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HARVARD RADIO ASTRONOMY STATION

FORT DAVIS, TEXAS 79734

Final Report
to
NASA
Grant NSG-7648

SOLAR MAXIMUM MISSION: GROUND SUPPORT PROGRAMS AT THE HARVARD RADIO ASTRONOMY STATION

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31 March 1983

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ABSTRACT

As part of the ground-support system for the Solar Maximum Mission program, observations of the spectral characteristics of solar radio bursts were made at the Harvard Radio Astronomy Station, Fort Davis, Texas, with new dynamic spectrum analyzers of high sensitivity and high reliability, over the frequency range 25-580 MHz. The observations also covered the maximum period of the current solar cycle and the period of international cooperative programs designated as the "Solar Maximum Year".

Radio data on shock waves generated by solar flares were combined with optical data on coronal transients, taken with equipment on the SMM and other satellites, and then incorporated into computer models for the outward passage of fast-mode MHD shocks through the solar corona. The MHD models are non-linear, time-dependent and for the most recent models, quasi-three-dimensional. They examine the global response of the corona for different types of input pulses (thermal, magnetic, etc.) and for different magnetic topologies (for example, open and closed fields). Data on coronal shocks and high-velocity material ejected from solar flares have been interpreted in terms of a model consisting of three main velocity regimes: shocks moving outward with a velocity of the order of 1,000-1,500 km s^{-1}; the leading edges of the fastest white-light coronal transients and the fastest Hα flare sprays, moving outward with velocities of the order of about 80 per cent that of the shock, that is about 800-1200 km s^{-1}; and slower moving phenomena, such as eruptive prominences, and most moving type IV radio emission regions, moving outward with velocities of a few hundred km s^{-1}. This work has been published in various papers.

GENERAL INFORMATION

NASA Grant NSG 7648 provided funds for ground-support programs in solar radio astronomy, carried out at the Harvard Radio Astronomy Station, Fort Davis, Texas, in association with the Solar Maximum Mission Satellite (SMM). The Grant covered the period 1 July 1979 through 31 December 1982 and the total funds awarded amounted to $217,427.

The Grant provided funds for the replacement of obsolescent vacuum-tube dynamic spectrum analyzers, used at the Harvard Station for recording information on radio emission from flares and active regions on the sun, with new solid-state spectrum analyzers of higher sensitivity and much higher reliability. The Grant also provided support for an extensive observing program, in which spectral data on solar radio bursts were recorded daily from approximately sunrise to sunset, throughout the whole period of the grant. Summaries of the solar radio data were made available to all investigators connected with the SMM program, as well as to other solar and interplanetary scientists in the United States and throughout the world. The Principal Investigator and Station staff provided data for and took part in various joint programs of analysis with various members of the SMM teams. In addition, PI and Station staff took an active part in programs connected with the Solar Maximum Year (SMY) which covered the period 1 October 1979 through 28 February 1981.

The PI and Station staff took a particularly active part in the international programs known as the Study of Travelling Interplanetary Phenomena (STIP) that were carried out during the SMY. This work involved comparison of solar radio data taken at the Harvard Station with data on coronal transients obtained with the coronagraph-polarimeter on the SMM, the matching of the optical and radio data with computer models for propagation of flare-generated disturbances through the solar corona, and the comparison of the coronal data with the subsequent property of the disturbances as they propagated through the interplanetary plasma.

During the period of the grant, the Principal Investigator attended seven scientific meetings and read papers at five of these meetings. He also attended two workshops. Details of these meetings and workshops are listed at the end of the report. During the period of the grant, the Principal Investigator was senior author or co-author of six papers published in scientific journals and of three further papers which are now in publication. Details of these papers are also listed at the end of the report.

EQUIPMENT

With money provided from the Grant, new dynamic spectrum analyzers with high sensitivity were put into operation, for the observation of solar radio bursts, at the Harvard Station during 1979-1980. The new analyzers, which were of solid state design and of high sensitivity and high reliability, replaced aging vacuum tube equipment that was rapidly nearing the end of its life. The change to the new equipment was made without interruption of regular daily observing programs at the Harvard Station.

