

## What is the Nature of EUV Waves? First STEREO 3D Observations and Comparison with Theoretical Models

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### Abstract

One of the major discoveries of the Extreme ultraviolet Imaging Telescope (EIT) on SOHO were intensity enhancements propagating over a large fraction of the solar surface. The physical origin(s) of the so-called ‘EIT’ waves is still strongly debated. They are considered to be either wave (primarily fast-mode MHD waves) or non-wave (pseudo-wave) interpretations. The difficulty in understanding the nature of EUV waves lies with the limitations of the EIT observations which have been used almost exclusively for their study. They suffer from low cadence, and single temperature and viewpoint coverage. These limitations are largely overcome by the SECCHI/EUVI observations on-board the STEREO mission. The EUVI telescopes provide high cadence, simultaneous multi-temperature coverage, and two well-separated viewpoints. We present here the first detailed analysis of an EUV wave observed by the EUVI disk imagers on December 07, 2007 when the STEREO spacecraft separation was  $\approx 45^\circ$ . Both a small flare and a CME were associated with the wave. We also offer the first comprehensive comparison of the various wave interpretations against the observations. Our major findings are: (1) high-cadence (2.5 min) 171Å images showed a strong association between expanding loops and the wave onset and significant differences in the wave appearance between the two STEREO viewpoints during its early stages; these differences largely disappeared later, (2) the wave appears at the active region periphery when an abrupt disappearance of the expanding loops occurs within an interval of 2.5 minutes, (3) almost simultaneous images at different temperatures showed that the wave was most visible in the 1-2 MK range and almost invisible in chromospheric/transition

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region temperatures, (4) triangulations of the wave indicate it was rather low-lying ( $\approx 90$  Mm above the surface), (5) forward-fitting of the corresponding CME as seen by the COR1 coronagraphs showed that the projection of the best-fit model on the solar surface was not consistent with the location and size of the co-temporal EUV wave and (6) simulations of a fast-mode wave were found in a good agreement with the overall shape and location of the observed wave. Our findings give significant support for a fast-mode interpretation of EUV waves and indicate that they are probably triggered by the rapid expansion of the loops associated with the CME.

**Keywords:** Flares, Dynamics; Corona

## 1. Introduction

One of the major discoveries of EIT on SOHO (Delaboudinière et al. 1995) was the existence of conspicuous large-scale EUV propagating intensity disturbances. These intensity fronts sometimes have the appearance of an almost circular wave front and are frequently called EIT or EUV waves (e.g., Moses et al. 1997; Thompson et al. 1998; Thompson et al. 1999). EUV waves are normally first seen in close proximity to a flaring and erupting active region and they subsequently propagate over a significant fraction of the visible surface before they become too faint to be detected. EIT observations have found that they travel at speeds 50-400 km/s. Statistical studies showed that they are mostly associated with Coronal Mass Ejections (CMEs) and not with flares (e.g., Biesecker et al. 2002). There is a tendency for the fastest EUV waves to be associated with similar phenomena in  $H\alpha$ , and soft X-rays and to produce type-II radio bursts (e.g., Moreton 1960; Athay and Moreton 1961; Klassen et al. 2000; Kahler and Hudson 2001; Cliver et al. 2001; Narukage et al. 2002; Hudson et al. 2003; Gilbert et al. 2004; Vršnak et al. 2006). There is an extensive literature on this subject (e.g., Wills-Davey and Thompson 1999; Delannée 2000; Klassen et al. 2000; Kahler and Hudson 2001; Wu et al. 2001; Narukage et al. 2002; Ofman and Thompson 2002; Gilbert et al. 2004; Zhukov and Auchère 2004; Podladchikova and Berghmans 2005; Warmuth and Mann 2005; Veronig et al. 2006; Vršnak et al. 2006). Reviews on the topic can be found in Chen and Fan (2005), Gopalswamy et al. (2006), Pick et al. (2006), Schwenn et al. (2006), Warmuth (2007).

Despite the extensive research on these phenomena, significant controversy remains over the physical origin(s) of the EUV waves. One interpretation states that EUV waves are global fast-mode waves triggered by the associated flare or CME (e.g., Thompson et al. 1999; Wang 2000; Wu et al. 2001; Ofman and Thompson 2002). The expectation of finding fast-mode waves in the corona was originally considered by Uchida (1968). Fast-mode waves can travel over large distances over the solar surface since they can propagate at right angles with respect to the ambient, radial to a first approximation, magnetic field of the quiet Sun regions which occupies most of the solar surface, particularly during solar minimum conditions. Moreover, they have a compressive character which can lead to the intensity enhancement associated with the EUV waves. In

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what follows we will refer to this interpretation as *fast-mode wave*. A sufficiently impulsive flare and/or CME can generate a wave or even a shock-wave which will then give rise to signatures over an extended range of wavelengths and physical regimes in the solar atmosphere such as, EUV waves, Moreton waves ( $H\alpha$ ), Soft X-rays and type II radio bursts.

Another school of thought states that the EUV waves are not waves at all, but rather the signature of the large scale propagation of the associated CME. We refer to such interpretations as pseudo-waves. One suggestion for a pseudo-wave is the disk projection of the large-scale current shells enveloping the erupting flux rope of the associated CME<sup>1</sup> (Delannée et al. 2008). Using a 3-D MHD flux rope model these authors proposed that these currents could be associated with enhanced Ohmic dissipation leading to coronal heating. This would then result into the enhanced EUV intensities of the wave fronts. It is not known whether this enhanced heating is steady or impulsive in nature. In what follows we will refer to this interpretation as *current-shell* model for brevity.

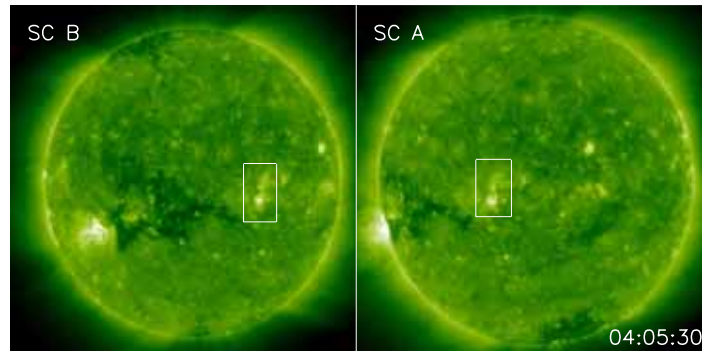
A hybrid model, with features from both wave and pseudo-wave models is the model of Chen et al. (Chen et al. 2002; Chen, Fang and Shibata 2005; Chen and Fang 2005 for a review). This model is based on the eruption of a flux rope and predicts two types of waves: a very fast, super-alfvénic piston-driven shock straddling the erupting flux rope which may be identified as the coronal counterpart of a Moreton wave and a slower pseudo-wave associated with successive opening the overlying magnetic field induced by the erupting flux rope. The latter type of wave is a pseudo-wave, which Chen et al. identify with the EUV waves and is the result of plasma compression, similar to the conclusion of Delannée and Aulanier (1999), who showed that fast expansion of the magnetic field should compress plasma at the boundaries between expanding stable flux domains, leading to enhanced emission. We will therefore treat the Chen et al. model in tandem with the Delannée et al. model since both models assert that the EUV waves are formed around the erupting flux rope by either enhanced current shells and/or plasma compression. Note here that Delannée et al. (2008) found that the disk projection of the current shells produces more contrast than that from the plasma compression.

Another possibility for a pseudo-wave is successive reconnections between the expanding large-scale CME with small-scale (cool loops) quiet Sun structures (e.g. Attrill et al. 2007a,b; van Driel-Gesztelyi et al. 2008). These reconnection events will give rise to enhanced heating which will in turn give rise to the bright front intensity. In what follows we will refer to this interpretation as *reconnection fronts*.

