Kinematical evolution of large-scale EUV waves in the solar corona

G. Mann, A. Warmuth©, and H. Önel©

Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
e-mail: GMann@aip.de

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ABSTRACT

Context. Large-scale coronal waves, also referred to as extreme-ultraviolet (EUV) waves, are a common phenomenon of solar activity in the Sun’s corona. They are observed in EUV light as global waves travelling over one hemisphere of the Sun. Previous studies of EUV waves defined three classes based on their kinematical properties. In particular, class 1 waves show a decrease in velocity during their evolution over the solar surface. These special EUV waves are considered as the manifestation of large-amplitude magnetohydrodynamic (MHD) waves in the corona.

Aims. We use a sample of seven class 1 EUV waves observed by the EUVI instruments onboard the two STEREO spacecraft to derive the relationship between the initial velocity and deceleration. This relationship can be explained in terms of the theory of large-amplitude MHD waves.

Methods. We employ non-linear MHD equations to describe large-amplitude, fast magnetosonic waves in terms of so-called ‘simple MHD waves’.

Results. The theory of simple MHD waves provides a relationship between the initial velocity and deceleration of the wave. The observations agree well with the non-linear evolution of a spherical large-amplitude, fast magnetosonic wave.

Conclusions. The kinematical properties of large-scale EUV waves can be well described by the theory of large-amplitude (simple) MHD waves.

Key words. Sun: corona – Sun: flares – Sun: coronal mass ejections (CMEs) – waves

1. Introduction

During the ESA/NASA space mission Solar Heliospheric Observatory (SOHO), a new wave phenomenon initially referred to as a coronal transient wave (Moses et al. 1997; Thompson et al. 1998) was discovered using the Extreme Ultraviolet Imaging Telescope (EIT; Delaboudiniere et al. 1995). These waves have subsequently become known as EIT waves, extreme-ultraviolet (EUV) waves, or more generally large-scale coronal propagating fronts (LCPFs). They appear as a bright rim (sometimes nearly circular) in EUV images, which propagates as a large-scale coronal disturbance over a significant fraction of the solar surface.

Immediately after their discovery, EUV waves were linked to Moreton waves (Moreton & Ramsey 1960), which are observed in the chromosphere. Moreton waves are often accompanied by solar type II radio bursts (Kai 1970), which are signatures of coronal shock waves (Wild et al. 1959). Because of this association, Moreton waves and the shock waves related to type II radio bursts were considered to be generated by the same phenomenon, namely a solar eruption (Uchida 1968). In contrast to Hα Moreton waves, EUV waves are visible in EUV spectral lines, for example at Fe XII at 195 Å, which is dominated by emission of coronal plasma at temperatures of $\approx 1.5 \times 10^6$ K. The velocities of Moreton waves seemed to be generally much higher than those of the EUV waves, which are found to have velocities in the range of 200–400 km s$^{-1}$ (Klassen et al. 2000; Thompson & Myers 2009).

Apparent discrepancies such as this have led to a prolonged discussion on the physical nature of EUV waves. In the ‘classical’ scenario, they are considered as large-scale fast magnetosonic waves and/or shocks (see e.g., Mann et al. 1999; Klassen et al. 2000; Warmuth et al. 2004b; Grechnev et al. 2008; Temmer et al. 2009; Veronig et al. 2010). According to this interpretation, a flare or a coronal mass ejection (CME) excites a fast magnetosonic wave in the corona, which is observed as an EUV wave that travels laterally along the solar surface. It may steepen into a shock wave and generate type II radio emission. This scenario explains the relationship between EUV waves and solar type II radio bursts as reported by Klassen et al. (2000). Accepting this model, EUV waves may be used to conduct coronal seismology. As an example, a magnetic field strength of $\approx 3$ G was deduced for the quiet corona (Mann et al. 1999; Warmuth & Mann 2005). The Alfven–Mach number of the shocks associated with type II radio bursts were found to be well above 1.6 (Mann et al. 1999).

An alternative interpretation of EUV waves is that they are the result of a magnetic restructuring of the corona in the framework of an expanding CME or an erupting flux rope (see e.g., Delannée & Aulanier 1999; Delannée 2000, 2008; Chen et al. 2002, 2005; Zhukov & Auchére 2004; Attrill et al. 2007; Wills-Davey et al. 2007; Dai et al. 2010). In this model, the disturbances are not real waves in a physical sense, but are propagating density and temperature variations induced by the expanding CME.