At the end of 1977, a small grant from NASA (Grant NSG-7391) made it possible to purchase components for one new experimental solar radio spectrum analyzer covering the band 50-100 MHz. The experimental analyzer functioned in an exceedingly satisfactory manner, covering the bands 25-50, 100-180, 180-320 and 320-580 MHz, were acquired with funds from Grant NSG 7648. The new analyzers were put into operation during the latter part of 1979 and 1980 and performed extremely well. Their higher sensitivity made it possible to record data on solar radio bursts at higher sensitivities. In particular, the new equipment made it possible to acquire important new data on solar radio bursts of spectral type II, which are generated by shock waves that originate in the more intense solar flares. Such shock waves are associated with the outward passage of higher-velocity optical transients recorded by coronagraph equipment carried on space vehicles such as the SMM.

OBSERVING PROGRAM

Observations of solar radio bursts were made at the Harvard Station daily throughout the complete period covered by the Grant, with dynamic spectrum analyzers covering the continuous frequency range 25-580 MHz. The Station was one of the main observatories providing 24-hour global coverage of the spectral characteristics of radio emissions from intense solar flares.

Summaries of the solar radio spectral data recorded at the station were prepared each month for publication in the NOAA Monthly Reports of Solar-Geophysical Data (Prompt Reports). In addition, the Harvard staff provided detailed information on radio emissions from specific solar flares to a large number of individual investigators.

Under the auspices of the international cooperative programs arranged for the SMY, the Principal Investigator took part in joint studies of a number of specified solar flares or flare sequences. Contributions of the

PI included provision of photographic records of solar radio spectral data recorded at the Harvard Station, examination of the relation of radio data on shocks generated by specific flares to optical data on associated ejecta, and the investigation of subsequent interplanetary phenomena. Some of theoptical data on these flares came from the coronagraph-polarimeter on SMM and some from the coronagraph on the P78-1 satellite.

RESEARCH PROGRAMS

Dryer and Maxwell (1979) examined the relation of radio data on shock waves generated by solar flares to computer models for the outward passage of fast-mode MHD shocks through the solar corona.

From data on a type II radio burst generated by a given flare, and with the assumption of an appropriate model for the electron density above the flare region, the radial velocity component of the outward-travelling shock that excited the type II burst was estimated to be about 1,100 km s^{-1}. The radio data on the shock were then compared on a minute-by-minute basis with a non-linear, two-dimensional, time-dependent computer simulation for the outward passage of a fast-mode MHD shock through the solar corona. The codes for the simulations were developed by Nakagawa et al., (1978), Steinolfson et al., (1978), Wu et al., (1978).

The magnetic topology assumed for the simulation 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 at the base of the corona over 5 degrees in heliographic latitude. 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 outwards in a quasi-exponential manner. (The density model for the computer simulation approximated the density model used for the interpretation of the radio data at heights of about 2 to 3 $R_{\odot}$.) The model was applied in the meridional plane, and the simulation was terminated at 6 $R_{\odot}$.

The computer simulation provided information on the global response of the corona to the input 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 investigation by Dryer and Maxwell, the best simulation for the radio data was given by a thermodynamic pulse which had the form of a square-wave of duration 10 min., containing a temperature (or pressure) increase of 40 times the ambient value. The energy in the applied pulse was of the order of 2×10^{32} erg. The ejected mass, as indicated by the computer simulation, was 6.4×10^{16} g. (It may be noted that Gosling et al. (1975) estimated the energy content and mass of matter ejected by a class 2B flare as 1.1×10^{32} erg and 2.4×10^{16} g, respectively.)

A comparison of the shock velocities derived from the computer model with shock velocities derived from radio data is shown in Figure 1. Velocity magnitudes and vectors for the movement of coronal plasma, determined from the computer simulation for times corresponding to 4 and 6 min after the input pulse was first applied, are shown in Figure 2.

Potential deficiencies of the present two-dimensional MHD computer models lie in their inability to simulate three-dimensional responses within complex magnetic topologies. Non-planar, two-dimensional (that is, quasi-three-dimensional) models are, however, now being developed by Nakagawa, et al., (1980). In the interim, the two-dimensional models seem to be in reasonable agreement with the observational data on the outward movement of shocks and material through the solar corona.