Finally, another interesting suggestion regarding the nature of EUV waves is that they represent *MHD solitons* (Wills-Davey, DeForest & Stenflo 2007). For solitary waves the wave speed is dependent on the pulse amplitude (a function of density enhancement; Wills-Davey, DeForest & Stenflo, 2007). As a general trend, the most well-defined coronal waves have higher density enhancement and travel faster. More observational signatures from this mechanism need to be

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<sup>1</sup>Flux ropes are an integral part of almost all CME models and a large fraction of coronagraphic CME observations finds evidence of such structures.



**Figure 1.** STEREO B (left panel) and A (right panel: full-disk images in the 195 channel showing the erupting AR, within the box. The separation between the 2 spacecraft was  $\approx 45$  degrees.

worked out in order to be able to distinguish, for instance, between solitary and non-solitary waves.

From the above it is clear that understanding the physical origin of EUV waves will supply important constraints on coronal conditions (magnetic field, temperature and density in the corona), for a fast-mode wave interpretation, or on CME initiation and early expansion, for a pseudo-wave interpretation. Part of the problem for conclusively determining the nature of EUV waves stems from the limitations of the EIT observations used almost exclusively to study

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these waves: relatively low cadence (12 min), one temperature (normally the 195 channel) and a single vantage point.

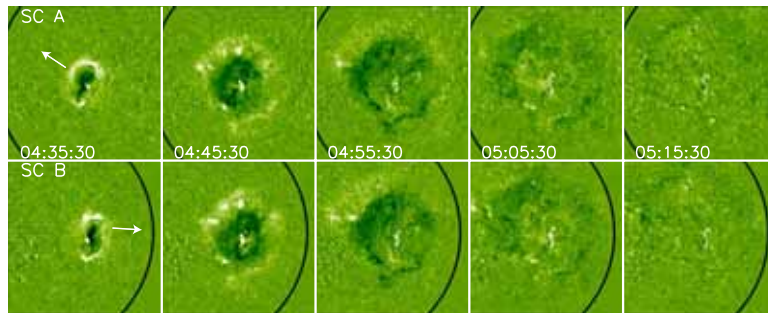
These limitations are largely overcome with the STEREO mission (Kaiser et al. 2008). The Extreme Ultraviolet Imaging Telescope (EUVI; Wuelser et al. 2004) of the SECCHI instrument suite (Howard et al. 2008) excels over EIT because of its faster cadence (2.5 min or less during campaign periods), simultaneous imaging at different temperature channels, and distinct vantage points allowing a truly 3D view of the Sun. Indeed, previous analyses of EUV waves with high cadence EUVI data showed that they propagate at higher speeds than previously determined, closer to the magnetoacoustic speed, (Long et al. 2008; Veronig et al. 2008). Additionally, Gopalswamy et al. (2009) detected wave reflection from a coronal hole. Finally, Patsourakos & Vourlidas (2007) found evidence of kink-like oscillations of quiet Sun loops in the wake of an EUV wave. MHD simulations showed that EUV waves can induce similar oscillations, at least in the source AR loops (Ofman 2007). All the above findings lend strong support to a wave interpretation.

However, these studies relied on a single viewpoint for their analyses. Here, we present the first stereoscopic study of an EUV wave which occurred on December 07 2007. Also for the first time, we perform a comprehensive comparison of predictions and/or expectations from each candidate wave interpretation and test them against the STEREO observations. We demonstrate how all the unique advantages of the STEREO observations place new and strong constraints on the nature of EUV waves.

## 2. Observations and Data Analysis

We analyzed the observations of an EUV wave seen by the two STEREO spacecraft (SC; hereafter A and B) from  $\approx 04:35$ - $05:15$  UT during 7 December 2007. The STEREO spacecraft were significantly separated by  $\approx 45^\circ$ . The wave was initiated from the small active region 10977, which was close to disk center as viewed by A and towards the East limb as viewed by B (Figure 1). The overall configuration of the corona was rather typical of solar minimum conditions: simple active regions, a low-latitude coronal hole, with the rest of the disk dominated by quiet Sun. Close to the time of the wave launch, a small B1.4 class flare started at around 04:35 in the same AR and peaked at around 04:41 UT. An associated CME was seen later in coronagraph data. This CME was rather slow, reaching speeds of  $\approx 300$  km/s in the coronagraphic fields of view, as determined by *CACTUS* (Robbrecht & Berghmans 2005) and was not particularly bright.

We focus here on EUV data and total brightness white-light images collected by the EUVI and the COR1 coronagraph (Thompson et al. 2003) on SECCHI, respectively. EUVI takes full disk images in EUV channels centered around 171, 195, 284 and 304 Å (hereafter referred as 171, 195, 284 and 304). EUVI has  $\approx 1.6$  arcsec pixels and our observations have a cadence of 2.5, 10 and 20 minutes for 171, 195-304 and 284, respectively. COR1 is an internally occulted coronagraph observing from 1.3-4.0  $R_\odot$ . The COR1 pixel size is 15 arcsec and nominal cadence is 15 minutes. The EUVI and COR1 data were processed with the standard



**Figure 2.** Successive snapshots of the EUV wave in the 195 channel for SC A (upper panel) and SC B (lower panel). We display running ratio images. All images have the same brightness scale. Ratio increases with color from black, to green and white. The arrows in the first column panels show the oppositely directed loops observed early in the wave event.

*secchi\_prep* routine. Note that the EUVI and COR1 A & B image pairs are synchronized; namely, the observations were taken at the *same* time on the Sun. Therefore, we do not have to worry about the different light travel times from the Sun to the two STEREO spacecraft.

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## 2.1. Multi-Viewpoint Temporal Behavior

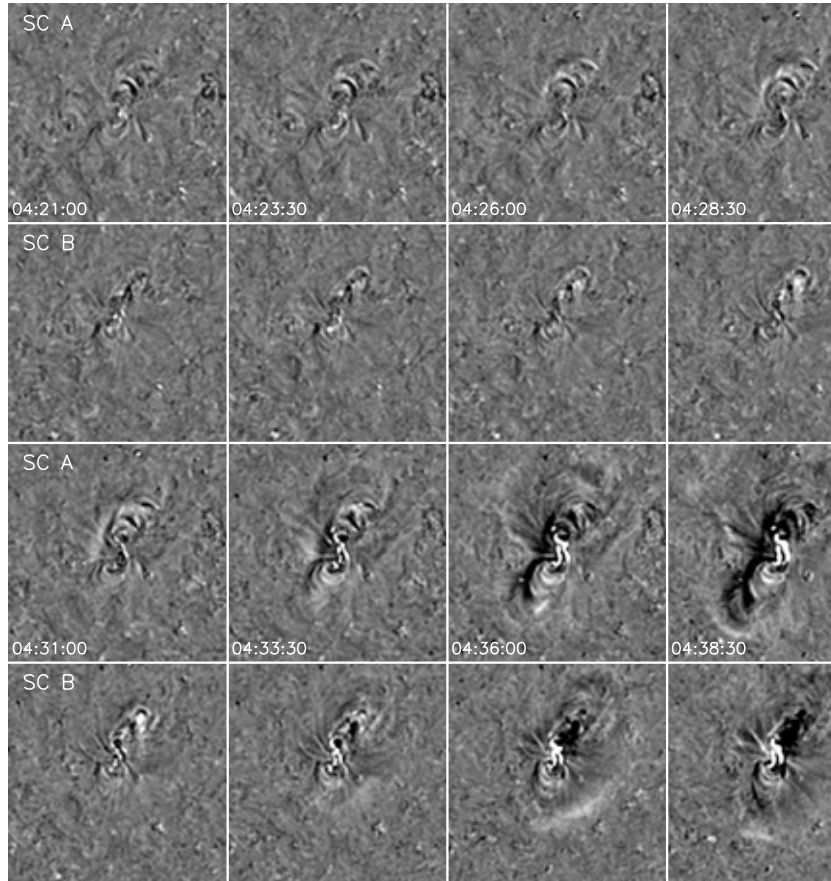
A running ratio movie of the EUV wave in the 195 channel for both spacecraft can be found online (video1.mov) and representative snapshots from this movie are shown in Figure 2. Each frame corresponds to the ratio of a given 195 image with the previous one. Note here that the cadence of the 195 EUVI data ( $\approx 10$  minutes) is similar to that of EIT ( $\approx 12$  minutes): the basic difference is in the multi-view point aspect of the EUVI observations together with the higher sensitivity of EUVI compared to EIT. The latter helps to better observe faint transients like EUV waves. Running ratio images emphasize changes of the brightness, location, and structure of emitting features between two subsequent images and highlight faint propagating disturbances such as EIT waves. These images correspond to the temporal derivative of the observed intensities. The dark regions do not necessarily represent true dimmings (e.g. Chertok & Grechnev 2005). We provide a movie of plain (non-differenced) 195 images (video2.mov), in which each frame has been first processed by a wavelet-based technique (Stenborg, Vourlidas & Howard 2007) to increase the image contrast. The propagation of a rather sharp wave-front is evident in this movie.