The apparent speed discrepancy between Moreton and EIT waves could be resolved by showing that both phenomena are consistent with a single, decelerating disturbance (Warmuth et al. 2001). Due to its low cadence (12–15 min), EIT recorded the EUV waves only when their speed had already decreased significantly. This was corroborated by observations in soft X-rays (Warmuth et al. 2005) and Helium I (Vršnak et al. 2002). Subsequently, the observational
capabilities in EUV were increased by the Extreme Ultra Vio-
let Imagers (EUVI) (Howard et al. 2008) on board the twin
spacecraft Solar-Terrestrial Relations Observatory (STEREO)
(Kaiser et al. 2008). The EUVI was designed with a much
better cadence in comparison to EIT, of namely ~2.5 min.
STEREO confers several advantages: it has a large field of
view, high sensitivity, and can obtain simultaneous obser-
vations from two well-separated vantage points in space.
Using these advantages of the STEREO spacecraft, EUV
waves have been investigated by means of the EUVI data
as reported in several papers (Long et al. 2008; Veronig et al.
2008; Gopalswamy et al. 2009; Patsourakos & Vourlidas 2009;
Dai et al. 2010; Podladchikova et al. 2010; Grechnev et al.
2011).

Finally, an additional step forward in terms of observa-
tional capabilities in EUV has been provided by the Atmo-
spheric Imaging Assembly (AIA; Lemen et al. 2012) on board
the Solar Dynamics Observatory (SDO; Pesnell et al. 2012)
spacecraft. This instrument provides superior temporal cadence
(12 s) as well as multi-temperature coverage due to the avail-
ability of six EUV channels. With AIA, it was possible to
show that LCPS propagate with an almost constant initial
velocity of \( \approx 1000 \text{ km s}^{-1} \) from the chromosphere up to the
corona (Chen & Wu 2011; Shen & Liu 2012a,b; Nitta et al.
2013; Shen et al. 2014).

Beyond individual case studies, a thorough physical under-
standing of coronal EUV waves requires the analysis of statisti-
cally significant samples. Warmuth & Mann (2011) analysed the
kinematics of a sample of 176 EUV waves recorded by EIT and
EUVI, and their findings revealed three distinct classes:
1. waves with initial velocities of \( > 320 \text{ km s}^{-1} \) showing pro-
nounced deceleration during their evolution;
2. waves propagating with a nearly constant speed of
\( 170 \sim 300 \text{ km s}^{-1} \);
3. disturbances with low speeds (~130 km s\(^{-1}\)) and showing a
rather erratic motion;
(see also Fig. 8 in Warmuth & Mann 2011). Class 1 events are
interpreted as large-amplitude magneto-hydrodynamic (MHD)
waves or shocks. Their velocity decreases during their evolu-
tion. Class 2 waves are considered to be linear waves travelling
with the local fast magnetosonic speed, because they travel with
a nearly constant velocity. Some authors (Shen & Liu 2012a,b;
Zhou et al. 2022a,b) reported on typical wave properties, such
as interference and reflection effects during the interaction of
EUV waves with coronal structures. These observations sup-
port the wave nature of EUV waves. Finally, class 3 events are
interpreted as disturbances caused by magnetic reconfigurations
(Warmuth & Mann 2011) and are not considered to be waves
in a physical sense. Thus, class 1 and 2 waves represent freely
propagating waves in the corona.

These results have been corroborated by statistical studies of
coronal waves using both EUVI (Muhr et al. 2014) and AIA
observations (Long et al. 2017a). In particular, the correlation
between deceleration and speed in fast events is now firmly
established. Together with other observations that have shown
typical wave properties such as reflection (e.g., Long et al.
2008; Veronig et al. 2008), refraction (e.g., Shen et al. 2013),
and transmission (e.g., Olmedo et al. 2012) at coronal structures,
as well as results from numerical simulations (e.g., Downs et al.
2021), this has led to a growing consensus that at least a signi-
ficant fraction of large-scale coronal waves are indeed fast-
mode MHD waves (cf. Long et al. 2017b). High-cadence and
stereoscopic EUV observations (e.g., Patsourakos & Vourlidas
2009; Kienreich et al. 2009; Patsourakos et al. 2010; Ma et al.
2011) have revealed that the waves are launched by erupt-
ing flux ropes. EUV waves can also be excited by coronal jets
(Shen et al. 2018b) and loop expansions caused by exter-
nal disturbances (Shen et al. 2017, 2018a). Initially, the afore-
mentioned drivers cause the disturbance, while later the per-
turbation becomes decoupled from the driver and continues
as a freely propagating wave. For more detailed descriptions
of the EUV waves and associated phenomena, we refer to the
reviews by Vrsnak & Cliver (2008), Wills-Davey & Attrill
(2009), Gallagher & Long (2011), Patsourakos & Vourlidas

