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EIT wave observations and modeling in the STEREO era

Andrei N. Zhukov [a,b,*]

[a] Solar–Terrestrial Center of Excellence – SIDC, Royal Observatory of Belgium, Avenue Circulaire 3, B-1180 Brussels, Belgium
[b] Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119992 Moscow, Russia

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ABSTRACT

"EIT waves" are large-scale bright fronts observed propagating in the solar corona in association with coronal mass ejections (CMEs). An overview of the observed properties of large-scale wave-like fronts in the solar atmosphere (Moreton waves, EIT waves and similar phenomena observed in other wavelengths) is presented. The models proposed to explain these phenomena are reviewed. A particular emphasis is put on the recent EIT wave observations made by the STEREO (Solar–TErrestrial RElations Observatory) mission launched in October 2006. New key observational results and their implications for EIT wave models are discussed. It is concluded that no single model can account for the large variety of observed EIT wave properties. Prospects for future investigations of this complex phenomenon are outlined.

1. Historical introduction

Transient solar phenomena occur on a variety of spatial scales. It may be considered surprising that it was not the large-scale but the small-scale transient phenomena (sunspot and faculae evolution, granules, spicules, flares, etc.) that were discovered first. These phenomena are relatively easy to detect in observations of the photosphere and chromosphere. However, due to the high density of the photosphere and chromosphere, it is difficult to produce large-scale disturbances in these layers. As we now know, at large scales the corona is more variable than the lower layers of the solar atmosphere, but observations of the corona are difficult (e.g. Golub and Pasachoff, 2010). This is especially true for regular observations over long periods that are needed to catch relatively rare and transient eruptive solar phenomena.

Solar prominences were discovered a long time ago using solar eclipse observations. They were usually found to be limited in size. However, since the observations of giant prominence eruptions have been made (e.g. Pettit, 1919), it became clear that transient phenomena in the solar atmosphere can occur at a large scale (comparable to the solar radius). The discovery of type II bursts in dynamic radio spectra of the Sun (Wild and McCready, 1950) was another indication of large-scale disturbances in the solar corona (e.g. Nelson and Melrose, 1985), although the large-scale nature of type II radio bursts became clear only later, after interferometric observations (Weiss and Sheridan, 1962; Weiss, 1963) and radio imaging of their sources (Wild et al., 1968; Kai and McLean, 1968) were made. The first intrinsically large-scale transient phenomenon discovered in the images of the solar atmosphere was Moreton wave (Moreton, 1960; Moreton and Ramsey, 1960). As it will be shown below, the link between EIT waves (that are the subject of the present review) and Moreton waves is still controversial. Nevertheless, very similar models are often applied to explain these two phenomena. It is thus instructive to start with a description of observations and modeling of Moreton waves.

Moreton waves are dark arc-shaped large-scale fronts propagating in the solar chromosphere as observed in the center and wings of the Hα line at 6563 Å (e.g. Moreton, 1960; Eto et al., 2002; Warmuth et al., 2004a). The speed of Moreton waves can reach 800-1000 km s^{-1} and even larger (Moreton and Ramsey, 1960; Athay and Moreton, 1961). Moreton waves are observed to propagate up to 5×10^5 km from the flare site in a limited angular sector (e.g. Moreton, 1964), although a global propagation in all directions can sometimes be observed as well (Pick et al., 2005; Muhr et al., 2010). Sometimes the propagation of Moreton waves can be inferred from a sudden oscillation of a distant filament (e.g. Moreton and Ramsey, 1960; Moreton, 1964; Dodson and Hedeman, 1964; Smith and Harvey, 1971; Eto et al., 2002; Gilbert et al., 2008). Another key property of Moreton wave fronts is their visibility in the Hα line wings. The front detected in the blue wing of the line propagates immediately behind the front detected in the red wing (Moreton, 1964; Dodson and Hedeman, 1964; Eto et al., 2002). This implies that the chromosphere locally moves downward and then upward (at a speed of around 10 km s^{-1}) as the wave front propagates through it.