The wave first appears at  $\approx 04:35$  UT at the periphery of the active region, following expanding loop motions which started around 04:15. After 04:35, the wave starts to expand over the solar surface, becoming progressively more diffuse and faint; after 04:45 it attains a quasi-circular shape and looks similar to data from both spacecraft. The wave seems to avoid the equatorial coronal hole eastwards of the source AR. By 05:15 the wave covers a significant part of the visible solar disk, but by this time is rather diffuse and faint. All these characteristics are pertinent to typical solar minimum EUV waves (e.g., Moses et al. 1997; Thompson et al. 1998).

However, we noticed a peculiarity in the wave propagation early on: around 04:35 the wave seems to propagate in opposite directions as viewed by the two instruments! It propagates eastward in EUVI-A and westward in EUVI-B (see video1.mov, video2.mov and Figure 2). At this time the wave is incomplete; it is not forming a full circle.

Higher cadence data are required to resolve this puzzling observation as well as to establish firmer conclusions about the relative timings between different aspects of the event (e.g., flare, loop openings, wave ...). For this reason, we turn our attention to the 171 images which were taken at a relatively high cadence of 2.5 min. We process them with the a wavelet-based technique to increase the image contrast (Stenborg, Vourlidas & Howard 2007). Video3.mov contains an 171 A & B movie of the area around the source active region. Several snapshots (in running ratio format to emphasize the motions) from the movie are given in Figure 5. Video4.mov contains a 171 A & B movie over a more extended area, covering a significant fraction of the solar disk, to capture the large-scale evolution of the wave. Figure 3 has several snapshots from this movie in running ratio format.

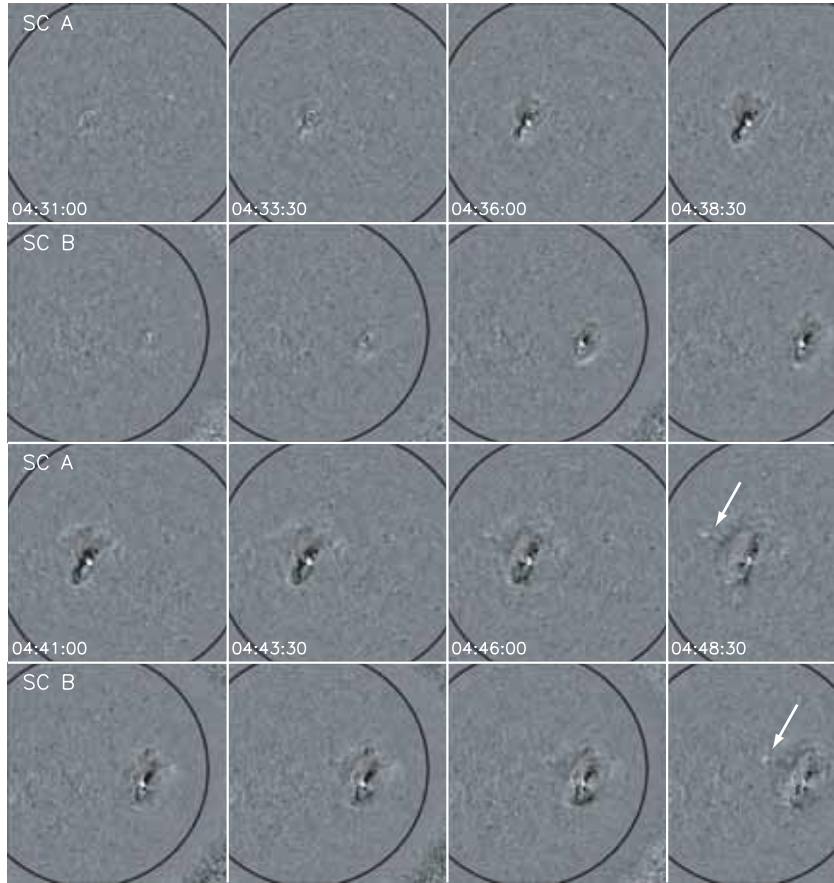
Several remarks can now be made. First, loops start to slowly rise around 04:11 in A and almost 8 minutes later in B (Figure 3 and video3.mov). They are directed towards West (East) in B (A), similarly to what is seen in the first



**Figure 3.** Running ratio wavelet-enhanced images of the target AR taken in the 171 channels of A and B with a cadence of 2.5 minutes. Same scaling applied to all images. A 4-frame running ratio is taken, i.e. each image is divided by the image taken 10 minutes before. Ratio increases with color from black to white.

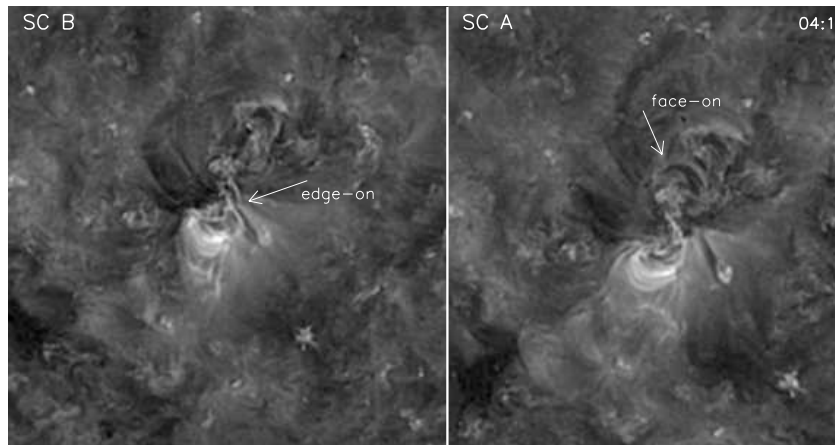
column of Figure 2. If we now consider the expanding loops in A indicated by an arrow in the right panel of Figure 3 we note that they are seen more or less face-on. Given the relatively large separation ( $\approx 45^\circ$ ) between A and B these loops should be then seen edge-on in B, as indicated by the arrow in the left panel of Figure 3. Therefore, the oppositely-directed early signature of the wave is associated with the expanding motions of the *same* loops observed from the two well-separated viewpoints. Between  $\approx 04:31:00$ - $04:33:30$  the expanding loops undergo a sudden jump and cannot be traced anymore; a wave front starts to





**Figure 4.** Running ratio wavelet-enhanced images over an extended area taken in the 171 channels of EUVI-A and -B with a cadence of 2.5 minutes. A 4-frame running ratio is taken, i.e. each image is divided by the image taken 10 minutes before. The same brightness scaling is applied to all images. Ratio increases with color from black to white. The arrows indicate a prominence that was disrupted by the wave.

develop (Figure 3 and video3.mov). This jump occurs slightly before the start of the associated flare ( $\approx 04:35$ ). Given that flare onset and impulsive CME acceleration seem to simultaneously occur (e.g., Zhang et al. 2001), it is very possible that the observed loops' jump also marked the the start of the impulsive acceleration of the associated CME. The first almost quasi-circular wave front forms around 04:41; the wave also seems to interact with a prominence to the East of the active region at around 04:43 (Figure 4 and video2.mov).