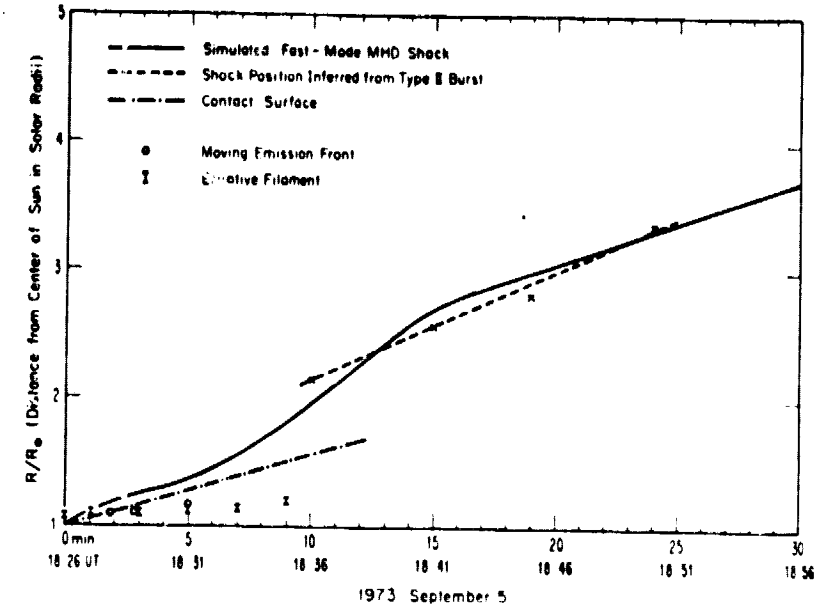

Figure 2. Comparison of radio data on a shock wave generated by a solar flare with the computer simulation for fast-mode MHD shock in the solar corona (Dryer and Maxwell, 1979).

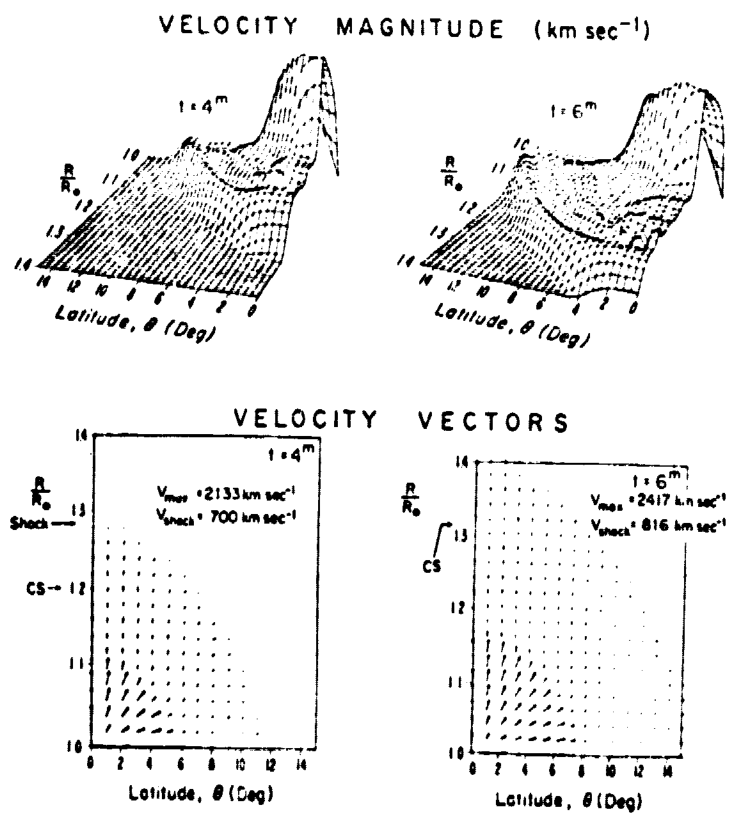

Figure 3. Bulk velocity magnitudes and vectors for the movement of coronal plasma, determined from a computer simulation, 4 and 6 minutes after the application of a given input pulse (Dryer and Maxwell, 1979).

