (Pallavicini et al., 1977). The energy in the applied pulse was of the order of 2×10^{32} erg.

A comparison of the shock velocities derived from the computer model with shock velocities derived from radio data for a given flare is shown in Figure 1. Density ratios and velocity magnitudes in the corona determined from the computer simulation for a time corresponding to 6 min after the input pulse was first applied (that is, at about the time the type II burst was first seen on the radio records) are shown in Figure 2. The ejected mass, as indicated by the computer simulation, was 6.4×10^{16} g. Full details of this work may be found in a paper by Dryer and Maxwell (1979).

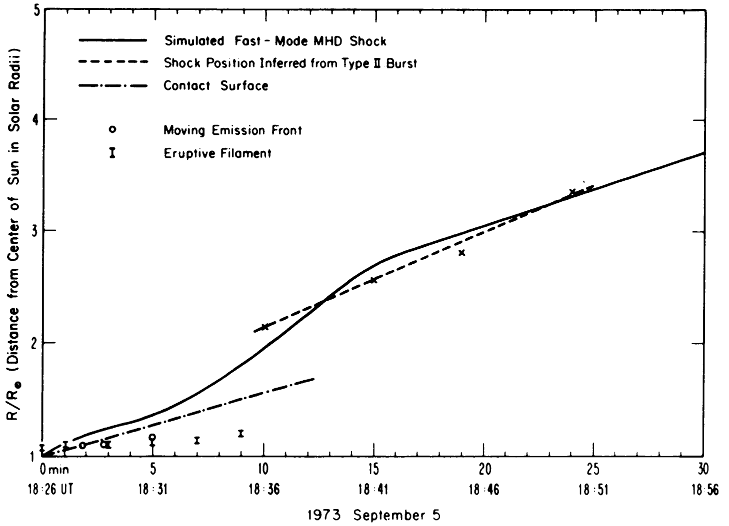

Figure 1. Comparison of radio data on a shock wave generated by a solar flare with the computer simulation for fast-mode MHD shock in the solar corona.

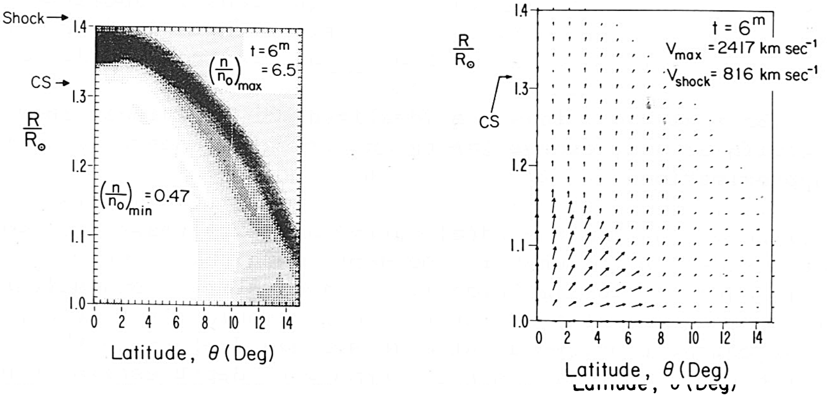

Figure 2. Density distribution and bulk plasma velocities in the solar corona inferred from the computer simulation, showing position of shock and contact surface (piston) 6 min after input pulse is first applied.

REFERENCES

Dryer, M. and Maxwell, A. 1979, Astrophys. J., 231, 945.
Nelson, G.J. 1977, Proc. Astron. Soc. Australia, 3, 159.
Pallavicini, R., Serio, S., and Vaiana, G. 1977, Astrophys. J., 216, 108.
Smerd, S.F. 1970, Proc. Astron. Soc. Australia, 1, 305.
Steinolfson, R.S., Wu, S.T., Dryer, M. and Tandberg-Hanssen, E. 1978, Astrophys. J., 225, 259.
Uchida, Y. 1974, Solar Phys., 39, 431.
Wu, S.T., Dryer, M., Nakagawa, Y., and Han, S.M. 1978, Astrophys. J., 219, 324.

DISCUSSION

Jackson: 6 x 10^{16} g and 2 x 10^{32} ergs are an order of magnitude more mass and more energy associated with ejected material than for the transients measured during Skylab. Do you feel that your results can be scaled to fit the Skylab observations?