**Figure 5.** EUVI-A & B image pair of wavelet-enhanced 171 images showing the expanding loops associated with the EUV wave onset. The arrows indicate the expanding loops which are seen edge-on and face-on in B and A respectively.

The most important findings of this Section, namely that the wave appeared different, i.e. it exhibited different shapes and direction of propagation, during its early phases from the two distinct vantage points, when loop expansion was clearly observed, (i.e. Figures 2, 3, 5) while later on basically the same quasi-circular pattern was observed have significant implications. Basically, both pseudo-wave theories expect a quasi-circular wave shape *at all times* (see Delannée et al. 2008; Attrill et al. 2007a) which is clearly in disagreement with our observations. Furthermore, the fact that during later times the wave seems similar on both EUVIs could be a problem for the *current shell* model of Delannée

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et al. (2008) which expects the wave to be the disk projection of a very high altitude current shell (280-407 Mm), which should appear significantly different from well-separated viewpoints. This is probably not the case for the *reconnection fronts* model of Attrill et al. (2007a) which assumes that the wave is formed at lower altitudes.

On the other hand, a quasi-circular shape is consistent with a wave theory, for which the wave is simply the projection of the 3D wave dome onto the solar surface (e.g. Uchida 1968, Wang 2000). To summarize, we find that the *transition* of the wave appearance, from an asymmetric loop expansion early on to a more symmetric and diffuse front, seems to be against the expectations of pseudo-wave theories. These theories invoke symmetric loop expansion at all times, either via ‘passive’ flux rope eruption or successive reconnections. On the other hand, the observed appearance is consistent with a wave driven by an impulsive loop expansion.

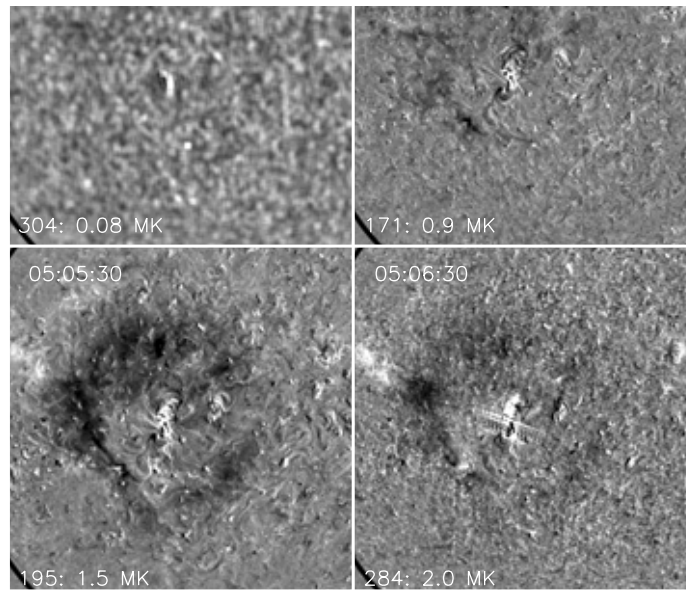
## 2.2. Multi-temperature Behavior

We now study the wave behavior as a function of temperature. Figure 6 contains almost simultaneous (within a minute) running ratio images of the wave seen in all EUVI-A, in which the wave was closer to disk center compared to EUVI-B. Note that we used the same 20-minute running ratio images in all channels, which is the slowest cadence among the EUVI channels. All ratio images have been scaled to the same ratio range and a spatial 3-pixel wide median filter has been applied in order to reduce the noise. Azimuthally-averaged radial intensity-ratio profiles of the images of Figure 6 are given in Figure 7. They were produced using a procedure similar to that described by Podlachikova & Berghmans (2005): the image data were first projected onto a spherical polar coordinates system with its center on the flare cite, and we then averaged those maps over polar angle to obtain the azimuthally-averaged radial intensity-ratio profiles of Figure 7. In this plot the wave front is located ahead of a region exhibiting a large-scale minimum of the intensity ratio (radial distances  $> 250$  pixels).

As can be seen from Figures 6 and 7 the wave is visible in the coronal channels of EUVI 171,195 and 284. It is better defined in 195 while its visibility decreases when going to 284 and 171. On the other hand, the wave is barely visible in the mainly chromospheric/transition region 304 channel. The wave in this channel was diffuse, and looked similar to what seen in the 284 channel. The intensity increase associated with the wave takes values in the range of  $\approx 5\text{-}30\%$ .

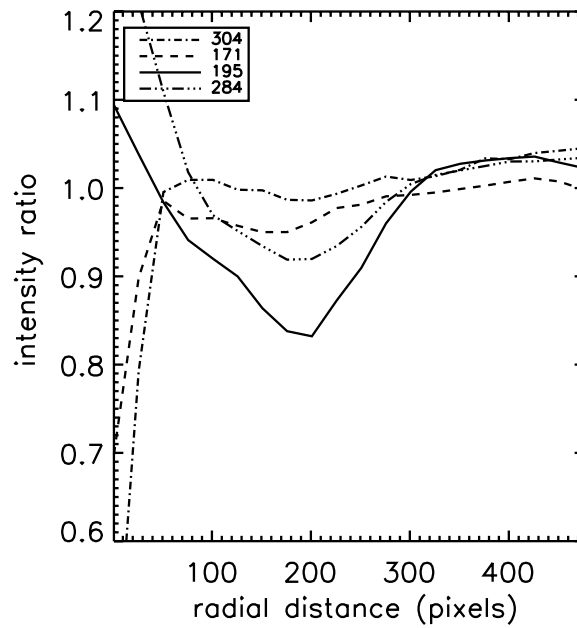
The wave propagates over quiet Sun regions, where the bulk of the coronal plasma lies in the temperature range 1-2 MK, with a peak in the quiet Sun Differential Emission Measure distribution around 1.5 MK (e.g. Brosius et al. 1995), a temperature close to the peak of the temperature response function of the 195 channel. The fact that the wave is best seen in this temperature range implies that it represents mostly a density increase without significant plasma heating taking place. Considering also the small intensity increase we conclude that the observed wave represents a small (i.e., linear) density perturbation of the ambient quiet Sun, without any significant plasma heating taking place.

This behavior is consistent with coronal propagation of a fast-mode wave. The wave has a compressive character and when propagating over the QS corona



**Figure 6.** Almost simultaneous snapshots of the EUV wave in the 4 channels of EUVI-A. The images were taken between 05:05:30-05:06:30 UT. Starting clockwise from the lower left panel 195, 304, 171, 284. Running ratio images are displayed. All images have the same brightness scaling. Ratio increases with color from black to white. Images have been median-filtered by a 3-pixel window to reduce noise in all channels except for 304 where we applied a 15-pixel smoothing to improve the wave visibility.