It can be easily seen that such a fast disturbance can hardly be explained by the propagation of a wave in the chromosphere. Indeed, taking typical chromospheric parameters (temperature $T = 10^4$ K, electron number density $n_e = 5 \times 10^{10}$ cm^{-3}, magnetic field $B = 10$ G), the sound speed is then $c_s = \sqrt{\gamma k T / m_p} \sim 12$ km s^{-1} and the Alfvén speed $v_A = B/\sqrt{4\pi m_p n_e} \sim 100$ km s^{-1} (k is the

* Correspondence address: Solar–Terrestrial Center of Excellence – SIDC, Royal Observatory of Belgium, Avenue Circulaire 3, B–1180 Brussels, Belgium.
Tel.: +32 2 790 3924.
E-mail address: Andrei.Zhukov@sidc.be

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Boltzmann constant, $\gamma = 5/3$ is the ratio of specific heats and m_p is the proton mass). These values are at least an order of magnitude lower than the observed speeds. The occurrence of a very fast shock (with the Alfvén-Mach number $M_A \sim 10$) seems unlikely as the observed large distances of the wave propagation contradict the expected quick dissipation of such a shock (Uchida, 1968). This led to Meyer (1968) and Uchida (1968) conjecturing that the wave actually propagates in the corona, but produces the observed Moreton wave signatures as it encounters the chromosphere. Indeed, taking typical values for the coronal density (around $n = 10^8$ cm^{-3}) and temperature (around $T = 10^6$ K), and assuming a coronal magnetic field of around $B = 5$ G, the sound and Alfvén speeds are then $c_s \sim 120$ and $v_A \sim 1000$ km s^{-1}, respectively. Unlike the propagation of the Alfvén and slow magnetosonic waves, which strongly depends on the direction of the ambient magnetic field, fast magnetosonic (or fast-mode) waves propagate in all directions with respect to the magnetic field at a speed given by the following equation:

$$v_f^2 = \frac{1}{2}\left(v_A^2 + c_s^2 + \sqrt{(v_A^2 + c_s^2)^2 - 4v_A^2 c_s^2 \cos^2\theta}\right), \quad (1)$$

where θ is the angle between the direction of the wave propagation and the ambient magnetic field. A coronal medium with a low plasma beta is usually assumed ($\beta = 8\pi p/B^2 \sim c_s^2/v_A^2 \ll 1$, where p is the plasma pressure). It can be seen that in such a low-beta plasma the fast magnetosonic speed is of the order of the Alfvén speed.

Uchida (1968) solved linearized magnetohydrodynamic (MHD) equations and presented a detailed model of a fast magnetosonic wave propagating in the spherically symmetric corona with the radial magnetic field. Uchida's model adopted the short-wavelength, or WKB (Wentzel–Kramers–Brillouin) approximation assuming that coronal parameters do not change at the scale comparable to the wavelength. This approximation allowed Uchida (1968) to consider the problem in a similar way to that of geometrical acoustics (see e.g. Blokhintsev, 1981), so this approach can be called "geometrical magnetoacoustics". The wave propagates in the medium with inhomogeneous distribution of the characteristic speed (in this case, the fast magnetosonic speed), so its raypaths are curved as the wave is refracted away from high-Alfvén speed regions. In the configuration described by Uchida (1968), the wave packets are refracted downward and eventually reach the surface, producing the down-up swing of the chromosphere in agreement with observations (Fig. 1).

Later, the model by Uchida (1968) was extended to more realistic configurations of coronal plasma and magnetic field parameters (Uchida et al., 1973). The narrow angular span of the Moreton wave propagation was explained via the reflection of the wave packets from the regions of high Alfvén speed (Uchida, 1970). Finally, a fast magnetosonic wave may steepen to form a shock wave. This shock may—under certain conditions—produce a radio type II burst (see e.g. Nelson and Melrose, 1985). Early imaging observations of type II source positions roughly agreed with locations where the fast magnetosonic wave was expected to be shocked due to local minima of the coronal Alfvén speed (Uchida, 1974). Observational data confirm a high association between type II bursts and Moreton waves (e.g. Smith and Harvey, 1971; Harvey et al., 1974; Thompson et al., 2000b; Warmuth et al., 2004b; Warmuth, 2010).