In an extension of the work described above, Maxwell and Dryer (1981) examined 10 specific cases in which investigators have related data on fast-moving optical ejecta from flares to data on type II radio bursts and coronal shocks. The optical data mainly concerned fast Hα sprays, which may have velocities up to 1000 km s^{-1} and which may be tracked out to about 2 $R_\odot$, and the leading edges of white-light coronal transients, which may have velocities of the order of 1,000 km s^{-1} and which may be observed from about 2 to 10 $R_\odot$ (Figure 3).

Maxwell and Dryer suggested that there exist three main velocity regimes for shocks and ejecta originating in intense solar flares. The regimes are illustrated in Figure 4, which 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 explosive phase (t=0) was assumed to be signalled by the commencement of impulsive radio 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 was also presumed to be associated with the large-scale heating in the chromosphere and lower corona that ultimately gave rise to the ejection of plasma and to an outward-travelling shock.

No attempt was made 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.) The model is concerned only with the secondary phase (fluid response) of the corona. The type of secondary phase discussed in the model is, however, consistent with the description by Syrovatskii and Somov (1980) of a primary, explosive phase which involves current sheet disruption triggered

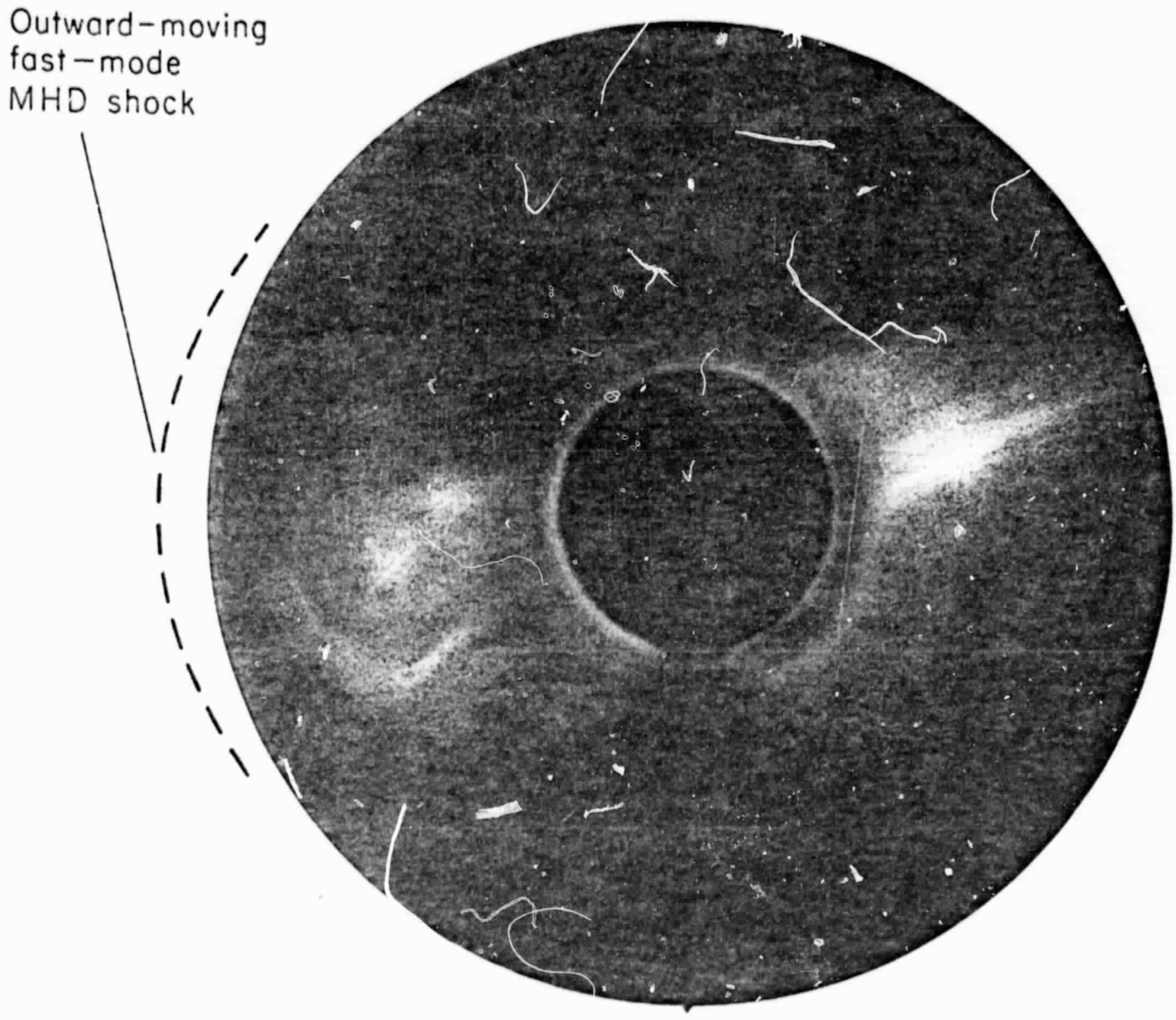

Figure 3 - White-light coronal transient photographed on 1973 October 27, 16:59 UT with eq pment on Skylab (Gosling et al., 1976). The flare that generated the transient commenced at 15:43 and was located at N20 E55. In the photograph, north is at the top and east to the left; the field of view is six solar diameters; the occulting disc is 1.5 solar diameters. The location of a shock wave, estimated to be 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 6.5 $R_{\odot}$ (Maxwell and Dryer, 1981).