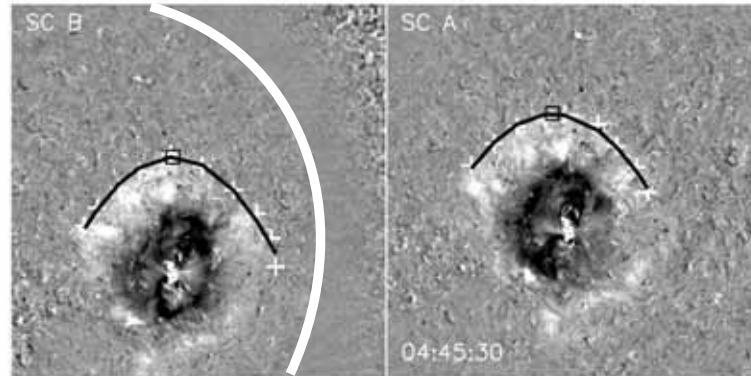
will compress the ambient plasma, thereby producing intensity increases which could be the observed wave. Given the much higher densities in the chromosphere/transition region it would be more difficult for a small amplitude wave to produce significant compression there, which explains the lack of a 304 signature. When the eruption is very fast ( $> \text{several hundred km s}^{-1}$ ) a shock wave can be produced. This will give rise to significant density and temperature enhance-



**Figure 7.** Azimuthally-averaged radial intensity-ratio profiles of the images of 6. An EUVI pixel corresponds to  $\approx 1.6$  arcsec.

ments over a larger temperature range and to sharp wave fronts observed not only in EUV but also in chromospheric emissions  $H\alpha$  and Soft-Xrays (i.e. the ‘brow’ and ‘S’ wave events) as well type-II radio bursts (e.g. see the review of Warmuth 2007).

The observed multi-temperature behavior of the wave poses problems to pseudo-wave interpretations. Consider first the *current shell* model of Delannée et al. (2008). According to this model the wave signature is due to Ohmic heating in large-scale current layers at high altitudes occurring around the erupting flux rope. Note here that our best current theoretical understanding of coro-



**Figure 8.** Fitting of segments of the EUV wave front seen in simultaneous EUVI-A and B running ratio images. Both images have the same brightness scaling. Crosses: points along the wave front selected by point-and-click; solid black line: parabolic fit of the manually selected points. The black boxes are the vertexes of the best-fit parabolas.

nal heating points to rather small-scale currents as a possible heating agent (e.g. Klimchuk 2006). Moreover, observations show little correlation between large-scale currents and SXR intensities (Fisher et al. 1998).

Note now that the density drops-off very rapidly with height in the solar atmosphere (it can drop by a factor of  $\sim 5$ -10 between the base of the corona and 250 Mm; see for example Figure 1.20 in the compilation of density measurements of Aschwanden 2005) and the EUV intensities are proportional to the line of sight integral of the density squared. One would then expect that a disk observation

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in the EUV, such as those of the EUV waves, would be largely dominated by the contribution of the lower (and more dense) layers and not from the higher layers. However, the *current shell* model finds that most of the contribution to the current density should originate from high-altitudes ( $> 250$  Mm), Delannée et al. (2008). The above discussion implies that the *current shell* model may not lead to any sizeable coronal signal at all.

We now turn our attention to the *reconnection front* model of Attrill et al. The observations showed a minimal wave signature in the 304 channel. Note here that the wave did not look substantially better in (plain) 304 images processed by wavelets. This operation has a similar effect on the data as differencing (i.e. enhance subtle features), but applies to plain images which takes out some of the ambiguities in the interpretation resulting from taking differences. Moreover, the 304 data of Figure 6 were largely smoothed by a box-car of 15 pixels to bring up the wave.

The *reconnection front* model of Attrill et al. relies upon small-scale reconnections between the laterally expanding CME and small loops in the surrounding QS. The energy content in these reconnections would be similar to that associated with the large array of transient phenomena known to occur over the QS which are widely believed to be the result of small-scale reconnections (see the review of Parnell 2002 for example). Therefore, one would expect brightenings of similar magnitude in the frame of the Attrill et al. model which should be easily observable. Note here that the magnitude of these brightenings would be smaller than those occurring in active regions because of the substantially weaker QS magnetic fields. The typical timescales in the chromosphere/transition region as well as the lifetimes of these transients are in the range 100s-few minutes. This means that the relatively low cadence of the 304 data (10 min), could cause us to miss the moment of maximum emission of some of the brightenings but not all of them. This would give rise to a rather inhomogeneous and more importantly incomplete wave-fronts which is probably not the case. Higher-cadence 304 observations are required to show if the above is really the case.

The footpoints of coronal structures, where the bulk of their TR/chromospheric emissions comes from, represent a very sensitive monitor of coronal conditions. In the case of steady or quasi-steady heating, for example, the TR emission is proportional to the coronal pressure (e.g. Klimchuk, Patsourakos and Cargill 2008; Equation A12). Impulsive heating would give rise to sizeable footpoint emissions, turning them visible in chromospheric/TR emissions like 304 (Antiochos et al. 2003; De Pontieu et al. 1999; Hansteen 1993; Klimchuk 2006; Klimchuk et al. 2008; Martens et al. 2000; Patsourakos and Klimchuk 2008; Spadaro et al. 2006; Winebarger, Warren and Flaconer 2008). And this occurs irrespectively of the spatial location of the heating along individual field lines; thermal conduction and mass flows are very efficient at redistributing any excess heat along the field.

Finally, it is well-known observationally that the quiet Sun transition region and chromosphere exhibit stronger variability than the overlying corona (e.g. Berghmans, Clette and Moses 1998; Patsourakos and Vial 2002; Teriaca, Madjarska, and Doyle 2002). Therefore, if an EUV wave is associated with some sort of impulsive heating, one may expect a significant chromospheric/transition

region signature maybe stronger than the coronal one. Our observations show the contrary.

The small impact of the wave in the transition region and the chromosphere may not be a problem for the *current shell* model. This is because the heating in that model occurs on much higher field lines than for the *reconnection front* model. And as we saw before footpoint emissions are proportional to the coronal pressure, which in turn is also proportional to the field line length and therefore height for the same temperature (e.g. the scaling-law of Rosner, Tucker and Vaiana 1978).

Another potential problem for pseudo-waves concerns their width. Assuming a rather low limit for the coronal cooling time of  $1000 \text{ s}^2$  and for a typical EUV wave propagation speed of  $\approx 300 \text{ km s}^{-1}$  one finds that a pseudo-wave should result in a very extended  $\approx 3 \times 10^5 \text{ km}$  (or  $\approx 0.5 R_{\odot}$ ) band of emission in its wake. This is clearly in disagreement with the rather sharply defined wave-fronts observed during the early stages of EUV waves (see for example video1.mov and particularly video2.mov with the plain wavelet images). For instance we estimated a full wave width of  $\approx 160 \text{ arcsec}$  (i.e.  $\approx 110 \text{ Mm}$ ) for a snapshot of the wave taken at 04:45:30; see Figure 2. This is only the  $1/7$  of  $R_{\odot}$ .

We finally comment on the  $304 \text{ \AA}$  channel emission. Although the passband is dominated by the He II line with a peak temperature of  $0.08 \text{ MK}$  (upper chromosphere and lower transition region), this passband also contains a contribution from Si XI at  $303.32 \text{ \AA}$  with a peak formation temperature of  $\approx 1.6 \text{ MK}$  which is more diffuse than the chromospheric He II emission (e.g. Stenborg, Vourlidis, & Howard 2008). However, spectrally resolved full disk CDS observations by Thomson & Brekke (2000) showed that the Si IX contribution in QS areas is very small (4 % of the He II) and diffuse. In our event, the wave signatures in the  $304$  images are diffuse and faint (similar to the  $284$  observations) which suggests a likely coronal origin for them. This is problematic for the *reconnection front* interpretation where, according to the preceding discussion, we should expect low corona/chromospheric signatures *in addition* to the coronal signal.

