Coronal shock waves observed in images

H. S. Hudson

Space Sciences Lab, UC Berkeley

Abstract. The large-scale coronal shock waves observed from radio type II bursts and from Moreton waves have proven surprisingly difficult to detect in coronal images. I review the evidence for such waves in radio, optical, EUV, and soft X-ray images. The data generally support the conclusion that the metric type II bursts can be identified with weak fast-mode shock waves launched at the impulsive phase of the associated flares. Other coronal waves, well seen by EIT, are more closely related to CMEs.

Keywords: Corona, Shock Waves, Flares, Coronal Mass Ejections
PACS: 96.60.Pb, 96.60.Rd, 96.60.Wh

INTRODUCTION

Flares and coronal mass ejections (CMEs) involve restructuring of significant volumes of the coronal magnetic field, and thus launch large-scale waves. The discovery of radio type II bursts showed immediately that these waves became shocks, following the now well-established theoretical picture that non-linear effects at the shock create Langmuir waves at the plasma frequency, and these then scatter and emit electromagnetic radiation (e.g., [1]). The further evidence from the phenomenon of the “Moreton wave” as observed in the chromosphere, via Uchida’s unified theoretical interpretation [2], convincingly demonstrated that large-scale shock waves commonly occur in the solar corona. In the heliosphere one has direct in-situ and geomagnetic observations of shocks driven by CMEs, but the relationship between these shocks and the ones sensed remotely in the solar corona still remain somewhat controversial.

New observational facilities have become available in the last decade of the twentieth century; these have made it possible to glimpse coronal shock waves at new wavelengths, including most directly soft X-rays (which show the direct thermal emission of the million-degree plasma). The soft X-ray images can be interpreted in terms of density and temperature jumps at a shock front. Because of observational limitations we can never actually resolve the structure of a coronal shock front; only the non-thermal signatures such as radio waves or particle acceleration can confirm that a given disturbance or wave has actually approached the shock condition. We present these briefly and then comment on the implications for our understanding of coronal dynamics, the relationship between the coronal phenomena and those observed in the heliosphere, and the physical parameters of the shocked material in the corona.
We still do not have much knowledge of large-scale wave generation and propagation in the corona (see discussion below), even with a long history of MHD model development (e.g., [4]) for flares and CMEs. This reflects our ignorance of the actual structural changes during the flare impulsive phase and the acceleration of the CME. To create a large-amplitude wave requires a motion perpendicular to the field that is rapid on the Alfvén time scale ([5]; [6]). We believe these initial motions to be in regions of low plasma beta, and the wave disturbance will therefore not reach the shock condition until it or the disturbance itself has propagated some distance (see Figure 1). Interplanetary shock waves observed in the heliosphere should have the character of bow waves; if the disturbance propagates into a region of reduced Alfvén speed, a high Mach number may result [7].

The imaging observations give us a means for assessing the Mach number of any given disturbance via the Rankine-Hugoniot jump conditions (see [8] for a discussion in this context). The first step here is to estimate the local plasma density (or temperature) from the observations. This is tricky because the observations only give line-of-sight integrations of a 3D structure of unknown dimensions (see below on modeling).

The relative roles of solar flares and CMEs in launching and driving large-scale waves remains controversial; for simplicity some would prefer to have CMEs be responsible for all large-scale waves, since the association of CME-induced driver gas and heliospheric shock waves is well established in the interplanetary medium. On the other hand the time development of the metric type II burst and Moreton wave point quite clearly to the flare itself. The observational situation is often confused because a well-studied major
FIGURE 2. Dynamic radio spectrograph of a prototypical event: impulsive type III bursts plus a very regular type II burst, fundamental and harmonic. Time scale is in minutes. Note the gap in time between the type III and type II, interpreted as the interval between the wave origination and the onset of the shock condition (e.g., [6]).

event will usually have examples of all phenomena (Kahler’s “big flare syndrome”). Theoretically we do not know much about the sources of the waves in the lower corona, which are usually outside the field of view of a coronagraph; worse yet, the usual PFSS\textsuperscript{1} modeling framework deliberately introduces geometrical artifacts between the corona and the solar wind.