Maxwell: There are many transients, and they have varying masses and energies. We are interested in the top end of the range. (For example, Gosling et al., (1975, Solar Phys., 40, 439), give 2.4 x 10^{16}g and 1.1 x 10^{32} erg for the white-light transient associated with the flare of 1973 September 7, 11:40 UT).

Dryer: Note also that magnetic energy and thermal energy are included in our energy calculations but not in the energy estimates for the white light transients measured with Skylab. I feel that our results can be scaled (via properly tailored input pulses chosen to represent the flare) to fit the Skylab, OSO-7, or P78-1 observations.

Petelski: Could you extend a bit on the algorithm employed in the calculations and, in particular, on the approximations used for solving the MHD equations?

Dryer: The complete set of nonlinear MHD equations is specified to the meridional plane (r, θ). Details of the algorithm and other numerical matters are given by Steinolfson et al. (Astrophys. J., 225, 259 (1978)).

Nakagawa: The basic equations are idealized MHD equations. They are totally nonlinear and, except for the numerical scheme used, involve no approximation.

Moore: How do you assign the total energy and total mass from your two-dimensional model; e.g., what is the depth into the plane?

Dryer: Our model is two-dimensional. We have to make some suitable assumption for the extent of the disturbance perpendicular to the plane. For the present computation, we assumed an average depth into the plane of 0.2 $R_\odot$ at t = 30 min (6 $R_\odot$). This conforms with depth estimates made for white-light transients by Poland and Munro. Since the observational estimates are uncertain (cf., an estimate of 0.6 $R_\odot$ by Gergely and Kundu, this symposium) and considering further that our model is not 3-dimensional, our estimates of total mass and energy are also uncertain by, say, a factor of three or so. Progress toward a time-dependent MHD, 3-dimensional model is being made by Nakagawa, Wu and Han (this symposium). We believe, however, that the present 2-dimensional model is adequate for providing insight into some of the basic physical processes present in the temporal mass motion.

Kahler: A temperature increase of a factor of 40 and a duration of 10 min. suggests that you are assuming the pulse is the impulsive phase of the flare. Have you attempted to match the start time and duration of the pulse to the hard X-ray or microwave burst?

Maxwell: We take the starting time of hard X-ray bursts and impulsive microwave bursts as defining the start of the explosive phase

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of the flare and as time zero for the initial application of the input pulse for our computer simulation. Our pulse length (10 min) may be a little longer than the observed durations of the hard X-ray bursts and microwave bursts.

Nakagawa: Rising loops do not necessarily represent the cause of the matter ejected outward. Rising loops could result from heating that has already occurred as seen, say, in hard X-ray bursts.

Uchida: I fully understand the existing mathematical and computational restrictions, but I would like to point out that a type II burst is a more complicated phenomenon of somewhat different nature. For example, the sources of type II bursts show more "ragged" structure, appearing sometimes even beyond the horizon, instead of your bowshock type surface. This seems to favor my previous work, in which I suggested that the type II burst may be caused by a weak blast-pulse, emitted in the impulsive phase of a flare, which "illuminates" favorable regions where the shock is strengthened due to the low Alfvén velocity. Your calculation, however, may apply to the interplanetary type IIs, which we expect in front of the mass ejecta in the form of a bowshock far out in the interplanetary space.

Maxwell: I agree. I did not have time in my talk to discuss shocks generated by short-lived blasts. Our work, of course, concerns piston-driven shocks, generated by large flares giving large input pulses.

Dryer: I would like to remind the audience that Dr. Uchida's pioneering work is confined to the regime of linear (ray-tracing) analysis. Hence one can only infer, as he has just noted, the situation regarding non-linear steepening of the MHD waves into MHD shock waves. Our calculations are fully non-linear; hence, a shock wave can indeed develop anywhere within the low corona as well as interplanetary space. Thus, the model can be applied to coronal, as well as interplanetary, type II spectral radio emission.

Somov: Your calculations of the dynamic response of corona on a pulse show that very large mass can be ejected. Is this mass contained in the corona before a pulse or ejected from below the boundary placed on the coronal base? In the last case the calculation assumes tacitly some unspecified reason for ejection of chromospheric plasma. Then, your resulting solution is the continuation of the solution for the corona into the chromosphere.

Dryer: This is correct. We have in mind the fact that the chromosphere (which is actually below our "coronal base" in the model) can provide substantial mass flux. Thus we allow mass flow across our lower boundary such that the time-dependent conservation requirements are continually satisfied.