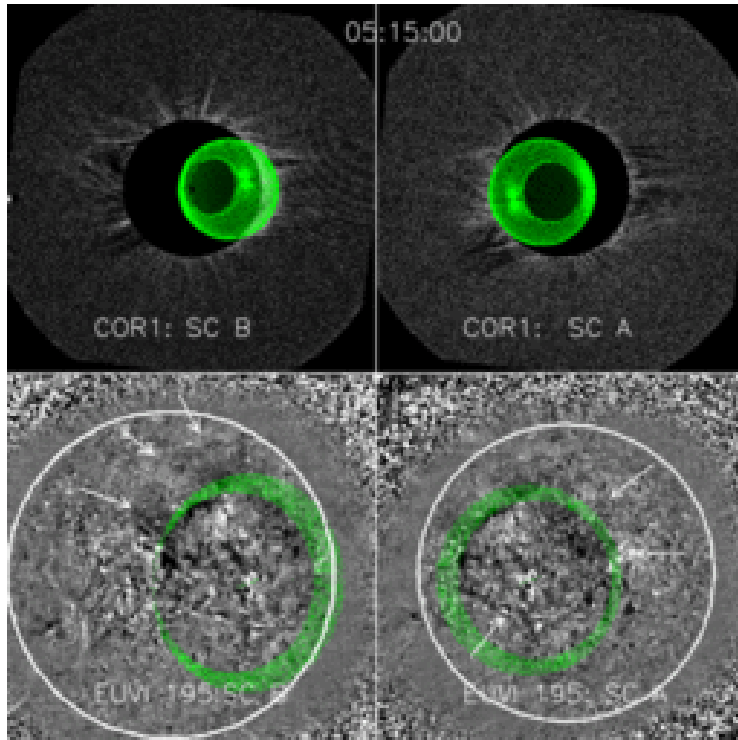
### 2.3. Stereoscopic Analysis

Thanks to the availability of the two SECCHI viewpoints, we are able to estimate the 3D location of the wave. We manually selected several points along a segment of the wave front in an EUVI running ratio images pair (Figure 8). The segment covered a significant fraction of the wave front so that our measurement can be considered as representative of the structure. We then fitted these points with a parabolic function for each telescope and determined the image  $x$ ,  $y$  coordinates of the corresponding vertexes. Approximating the wave front with a parabola is a reasonable but by no means unique choice: CME fronts almost universally exhibit concave-outwards fronts and wave fronts can be spherically symmetric.

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<sup>2</sup>Coronal cooling times depend almost linearly on field line length (e.g., Cargill, Mariska and Antiochos 1995) and therefore should increase in the expanding field lines associated with a CME and the pseudo-wave.





**Figure 9.** Simultaneous fitting of the CME in COR1-B and A with a flux rope model, upper left and right panels respectively. The best-fit flux rope model is shown in green. COR1 total brightness images are shown in black and white. Pre-CME images were subtracted. Projection (green) of the best-fit flux rope on nearly simultaneous EUVI 195 running ratio images for B and A, lower left and right panels respectively. We consider rather generous extensions for the wave in the North and West direction as indicated by the arrows, which takes care of the uncertainties in defining the wave. The South East arrow indicates the wave front position in that direction.

Triangulation of the vertex locations using the *scc.triangulate* routine; (see Inhester (2006) for the basics of triangulation and stereoscopy) supplied the 3D coordinates  $(x,y,z)$  of the vertex of the parabola.

The height  $h(= \sqrt{x^2 + y^2 + z^2} - R_{\odot})$  of the wave above the solar surface is about  $0.13 R_{\odot}$  or  $\approx 90 \pm 7$  Mm (the error is the standard deviation of the heights determined from 10 repetitions of the above procedure) and is comparable to the coronal scale-height for quiet Sun temperatures ( $\approx 70$  Mm for a temperature of 1.5 MK). This is consistent with fast-mode wave propagation over quiet Sun areas, since the wave perturbs the ambient coronal plasma with its bulk confined within a coronal scale-height.

A height of  $\approx 90$  Mm is probably too small for large-scale current layers around an erupting flux rope of the *current shell* model. Our stereoscopic height observations of the wave of Figure 8 were taken around 30 minutes after loop expansion was first observed and not very far from when the CME first emerged in the COR1 field of view ( $1.5 R_{\odot}$ ) which means that the height of the erupting structure would have been substantially large. Moreover, Delannée et al. (2008)

expect that the current shells most contributing to the wave should be high-lying ( $> 250$  Mm).

Finally, our height measurement is probably too large to be consistent with the *reconnection front* model. The fraction of quiet Sun loops which extend to substantially large heights ( $> 10$  Mm) represents a small fraction of the QS magnetic flux (10 % maximum); with the majority of QS loops not reaching heights larger than 10 Mm (Close et al. 2004). In the frame of the Attrill et al model, we expect more reconnections to occur between the shorter QS loops and the expanding flux-rope. Also note that since the magnetic field strength decays with height, reconnections employing low-lying QS loops would be more energetic than those employing larger ones. Therefore, the radiative signal of the wave in the frame of the *reconnection front* model will be dominated by the contribution of the low-lying loops. Larger loops could prevent some of the interactions between the lower loops and the expanding CME, but possibly not all of them since the small loops are more numerous.

From the above, and given the lack of any predictions on the height of reconnections for the *reconnection front* model, we speculate that the wave height in this scenario would be that of QS cool loops; namely 5-10 Mm tall (e.g., Aiouaz and Rast 2006; Dowdy, Rabin, and Moore 1986; Feldman, Widing, and Warren 1999; Close et al. 2004; Patsourakos, Gouttebroze, and Vourlidas 2007; Peter 2001; Sánchez Almeida et al. 2007; Tu et al. 2005).

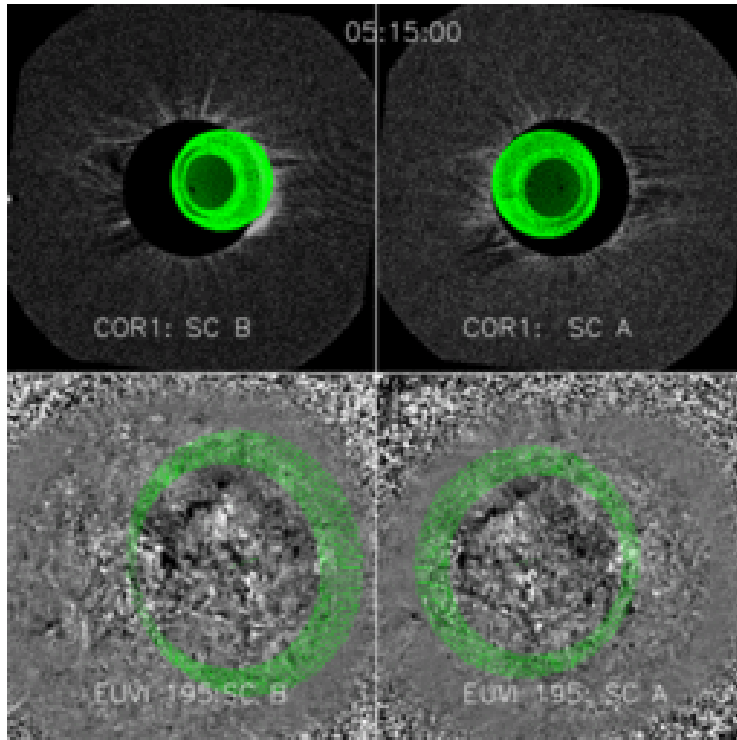
#### 2.4. Pseudo-wave Modeling

To further test the suggestion that EUV waves could be pseudo-waves directly linked to the CME expansion, we performed forward modeling of the associated CME as seen by COR1.