Figure 2 illustrates the possible ambiguities. In this example, an observation from the Culgoora spectrograph, the type III emission presumably mark the impulsive phase of the solar flare. The type II emission begins about 5 minutes afterwards, with its plasma-frequency fundamental band at about 60 MHz. At an exciter speed of \(\sim 2000 \text{ km s}^{-1}\) (the Alfvén speed in an active region at \(B = 300 \text{ g}, n = 10^9 \text{ cm}^{-3}\), this would correspond to a travel distance on the order of \(1 \text{ R}_\odot\) to a location at a density of some \(5 \times 10^7 \text{ cm}^{-3}\). How does this information fit into the real corona at the time of the observation? This density is much higher than that of a spherically-symmetric model corona at a height matching this travel distance (e.g., [9]). On the other hand [10] note a good agreement between UV coronagraphic observations of density and the directly observed type II burst frequency for a flare event on June 11, 1998.

\textsuperscript{1} Potential Field Source Surface
FIGURE 3. Soft X-ray observations of a large-scale wave from a W limb flare on May 6, 1998 ([14]). The image is about 0.2 R⊙ across and the limb runs vertically through the (saturated) flare core; the wave thus extends into the corona in projection.

NEW OBSERVATIONS

There are as many as five new observational windows on large-scale coronal shock waves: the EUV observations of “EIT waves” ([11]; [12]); soft X-ray observations from Yohkoh/SXT ([13]; [14]; Figure 3); microwave observations at 17 GHz from Nobeyama ([15]); meter-wave observations from Nançay ([16]); and HeI 10830Å observations from Mauna Loa ([17]). All of these except for the Nançay data reflect thermal emissions; at metric wavelengths one presumably sees synchrotron emission from relativistic electrons trapped in expanding CME structures (e.g., [18]).

The passage of a compressive wave through the corona will produce a front of temperature and density increase. The thermal response at radio wavelengths will be free-free emission (bremsstrahlung), with the intensity increasing directly with temperature according to the Rayleigh-Jeans law. At short wavelengths the wave will have more complicated effects, depending upon the passband of the detector. A broad-band observation, such as soft X-rays, will generally see an increase at the shock front, but a narrow-band observation could actually show a decrease in intensity if the temperature change results in the disappearance of a strong emission line from the passband. The sensitivity in the EUV or in a coronal emission line would therefore depend not only on the geometry of the wave structure, but also the ambient temperature.

The new observations generally are consistent with a “two-wave” scenario: a weak fast-mode blast wave in the lower corona, plus a CME-driven disturbance. The extensive EIT observations appear to show both kinds of wave activity ([19]; [20]). Figure 4 illustrates a good association between an EIT wave (seen in EUV) and a Moreton wave (seen in bbHα).
MODELING IDEAS AND CONCLUSIONS

Blast waves running freely away from their launch site propagate through unperturbed coronal field. A model corona consisting of a realistic extrapolation of the photospheric field, plus a mass loading consistent with the X-ray observations, could in principle be used to study blast-wave propagation. The refraction of these waves around magnetic obstacles is known observationally [14] and also expected theoretically [2] as the wave normals bend towards regions of lower Alfvén speed. Ideally the mass loading would be computed self-consistently along with the field structure, but an easier approach would be to make use of a PFSS (potential-field source surface) model, as for example in the recent simulations of the global corona by [22]. This model makes allowances for electric currents flowing in the body of the solar corona by using a fictitious current system on a solar-wind source surface, typically taken to be at 2.5 R⊙. This approach provides suprisingly good fidelity in many applications, for example in tracing the locations of open field lines, but it clearly distorts the field geometry near the source surface itself. Nevertheless, until a self-consistent model based on better knowledge of the physics appears (e.g., [20]), the PFSS framework should be explored as a guide to interpreting images in terms of large-scale waves.

The imaging of large-scale wave disturbances in the solar corona, together with models of ambient (and transient) coronal structure can help us to understand the formation of the waves. It may also ultimately help us to understand the basic mechanisms of coronal restructuring by flares and CMEs.

ACKNOWLEDGMENTS

Corona solaris in undas divisa est. This work has been supported by NASA under grant NAG5-12878. For more graphics related to the conference presentation, please see http://sprg.ssl.berkeley.edu:80/ ~hhudson/presentations/palmsprings.050303/.
REFERENCES