We now focus on the kinematics of class 1 EUV waves,
which show a characteristic decrease in propagation speed dur-
ing their evolution. As the EUV waves travel over one hemi-
sphere, they travel mainly outside active regions, that is, they
move through regions of the quiet Sun, where the magnetic
field is predominantly radially directed. For this reason, the
fast magnetosonic speed should be regarded as almost con-
stant in this region. Therefore, EUV waves start with a veloc-
ity greater than the local fast magnetosonic speed, but their
velocities decrease during their further propagation. This prop-
erty can be explained in terms of non-linear waves. The veloc-
ity of a non-linear wave is typically dependent on its amplitude
(Landau & Lifschitz 1987). The EUV wave is initially excited in
a small region in the corona; during its evolution, it is distributed
over an increasing region, as in a spherical, cylindrical, or circu-
lar wave. This distribution leads to a decrease in the amplitude
of the wave. As its velocity depends on its amplitude, the velocity
becomes smaller during the evolution of the wave in the corona.
This behaviour is only seen in the EUV waves of class 1 (see
Fig. 8 in Warmuth & Mann 2011).

The aim of this paper is to describe this process in a quanti-
tative manner. In the paper by Warmuth & Mann (2011), Fig. 8
reveals for class 1 EUV waves that the higher initial velocity is
related with a higher deceleration. This relationship has yet to be
explained theoretically. As an observational basis, we have cho-
sen a sample of seven EUV waves from the large sample treated
by Warmuth & Mann (2011). These seven waves belong to class 1
and were recorded by the EUVI instruments (Howard et al. 2008)
on board the twin STEREO spacecraft. Because of the cadence
of ~2.5 min, the resulting data are appropriate for studying the
kinematical properties of freely propagating large-amplitude
EUV waves (see Sect. 2). The relationship between the initial
velocity and the deceleration during the first 300 s is derived for
each event of this sample and is compared with the theoretical
results in Sect. 4. The corona is a magnetised plasma. Therefore,
the EUV waves must be described in terms of non-linear MHD
waves. A brief description of simple MHD waves is presented in
Sect. 3. In Sect. 4, the theoretically obtained results regarding
the kinematics of simple MHD waves are compared with the
observations of EUV waves given in Sect. 2. The results of the
paper are summarised in the last paragraph of Sect. 4.

2. Data analysis

Seven EUV waves of class 1 (observed with EUVI) were chosen
from the sample studied by Warmuth & Mann (2011). They are
observed at 171 Å and 195 Å. The high cadence of these instru-
ments allows us to study the spatio-temporal evolution of these
waves. The observational data of these events are summarised
in Table 1. The event starts at the time \( t_s \). The bright rim of
the EUV wave is approximated by a cycle, allowing us to determine
the centre of the cycle (see Warmuth et al. 2001, 2004a for a detailed description of this method). Then, \(d_i\) gives the distance of the bright rim from the centre of this cycle at the starting time \(t_i\). The event disappears at the time \(t_e\) at a distance \(d_e\) from the centre of the cycle. The EUV wave starts with a velocity \(v_e\) and its final speed is \(v_f\). As \(v_r > v_e\) according to Table 1, the EUV wave is decelerated.