We used the flux rope CME model (graduated cylindrical shell; GCS) of Thernisien, Howard and Vourlidas (2006). GCS is a purely geometrical 3D model aiming to reproduce the large-scale appearance of CMEs in coronagraph data and in particular the CME envelopes: it does not aim to reproduce the fine internal structure of CMEs. It makes no assumption about the physical mechanisms producing the observed CME envelopes. The model consists of a tubular section attached to two cones, which approximate the main body of the flux-rope and its legs, respectively. The model is formulated in terms of few adjustable parameters, i.e. location, longitude and latitude of the source region, height of the CME front, etc (see Thernisien et al 2006 for details).

The GCS model makes it easy to calculate projections onto the plane of the sky from any viewpoint (e.g. STEREO, SOHO) and compare them with coronagraphic CME observations (COR1 in our case); the free parameters of the model are modified until the best match is found simultaneously in both viewpoints. This requirement makes the model sensitive to changes of its free parameters and therefore results in more accurate CME fits than possible with a single viewpoints (Thernisien et al 2009).

We applied the GCS model to an image pair of total brightness COR1 images taken around 05:15 (upper panel of Figure 9). At this time, the wave-associated CME has just emerged above the COR1B occulter while it was never seen in



**Figure 10.** Determining a flux rope CME model with an on-disk projection (green) comparable to the size and location of the observed in EUVI 195 wave on both B and A, lower left and right panel respectively. Projection (green) of this flux rope model on COR1 total brightness images from B and A displayed in black and white (upper left and right panel, respectively). Pre-CME images were first subtracted from the COR1 images. The COR1 and EUVI data were taken almost simultaneously.

COR1A data. Moreover, the EUV wave was still visible on the disk but was rather diffuse (lower panel of Figure 9). To construct Fig. 9 we did the following: (1) we found the GCS model best reproducing the associated CME observed by COR1 (upper panel of Figure 9) and, (2) projected the upper (i.e. spherical) section of the model onto the co-temporal EUVI running ratio images containing the wave (lower panel of Figure 9). Note that step (1) reproduced the large-scale CME seen by COR1-B (top left panel of Figure 9), and indicated that the CME in COR1-A should lie behind the occulting disk (top right panel of Figure 9), as it was observed. In step (2) self-similar expansion of the flux-rope like CME was assumed as suggested by both observations (Schwenn et al. 2003; Cremades & Bothmer 2004; Thernisien et al. 2006; Thernisien et al. 2009) and models (Török and Kliem 2005; Attrill et al. 2007a; Delannée et al. 2008).

According to pseudo-wave models, the EUV 'waves' correspond to either the disk projection of the CME envelope for the *current shell model* or to the low coronal lateral extent of the CME for the *reconnection fronts model*. Therefore, the procedure of Figure 9 allows to validate the realism of pseudo-wave models. Note here that our procedure calculates the projection of the upper section of

the CME only, and not of its footpoints, which are line-tied to their low corona and presumably correspond to areas of strong dimmings. In principle, the CME envelope will laterally expand either by being ‘pushed’ by the erupting flux rope or by successive reconnections with QS loops. In any case, the projection of the CME on the low corona—the pseudowave— will always follow the CME evolution. Since the GCS model of Figure 9 is constrained by the position and morphology of the CME in the coronagraph data, it accounts for any possible deflections of the CME from its original propagation direction (e.g., Thernisien et al. 2006). However, the CME projection disagrees with the actual observed wave in two important aspects: (i) it is displaced with respect to the wave and, (ii) its projected area is smaller than the wave.

The displacement between the projected CME and the wave is a strong argument towards a wave interpretation (wave and CME propagate independently) and against pseudo-wave models (there is a direct link between the CME and the wave). The latter would need to invoke special conditions to account for such displacements. Besides, the often reported CME deviations (due to nearby coronal hole boundaries) are based on single viewpoint observations (LASCO) and therefore may suffer from projection effects. Note here that Delannée et al. (2008) show a projection of the current shell from their model on two snapshots of an observed wave, and a good match was found (Figure 11 of Delannée et al. (2008)). However, this lacked both the co-temporal snapshot of the associated CME and the multiple lines of sights used in our modeling, thereby not fully constraining the problem. This underlines the importance of multiple viewpoints and of coronagraphs going as close as possible to the solar surface.

The size disparity between CME projection and wave poses another problem for pseudo-wave models which by definition assume they are equal. Indeed, if we consider the very rapid decrease of density with height and the strong dependence of EUV intensity on it ( $\propto n^2 dl$ , with  $dl$  the path length along the line of sight) the signal from a disk observation of a CME in the EUV would be dominated by the contribution of its lower sections rather of its upper sections. Actually, since CMEs expand with height, the disk projection of the CME of Figure 9 largely overestimates its actual size which makes the comparison between the observed wave and pseudo-wave models even more problematic.

As explained above, the disk projection of the GCS model corresponds to the projection of the upper part of CME onto the solar disk, and therefore does not correspond to the flux-rope footpoints. In Figure 10 we do the inverse. We first find a flux-rope model with a projection on the disk that matches the observed EUV wave simultaneously in A and B. Then we compare its projection on the COR1 images. We believe that this is a good method to test the pseudo-wave model prediction; namely that the outer CME envelope is the wave. Again, however, we find that the pseudo-wave interpretation cannot account for the observations.

The forward modeling of pseudo-waves of this Section is by no means unique, in the sense that different geometries and/or eruption scenario may be employed. However, as explained above, the employed geometry (i.e., flux-rope like and self-similar expansion) find substantial backing in both observations and modeling and therefore represents a reasonable choice. Finally note here that if CME

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and EUV waves had been different facets of the very same phenomenon (i.e. a pseudo-wave), then our fittings of Figures 9 and 10 would have been mutually consistent (e.g. the CMEs of Figures 9 and 10 should have been the same), which is not the case.

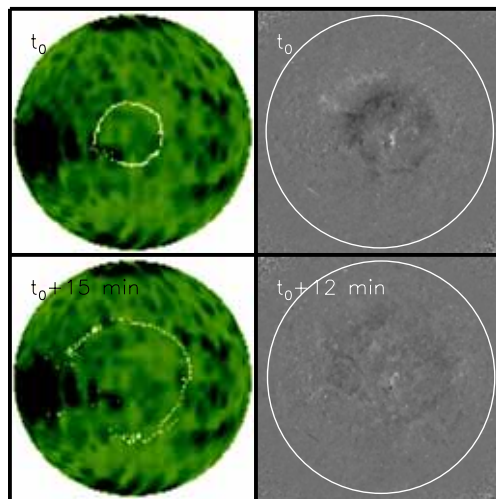
For our pseudo-wave modeling we had to use co-temporal images of the wave and the CME. Because of its slow speed, the CME took about 40 minutes after the first appearance of the wave to enter the COR1 field of view. By that time the wave had already traveled over a significant fraction of the solar area and was very diffuse. We have to wait for observations of more impulsive CMEs to perform CME-wave comparisons, with a better defined wave signature.

## 2.5. Fast-mode Modeling

Having tested the pseudo-wave interpretation against the observations in the above, we turn to the wave interpretation. We perform a fast-mode wave simulation for the observed EUV wave following Wang (2000). First, a Potential Full Source Surface Extrapolation of the global coronal magnetic field was carried out using MDI synoptic maps centered at the day of our observations. For each traced field line, a hydrostatic isothermal atmosphere at 1.5 MK was then attached following a scaling-law relating density and base magnetic field. The above steps supplied the 3D distribution of the fast-mode speed in the corona. Finally, a number of rays have been initiated at the periphery of the active region, and tracked as a function of time. Essentially the fast-mode wave is diffracted away from regions with high gradients in the fast-mode speed. This happens in active regions (upward wave diffraction) and in coronal holes (diffraction away from the coronal hole). Less diffraction occurs in quiet Sun, where the fast-mode speed gradients are smoother. Note that the model makes no explicit assumption about the physical mechanism triggering the wave. For more on the model refer to Wang (2000).

