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# Large-scale waves in the solar corona: The continuing debate

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**Abstract**

Ten years after the first observation of large-scale wave-like coronal disturbances with the EIT instrument aboard *SOHO*, the most crucial questions concerning these "EIT waves" are still being debated controversially – what is their actual physical nature, and how are they launched? Possible explanations include MHD waves or shocks, launched by flares or driven by coronal mass ejections (CMEs), as well as models where coronal waves are not actually waves at all, but generated by successive "activation" of magnetic fieldlines in the framework of a CME. Here, we discuss recent observations that might help to discriminate between the different models. We focus on strong coronal wave events that do show chromospheric Moreton wave signatures. It is stressed that multiwavelength observations with high time cadence are particularly important, ideally when limb events with CME observations in the low corona are available. Such observations allow for a detailed comparison of the kinematics of the wave, the CME and the associated type II radio burst. For Moreton-associated coronal waves, we find strong evidence for the wave/shock scenario. Furthermore, we argue that EIT waves are actually generated by more than one physical process, which might explain some of the issues which have made the interpretation of these phenomena so controversial.


*Keywords:* Sun; Solar corona; Solar flares; Coronal mass ejections; Waves; Shocks

## 1. Introduction

Signatures of large-scale wavelike disturbances propagating through the solar atmosphere have first been observed in the solar chromosphere in the 1960s (Moreton, 1960). These *Moreton waves* appear as arc-shaped fronts propagating away from flaring active regions (ARs) at speeds of the order of 1000 $\mathrm{km\,s^{-1}}$. The fronts are seen in emission in the center and in the blue wing of the H$\alpha$ line, whereas in the red wing they appear in absorption, which is interpreted as a Doppler shift due to a depression of the chromosphere by an invisible agent (Moreton, 1964). In combination with their high speed, this was taken as evidence for the scenario that Moreton waves are just the ground-track of a dome-shaped MHD wavefront that expands through the corona and sweeps over the chromosphere (Uchida et al., 1973; and references therein). The same *MHD wave* can generate metric type II bursts when it steepens to a *shock* (Uchida, 1974), and it can excite filament oscillations (e.g. Eto et al., 2002). Originally the wave was considered as a flare-launched freely propagating blast wave, but in principle also a coronal mass ejection (CME) can launch such a wave, or alternatively create a driven disturbance.

A decade ago, the Extreme Ultraviolet Imaging Telescope (EIT; Delaboudinière et al., 1995) aboard *SOHO* first detected actual coronal signatures of large-scale propagating wave-like disturbances (Thompson et al., 1998). They were originally interpreted as the coronal counterpart of the chromospheric Moreton waves, and some events have been successfully modelled as fast-mode waves (Wang, 2000; Wu et al., 2001). However, it quickly turned out that EIT waves, as these disturbances came to be known, have rather different characteristics. They show a wider range of morphological patterns (cf. Klassen et al., 2000), ranging from sharp Moreton-like fronts to diffuse and irregular brightenings. They are significantly slower than Moreton

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waves, with typical propagation speeds of only a few 100 km s$^{-1}$. Moreover, they show a large velocity spread – the slowest disturbances propagate with only a few tens of km s$^{-1}$ (cf. Wills-Davey et al., 2007), which is significantly slower than both the sound and the Alfvén speed in the corona. Some EIT fronts seem to stop at coronal hole boundaries (e.g. Delannée and Aulanier, 1999; Delannée et al., 2007), and there are reports of rotating wavefronts (Attrill et al., 2007).

These observations have led to the development of some alternative models. In the *magnetic reconfiguration scenarios*, EIT waves are not waves in the physical sense, but rather the consequence of the reconfiguration of magnetic field lines during a CME lift-off (Delannée, 2000; Delannée and Aulanier, 1999). Depending on the magnetic topology, this mechanism can generate propagating as well as stationary bright fronts, either due to the generation of currents (Delannée et al., 2007; and references therein) or driven magnetic reconnection (Attrill et al., 2007) at the boundary between the expanding magnetic structure and the ambient field. Finally, both models can be combined, since an expanding CME will also generate waves. Such a scenario has been developed by Chen et al. (2002). Here, an erupting flux rope drives a piston shock. The top of this CME-driven shock generates the type II radio burst, while its legs extend down to the solar surface where they can produce Moreton waves. Simultaneously, behind the legs of the shock a plasma density enhancement is propagating at a lower speed (it may be even stationary). This feature is due to successive stretching or opening of closed field lines covering the erupting flux rope, and based on its velocity it is interpreted as the EIT wave. The Chen model thus explains the velocity discrepancy between Moreton and EIT waves by invoking two physically distinct disturbances.