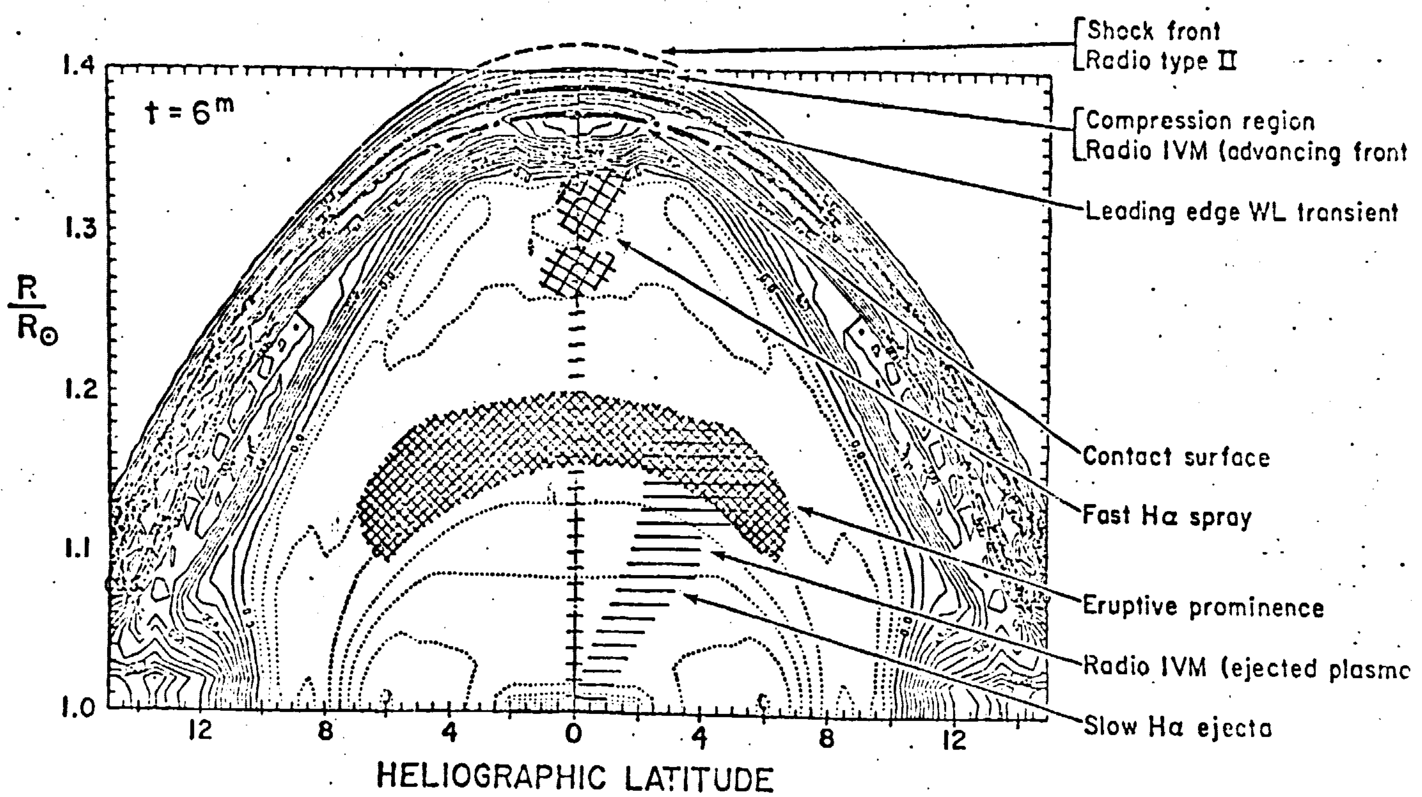

Figure 4 - Suggested model for the location of shock, contact surface, and flare ejecta 6 min after the explosive phase of a flare. Solid lines represent excess density contours; in the compressed region, densities reach about 5 times ambient values. Dotted lines indicate rarefaction (Maxwell and Dryer, 1981).

by tearing-mode instabilities, which are then followed by intense local chromospheric and coronal heating, etc. Mass within the chromosphere is thus 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 as a "pressure pulse" at the base of the corona. Magnetic control dominates 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), and by Wu et al. (1978). 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 in the corona.

Maxwell and Dryer suggested that the fastest velocity regime that develops after the explosive phase of a flare corresponds to that of a quasi-hemispherical shock wave moving outward from the flare with a velocity of the order 1,000 to 2,000 km s^{-1} and with an Alfvén Mach number of approximately 1.5. When the shock is fully developed it gives rise to type II radio bursts. The fast-moving type IV emission that is sometimes seen immediately behind a 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. 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 front-edge 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). This regime would also include the leading edges of fast white-light transients. (Behind the leading edges of the transients there may be white-light loops expanding outward at somewhat lower velocities.) Plasma betas in the region of the contact surface may be $\lesssim 0.1$. This regime might also cover higher-velocity flare sprays.