Each event provides a series of distances \(d_i\) from the centre of the approximated cycle at subsequent times \(t_i\). This series can be approximated using a power-law approach (Warmuth et al. 2001, 2004a) according to

\[
d(t) = d_0 \cdot (t - t_0)^\delta.
\]

The quantities \(d_0\), \(t_0\), and \(\delta\) are determined for each event from the measurements and are presented in Table 2. The initial velocities \(v_0\) of each event are calculated as follows:

\[
v(t) = \frac{d}{dt} \cdot d(t) = d_0 \cdot \delta \cdot (t - t_0)^{\delta-1},
\]

as \(v_0 = v(t = 0)\). The values resulting from this method are given for each individual event in Table 2. The initial deceleration is found by

\[
a_{300} = \frac{v(t = 300 \text{ s}) - v(t = 0)}{300 \text{ s}},
\]

which gives the velocity decrease after the first 300 s (5 min) of the event. The values of \(a_{300}\) are presented in Table 2 for each event. The pairs of values \((a_{300}; v_0)\) for each event (see Table 2) are inserted as bold dots in Fig. 3.

Averaging over all events, one obtains \(d_0 = 5443 \text{ Mm}, t_0 = -217 \text{ s}, \text{ and } \delta = 0.662\) as typical values for EUV waves (see bottom line in Table 2). Figure 1 shows the temporal behaviour of the local distance \(d(t)\) from the centre of the cycle, the local velocity \(v(t)\), and the local deceleration \(a(t)\) of a typical EUV wave according to Eqs. (1)–(3). The deceleration is calculated as

\[
a(t) = \frac{d^2d(t)}{dt^2} = d_0 \cdot \delta \cdot (\delta - 1) \cdot (t - t_0)^{\delta-2}.
\]

Figure 1 shows that a typical EUV wave starts at a distance of 192 Mm from the centre of the corresponding cycle with a velocity of 585 km s\(^{-1}\). The final velocity is 275 km s\(^{-1}\) after 30 min

### Table 1. Parameters of the class 1 EUV waves studied in this paper.

<table>
<thead>
<tr>
<th>#</th>
<th>Date (YYYY/MM/DD)</th>
<th>(\lambda) (Å)</th>
<th>(t_i) (s)</th>
<th>(d_i) (Mm)</th>
<th>(v_i) (km s(^{-1}))</th>
<th>(t_e) (s)</th>
<th>(d_e) (Mm)</th>
<th>(v_e) (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05/19/2007</td>
<td>171</td>
<td>391</td>
<td>132</td>
<td>588</td>
<td>1291</td>
<td>503</td>
<td>284</td>
</tr>
<tr>
<td>2</td>
<td>12/31/2007</td>
<td>171</td>
<td>422</td>
<td>162</td>
<td>391</td>
<td>2222</td>
<td>710</td>
<td>248</td>
</tr>
<tr>
<td>3</td>
<td>12/22/2009</td>
<td>171</td>
<td>600</td>
<td>354</td>
<td>409</td>
<td>2400</td>
<td>850</td>
<td>173</td>
</tr>
<tr>
<td>4</td>
<td>12/06/2010</td>
<td>171</td>
<td>45</td>
<td>66</td>
<td>685</td>
<td>720</td>
<td>382</td>
<td>304</td>
</tr>
<tr>
<td>5</td>
<td>08/07/2010</td>
<td>171</td>
<td>433</td>
<td>68</td>
<td>501</td>
<td>1543</td>
<td>499</td>
<td>217</td>
</tr>
<tr>
<td>6</td>
<td>08/14/2010</td>
<td>171</td>
<td>300</td>
<td>98</td>
<td>501</td>
<td>2099</td>
<td>657</td>
<td>195</td>
</tr>
<tr>
<td>7</td>
<td>08/09/2010</td>
<td>195</td>
<td>1300</td>
<td>373</td>
<td>503</td>
<td>2700</td>
<td>852</td>
<td>285</td>
</tr>
</tbody>
</table>

Notes. These waves were recorded by the 171 Å and/or 195 Å channels of the EUV instruments on board the STEREO A and B spacecraft. The first, second, and third column give the number and date of the event and at which wavelengths the EUV waves were observed, respectively. \((t_i)\) is the time at which the event starts; \(d_i\) is the initial distance of the wave from the centre of the corresponding cycle; \(v_i\) is its initial velocity; \(t_e\) is the time at which the EUV wave disappears; \(d_e\) is the final distance at which the EUV wave disappears; and \(v_e\) is its final velocity.