Thus, 10 years after the discovery of EIT waves, the physical nature of these disturbances is still discussed controversially. Determining which of the competing models best conforms to reality requires accumulating as much information as possible about the wave events. Luckily, wave signatures have also been discovered in soft X-rays (SXR; Narukage et al., 2002; Khan and Aurass, 2002) and in chromospheric Helium I (HeI) filtergrams (Gilbert et al., 2001; Vršnak et al., 2002), opening up new channels of information. In this paper, we therefore combine two approaches: on the one hand, we study in detail the kinematics and perturbation evolution of coronal waves with the help of multiwavelength data set including Hα, extreme ultraviolet (EUV), soft X-rays (SXR), Helium I (HeI) and radio observations. On the other hand, we include significantly more events than is typical for in-depth case-studies. This allows us to study correlations between different wave parameters and possible wave sources.

## 2. Events and data sources

In this paper, we focus on coronal waves that show Moreton wave signatures. These waves may be regarded as the "large-amplitude limit" of the phenomenon, since it requires a stronger perturbation to perturb the dense chromosphere (cf. Warmuth et al., 2004b). Early in these events, also the coronal signatures of the disturbances tend to be more intense and coherent than in an average coronal wave event. This allows to measure the kinematics and profile evolution with sufficient accuracy. In addition, Hα data usually provide much better temporal cadence than coronal observations, and can be easily corrected for projection effects. These are the main reasons for the restriction to this subclass of events.

An in-depth search of various Hα data archives has turned up 27 Moreton wave events in the range from 1997 to 2006. The multiwavelength approach is crucial, since the image cadence of EIT (typically 12 min) is too low for a detailed study of the waves' kinematics. Besides EIT data (for 21 events), additional coronal observations in the SXR regime were available from *Yohkoh*/SXT (Tsuneta et al., 1991; 6 events) and *GOES*-SXI (Hill et al., 2005; Pizzo et al., 2005; 12 events). Full-disk Hα data were provided by the solar observatories at Kanzelhöhe (Otruba and Pötzi, 2003), Big Bear (Denker et al., 1999), Mauna Loa (the PICS instrument; Fisher et al., 1981; see also Gilbert et al., 2008), Hida (the FMT telescope[1]; Kurokawa et al., 1995; and the SMART telescope[2]; UeNo et al., 2004), Meudon (see Manoharan and Kundu, 2003; and references therein), and by the O-SPAN (Neidig et al., 1998) instrument. The cadence of Hα images is typically between 30 s and 3 min, which is significantly better than the cadence of the coronal observations. Additional chromospheric observations in the HeI line at 10,830 Åwere available from the CHIP instrument (Elmore et al., 1998) at Mauna Loa for 11 events.

The relation of the coronal waves with associated type II bursts was studied using dynamic radiospectra from the following radiospectrographs: Potsdam-Tremsdorf (Mann et al., 1992), Culgoora (Prestage et al., 1994), and the RSTN network of the US Air Force (Guidice et al., 1981).[3] Coronagraphic data for low heights was available for one event from the Mk-3 K-coronameter at Mauna Loa Solar Observatory (Fisher et al., 1981). The timing of the associated hard X-ray (HXR) bursts was derived from *CGRO*/BATSE (Fishman et al., 1989), *Yohkoh*/HXT (Kosugi et al., 1991) and *RHESSI* (Lin et al., 2002) data.

Table 1 shows an overview of the large-amplitude coronal wave events and some associated phenomena. Shown are the event date, the NOAA number of the source active region, *NOAA no.*, the coordinates and GOES importance of the associated flare, *flare loc.* and *flare imp.*, the linear speed of the associated CME in km s$^{-1}$, $v_{lin}$, and whether

[1] http://www.kwasan.kyoto-u.ac.jp/general/facilities/fmt/index_en.html.

[2] http://www.hida.kyoto-u.ac.jp/smart/.

[3] http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarradio.html#spectralgraphs.