The third velocity regime would consist of slower-moving Hα ejecta, with velocities of the order of 300-500 km s^{-1}. This regime would also cover slower flare sprays, eruptive prominences, surges, moving type IV bursts of the ejected plasmoid or expanding arch varieties, and so on.

The two-dimensional MHD models described above made no allowance for the effect of the solar wind in the corona. The effect of the solar wind background in the corona on the models was, however, examined by Wu et al. (1981) who incorporated a parameter for the solar wind background in a model containing a simple radial magnetic field. Wu et al. found that the solar wind did not significantly affect the general dynamic characteristics of the mass motion as described in the earlier models. It was found, as anticipated, that the ambient solar wind merely increased the velocity of the mass motion and of the shock wave, as well as making moderate changes in the thermodynamic properties of the coronal plasma.

Potential deficiencies of the two-dimensional models lie mainly in their inability to simulate three-dimensional responses within complex magnetic topologies. In a recent fundamental and extensive development of the simulations, Nakagawa et al., 1981, and Wu et al., 1982 have extended the planar two-dimensional models to include the third components of the velocity and magnetic field vectors, thus providing quasi-three-dimensional simulations.

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Wu, S.T., Dryer, M., Nakagawa, Y., and Han, S.M., 1978, Astrophys. J., 219, 324.

Wu, S.T., Steinolfson, R.S., Dryer, M., and Tandberg-Hanssen, E., 1981, Astrophys. J., 243, 641.

Wu, S.T., Nakagawa, Y., Han, S., and Dryer, M., 1982, Astrophys. J., 262, 369.