The works by Uchida (1968, 1970) represent a prediction of the existence of large-scale coronal fast magnetosonic waves. Imaging observations of type II burst sources allowed us to make early tests of this prediction, with some success. Another test of this prediction was made when routine high-cadence observations of the solar corona became available in the 1990s with the advent of the Yohkoh and SOHO missions.

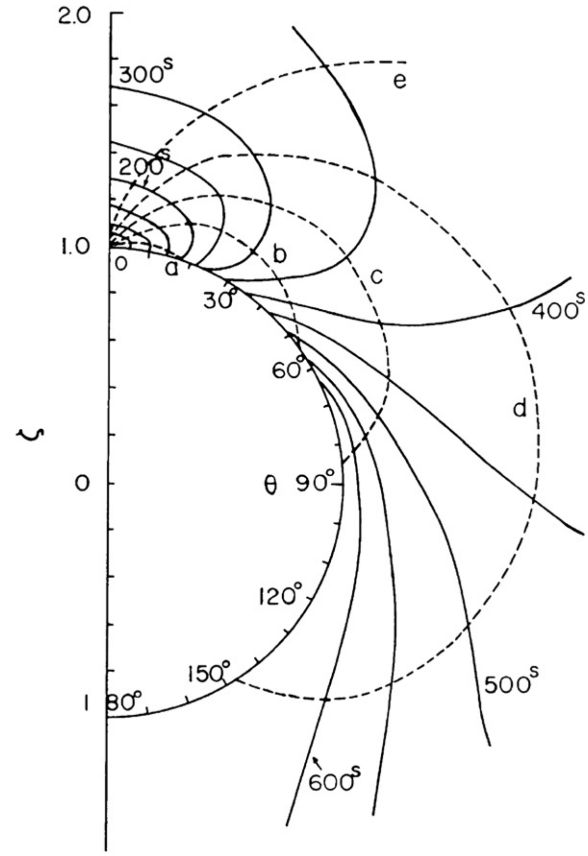

Fig. 1. Several representative paths of fast magnetosonic wave packets (dashed lines) propagating in the solar corona as calculated by Uchida (1968). The circle of a radius $\zeta = 1.0$ centered at $\zeta = 0$ is the solar surface. Solid lines represent corresponding wave fronts. The source of the wave is located at $\zeta = 1.0$, $\theta = 0^\circ$. Note that the wave packets are deflected downward (towards the solar surface). From Uchida (1968).

2. Pre-STEREO observations of EIT waves

The first years of coronal observations made by the Yohkoh Soft X-ray Telescope (SXT, see Tsuneta et al., 1991) did not result in detection of large-scale coronal waves. However, the observations made by the Extreme-ultraviolet Imaging Telescope (EIT, see Delaboudinière et al., 1995) onboard the Solar and Heliospheric Observatory (SOHO) produced a drastically different result. Coronal images taken in the 195 Å extreme-ultraviolet (EUV) bandpass dominated by the Fe XII emission line (peak formation temperature around 1.5 MK) showed the occurrence of large-scale wave-like events (Thompson et al., 1998, 1999), see Fig. 2. As the waves were discovered in the EIT data, they were named "EIT waves".[1] For earlier reviews of EIT waves, see e.g. Zhukov (2004), Warmuth (2007), Wills-Davey and Attrill (2009) and Gallagher and Long (2010).

2.1. Interpreting EIT images

The interpretation of data taken by an EUV imager like SOHO/EIT will be briefly described in this section. The intensity of a coronal collisionally excited optically thin spectral line can be written as follows (e.g. Phillips et al., 2008):

$$I_\lambda = \int_h G(T, n_e) n_e^2 \, dh, \quad (2)$$

[1] EIT waves were briefly mentioned in earlier works by Moses et al. (1997) and Dere et al. (1997a), but the work by Thompson et al. (1998) was the first to present a detailed analysis of the EIT wave phenomenon.