Two snapshots of our simulations are given in Figure 10 where we plot the projection of the wave front (white dotted line) on the solar surface. A viewing point from SOHO has been assumed. The simulated snapshots are separated by 15 minutes, which is also approximately the time separation (12 minutes) between the 2 running-ratio EIT images (Delaboudinière et al. 1995) which complement Figure 11. We see that the fast-mode simulation essentially manages to track the large scale appearance of the wave both in terms of size and shape. It follows rather closely the location and shape of the wave between the two successive snapshots and even reproduces some details of the wave, like the avoidance of the coronal hole.

It is interesting to note that if the wave is launched at the center of the active region, it will expand very rapidly in the radial direction which is at odds with the observations. The radial expansion is due to the very rapid decrease of the fast-mode speed with height, which leads to very strong wave diffraction in the upward direction. Instead, the observations in section 2.1 show that the wave is low-lying and appears in the periphery of the active region. This is also a strong argument against the flare as a trigger of the wave since the wave would form at the heart of the active region in that case.



**Figure 11.** Fast-mode wave simulation of the 2007 December 7 EUV wave (left column) and corresponding EIT running ratio images (right column). In the left column the location of the wave front projection on the solar surface is indicated by white pixels. It is superimposed on the distribution of the magnetoacoustic speed at the solar surface: black indicates speeds exceeding 500 km/s while green and white indicate lower speeds. The 2 snapshots from the simulation are separated by 15 minutes. A SOHO vantage point is assumed. In the right column the 2 EIT snapshots of the wave are separated by 12 minutes. Both images have the same scaling with ratio increasing with color from black to white.

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### 3. Summary and Conclusions

We have performed the first detailed analysis of an EUV wave from two vantage points as observed by the SECCHI disk imagers and coronagraphs. The high cadence and stereoscopic observations allowed us for the first time to precisely determine *where* (i.e. in the AR periphery) and *when* (i.e. closely associated with the impulsive acceleration phase of the CME and the start of the associated flare) the first signature of the EUV wave is seen. Our findings place new and tighter constraints on the physics of EUV waves and are summarized as follows:

- High-cadence (2.5 min) images showed a strong association between expanding loops and the EUV wave onset and significant differences in the wave appearance during early stages as viewed by the two EUV imagers; these differences largely disappear later.
- The wave first appears at the AR periphery when an abrupt jump of the expanding loops occurs within an interval of 2.5 minutes and before the first flare signature.
- The wave is seen more prominently in emissions formed in the  $\approx 1\text{-}2$  MK range; little, if anything, is seen in the chromosphere/transition region. The wave represents a rather modest intensity increase of  $\approx 5 - 30\%$  over the background.
- Triangulations showed that the wave was low-lying with a height of  $\approx 70$  Mm.
- The on-disk projection of a geometrical flux rope model of the associated CME did not show good agreement with the observed wave; a disparity of the size and the location of the projection and of the observed wave was found.
- Simulations of fast-mode wave were found to be in a good agreement with the observed wave.

The comparison of our findings with the expectations of the different proposed mechanisms for EUV waves were discussed in the previous Sections and are summarized in Table-1. We consider that a fast-mode wave is the most probable interpretation. Pseudo-wave theories run into significant trouble when trying to reconcile several important elements of the observations: an asymmetric-to-symmetric transition in the wave appearance as seen from the two SC, a rather poor chromospheric/transition region signature (inconsistent at least with the *reconnection front* model), probably too small wave height for the *current shell* model and too large for the *reconnection front* model and a mismatching CME on-disk projection with respect to the observed wave. On the other hand, a fast-mode wave interpretation is consistent with all observations.

We wish to iterate it here, that by EUV waves we are exclusively referring to large scale propagating intensity enhancements, which reach significant distances from the source region, especially during periods of solar minimum when the coronal landscape is rather simple. We do not exclude the possibility that other propagating intensity fronts which follow closely the expanding dimmings could be indeed pseudo-waves. However, these dimmings would normally never reach

**Table 1.** Comparison of the EUVI wave observations to the predictions of various proposed mechanisms to explain EUV waves. The first column gives the physical mechanism, the second column the observables and the third column outlines the observations first and the corresponding model predictions next. TR/chromo = transition region/chromosphere.

Mechanism	Observable	Observations/Model Predictions
fast-mode wave current shells reconnection fronts	<i>multi-viewpoint appearance</i>	initially asymmetric and then $\approx$ circular $\approx$ circular after wave is set up significant differences $\approx$ circular at all times
	<i>multi-temperature</i>	( $\approx$ 1-2 MK) ( $\approx$ 1-2 MK) weak coronal/TR/chromo TR/chromo
	<i>height</i>	( $\approx$ 90 Mm) coronal scale-height ( $\approx$ 70 Mm) CME height ( $>$ 250 Mm) cool loop height ( $<$ 10 Mm)
	<i>CME projection</i>	offset and smaller (than the wave) N/A cospatial and equal cospatial and equal

the rather global scales of the EUV waves we are considering here. Statistical studies of EUV dimming showed an average width of only  $\approx 36^\circ$  (Reinard and Biesecker 2008). We think that models such as the hybrid model of Chen et al. may be able to explain both the dimming and the ‘true’ wave. Further MHD simulations mapping the parameter space of different CME-wave-dimming scenarios are required.

We can now draw the following picture about the observed EUV wave. Coronal loops start to slowly expand (e.g. Figure 3 and video3.mov). This happens clearly before the onset of the flare. The angular separation of our observations was large enough ( $\approx 45^\circ$ ) to allow us to observe the *same* loops from strikingly different perspectives early on in the event (edge-on and face on; first column of Figure 2, Figure 5). Just before the start of the associated flare, the loops abruptly disappear and cannot be traced anymore; a well-defined wave front forms at the periphery of the active region. This front could be generated by a large scale disturbance induced by either the impulsive CME acceleration or the associated flare. The latter possibility can be rather safely excluded for the following reasons: (1) the associated flare was weak, (2) we found in Section 2.5 that launching the wave in the AR core, as expected from a flare-associated



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blast-wave, would not lead to wave fronts consistent with the observations. It is possible that the catastrophic energy release that apparently destroys the ascending loops within 2.5 minutes is also responsible for the launch of the wave which starts to propagate freely. A freely-propagating wave is consistent with the fact that the wave becomes more diffuse as it propagates farther from the active region (e.g. Parker 1961; Hundhausen 1985; Wartmuth 2007).

Before closing we note that clearly more work from both observational and theoretical approaches is required. First, although the analyzed event could be considered as a ‘typical’ solar minimum EUV wave, our study needs to be extended to larger sets of EUV wave events seen by STEREO. More emphasis should be given to higher cadence wave observations in the 195 channel, in which waves are best visible, in order to obtain a larger number of usable measurements per event. Moreover, higher cadence is needed also in the 304 channel in an attempt to search for evidence of transient brightenings that could be associated with reconnection fronts. Combination of stereoscopic wave observations by STEREO with the ultra-high cadence EUV observations from SDO will certainly help into that direction.

Finally, we note that the theories of EUV waves have reached various degrees of sophistication. However none of these theories are yet at a level to construct synthetic EUV images out of the particular physical mechanism to allow direct comparison with the observations. For this reason, we relied in this study upon morphological concepts like wave fronts, CME projections, geometrical shapes etc, which have led us to physical insights but are not sufficiently quantitative, at least to our satisfaction. We welcome the recent development of full Sun MHD models of Linker et al. (2008) which treat in a self-consistent manner both the CME eruption (i.e. the wave driver) and plasma thermodynamics (i.e. what it ultimately required for calculating realistic EUV intensities). The simulated EUV images showed the appearance of propagating intensity fronts similar to typical EUV waves. The analysis of these fronts showed they were associated with fast-mode waves.

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