SCIENTIFIC MEETINGS AND WORKSHOPS

During the period covered by the Grant the PI attended the following meetings and workshops:

1. IAU Symposium No. 86, "Radiophysics of the Sun"
   College Park, Maryland, August 1979

2. IAU General Assembly
   Montreal, Canada, August 1979

3. IAU Symposium No. 91, "Solar and Interplanetary Dynamics"
   Cambridge, Massachusetts, August 1979
   Paper: "Radio Data and Computer Simulations for Shock Waves Generated by Solar Flares" (with M. Dryer)
   IAU Symp. No. 91 (pub. D. Reidel), p. 251 (1980)

4. SCOSTEP-STIP Workshop on Shock Waves in the Solar Corona and Interplanetary Space
   Smolenice, Czechoslovakia, June 1980
   Paper: "Characteristics of Shocks in the Solar Corona, as inferred from Radio Optical and Theoretical Investigations" (with M. Dryer)
   Space Sci. Rev., 32, 11 (1982)

5. AAS Solar Physics Division
   Taos, New Mexico, January 1981
   Paper: "Solar Radio Bursts of Spectral Type II, Coronal Shocks, and Optical Coronal Transients" (with M. Dryer)
   Bull. Amer. Astron. Soc., 12, 899.

6. ISEE-3 Workshop on Flare-Generated Shock Waves, etc.
   Meudon, France, July 1981

7. Solar Maximum Year Workshop (STIP, SERF and FBS) on data acquired during the SMY
   Annecy, France, October 1981

8. American Astronomical Society 159th Meeting
   Boulder, Colorado, January 1982
   Paper: "Velocities of Shock Waves Generated by Solar Flares"
   Bull. Amer. Astron. Soc., 13, 861 (Abstract)

9. Fifth International Symposium on Solar Terrestrial Physics
   Ottawa, Canada, May 1982
   Paper: "Confrontation of MHD Computer Models with Observational Data on Optical and Radio Transients in the Solar Corona" (with M. Dryer)
   COSPAR 24th Plenary Meeting, Abstracts, p. 38 (Abstract)

PAPERS PUBLISHED

The following papers were published or accepted for publication:

Radio data and a theoretical model for the fast-mode MHD shock wave generated by the solar flare of 1973 September 5, 18:26 UT, Dryer, M. and Maxwell, A., Astrophys. J., 231, 945 (1979).

Abstract: Data on the solar radio burst of spectral type II generated by the solar flare of 1973 September 5, 18:26 UT are analyzed, and the radial velocity of the shock wave that gave rise to the radio burst is estimated at about 1,100 km s^{-1}. This estimate is critically dependent on the model assumed for electron density above the flare region and existing density models are therefore reviewed. Radio data on the shock are then compared with a theoretical model for the propagation of a fast-mode magnetohydrodynamic (MHD) shock through the corona. The simulated magnetic, velocity and thermodynamic parameters for the global coronal mass motion are presented. The input function used for the shock model is a square-wave pulse, of duration 10 min, containing a temperature increase of 40 times the ambient value. The energy in this pulse is 2×10^{32} erg and the ejected mass, as indicated by the MHD simulation, is 6.4×10^{16} g.

Radio data and computer simulations for shock waves generated by solar flares, Maxwell, A. and Dryer, M., IAU Symp. No. 91, p. 251 (1980).

Abstract: 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.

Solar radio bursts of spectral type II, coronal shocks, and optical coronal transients, Maxwell, A. and Dryer, M., Solar Phys., 73, 313 (1981).

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.

Characteristics of shocks in the solar corona, as inferred from radio, optical and theoretical investigations, Maxwell, A., and Dryer, M., Space Sci. Rev., 32, 11 (1982).

Abstract: Solar radio bursts of spectral type II provide one of the chief diagnostics for the propagation of shocks through the solar corona. Radio data on the shocks are compared with computer models for propagation of fast-mode MHD shocks through the solar corona. Data on coronal shocks and high-velocity ejecta from solar flares are then discussed in terms of a general model consisting of three main velocity regimes.

Solar radio bursts of spectral types II and IV during September 1977, Maxwell, A., UAG Report No. 83, pp. 105-108, pub. NOAA, Boulder, Colorado (February 1982).

Abstract: Data on solar radio bursts of spectral type II, recorded at Fort Davis, Texas, over the band 25-320 MHz for the month of September 1977 are presented, together with information from other radio observatories on solar radio bursts of spectral types II and IV. The relation of the radio bursts to the arrival of high-energy electrons and high-energy protons at the vicinity of earth is examined.

Measurements on a shock wave generated by a solar flare, Maxwell, A., and Dryer, M., Nature, 300, 237, (1982).

Abstract: Shock waves generated by intense solar flares may be driven by a large amount of ejected mass, about $5x10^{16}$ g, and the total energy invvolved may be of the order of 10^{32} erg. The shocks may have initial velocities of the order of 2000 km s^{-1} and, in their exodus through the corona, may be accompanied by fast-moving optical transients, the emission of highly characteristic radio signatures and the acceleration of particles to quasi-relativistic velocities. We review data on a high-velocity shock generated by a flare on 1979 August 18, 14:00 UT, comment on some previously deduced velocities for the shock, and discuss the propagation of the shock through the interplanetary plasma.

Shock Waves Generated by Solar Flares, Maxwell, A., Sky and Telescope, in press (1983).

Abstract: This paper discusses radio observations of shock waves generated by solar flares, optical observations of fast-moving coronal transients, and the manner in which the optical and radio data have been related to MHD computer simulations of shocks and ejecta from solar flares. The disturbances generated by intense solar flares are compared and contrasted by those resulting from hydrogen bombs on the Earth.

Velocities of flare-generated shock waves derived from data on solar radio bursts of spectral type II, Maxwell, A., Solar Phys., in press (1983).

Abstract: The velocities of flare-generated shocks, as they propagate outward through the solar corona and the interplanetary plasma, may be determined from the spectral characteristics of solar radio bursts of spectral type II, if an appropriate model for thedistribution of electron density with height is assumed. Most investigators have used an electron density model of the order of 10 times the quiet sun level at solar minimum and obtain shock velocities of the order of 1000-1500 km s^{-1}. Recently, however, some authors haveused electron density models of the order of two times the quiet sun levels and deduce shock velocities of the order of 500-700 km s^{-1}. The validity of the low electron density models and of resulting low shock velocities is examined.

Magnetohydrodynamic simulation of the coronal transient associated with the solar limb flare of 1980 June 29, 18:21 UT, WU, S.T., Wang, S., Dryer, M., Poland, A.I., Sime, D.G., Wolfson, C.J., Orwig, L.E., and Maxwell, A., Solar Phys., in press (1983).

Abstract: Soft X-ray data from the XRP experiment on SMM are used to generate the temperature and density in the flaring region of the 1980 June 29, 18:21 UT solar flare. The temporal data ($T_{max} \approx 20 \times 10^6$ °K and $n_{max} \approx 4 \times 10^{11}$ cm^{-3}) are used to simulate mass injection as the input pulse for the MHD model of Wu et al. (1982a). The spatial and temporal coronal response is compared with the ground-based, Mark III K-coronameter observations of the subsequent coronal transient. The simulation produces a spatially-wide, large amplitude MHD wave for either of the two "canonical" magnetic topologies (closed and open), but no shock wave. This result appears to be confirmed by the fact that a type II radio event was observed late in the event for only a few minutes. The density enhancements produced by the simulation move away from the sun at the same velocity observed by the K-coronameter. However, the observation of the coronal transient included a rarefaction that does not appear in the simulation. A probable explanation for this discrepancy is the likelihood that the magnitude and temporal profile of the density of the soft x-ray emitting plasma should not have been used as part of the mass injection pulse. We believe that the temperature profile alone, as suggested by earlier simulations, might have been a necessary and sufficient condition to produce both the compression and rarefaction of the ambient corona as indicated by the K-coronameter data. Hence, the dense plasma observed by XRP was probably confined, for the most part, close to the sun during the 17 min duration of the observations.