### Table 2. Parameters of the power-law approximation for the individual class 1 EUV waves studied in this paper.

<table>
<thead>
<tr>
<th>#</th>
<th>(d_0) (Mm)</th>
<th>(t_0) (s)</th>
<th>(\delta)</th>
<th>(v_0) (km s(^{-1}))</th>
<th>(a_{300}) (m s(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9498</td>
<td>-101</td>
<td>0.572</td>
<td>754</td>
<td>-1120</td>
</tr>
<tr>
<td>2</td>
<td>2923</td>
<td>-143</td>
<td>0.586</td>
<td>693</td>
<td>-863</td>
</tr>
<tr>
<td>3</td>
<td>4675</td>
<td>-58</td>
<td>0.670</td>
<td>820</td>
<td>-1233</td>
</tr>
<tr>
<td>4</td>
<td>3203</td>
<td>-101</td>
<td>0.705</td>
<td>579</td>
<td>-647</td>
</tr>
<tr>
<td>5</td>
<td>4104</td>
<td>-140</td>
<td>0.675</td>
<td>556</td>
<td>-577</td>
</tr>
<tr>
<td>6</td>
<td>3322</td>
<td>-559</td>
<td>0.745</td>
<td>493</td>
<td>-270</td>
</tr>
<tr>
<td>7</td>
<td>4065</td>
<td>-420</td>
<td>0.679</td>
<td>397</td>
<td>-210</td>
</tr>
</tbody>
</table>

Notes. The bottom line gives the values averaged over all values of the parameters of all events.

(1800 s). In the initial state, the wave is rapidly decelerated. For instance, the velocity decreases from 585 km s\(^{-1}\) to 436 km s\(^{-1}\) during the first 300 s leading to a deceleration of 497 m s\(^{-2}\). These values are inserted as a cross in Fig. 3.

### 3. Simple MHD waves

The large-scale EUV waves of class 1 according to the classification by Warmuth & Mann (2011) are considered as the manifestation of non-linear, fast magnetosonic waves. Therefore, non-linear MHD wave theory must be employed. This is done in terms of so-called simple waves in Riemann’s sense (Landau & Lifschitz 1987). The approach of simple waves was performed in MHD by Mann (1995). According to this approach, all varying quantities of the wave depend only on the spatial (x) and temporal (t) coordinates. However, there are relations between all varying quantities without any explicit dependence on x or t. In MHD, these varying quantities are the particle number density \(N\), the streaming velocity \(v_x\), \(v_y\), and \(v_z\) of the magnetic field \(b\) with its components \(b_x\), \(b_y\), and \(b_z\). The ambient magnetic field is put in the x-z plane and takes an angle \(\theta\) to the x-axis. The relationships between these varying quantities, namely

\[
0 = \frac{d\psi}{N^2} \cdot dN,
\]
and (4).

with the propagation velocity of the wave, and the velocity of the streaming velocity, that is $v_y = 0$ and $v_z = 0$. Equations (5) and (6) result in a system of non-linear differential equations:

$$\frac{dv_y}{dN} = \frac{V}{N}$$

$$\frac{db}{dN} = \frac{V^2 - c_s^2}{b}$$

leading to $b(N) = N$ with the initial conditions. Finally, Eq. (10) can be written as

$$b(N) = N^\gamma$$

Equations (11) and (14) are numerically solved for $v_{A,0} = 209 \text{ km s}^{-1}$ and $c_s,0 = 179 \text{ km s}^{-1}$ (see Sect. 4 for the choice of these parameters). In the case of simple waves (Landau & Lifschitz 1987), the top of the wave pulse propagates with the velocity $W = V + v_y$. The dependence of $W$ on $N$ is presented in Fig. 2 showing that $W$ is a monotonically increasing function of $N$.

4. Discussion

As described in Sect. 1, the EUV waves of class 1 have a basic property whereby their velocities decrease during their evolution; a high initial velocity is related with a strong deceleration during the initial phase of evolution (see Fig. 8 in Warmuth & Mann 2011). Such a property is typical for non-linear waves, where the propagation velocity of the wave is dependent on its amplitude. An EUV wave starts at a distance $d_0$ from the origin with the velocity $v_0$ and propagates as a circular (or cylindrical) or spherical wave over the solar surface. During this evolution, its amplitude, and therefore also its velocity, become smaller, leading to a deceleration of the wave. This is demonstrated for a EUV wave with typical parameters in Fig. 1. At the end of its appearance, it becomes a linear wave travelling with the linear wave speed.

$$V = v_{A,x}$$

Fig. 1. Temporal behaviour of the distance $d$ from the origin of the EUV wave, and the velocity $v(t)$ and deceleration $a(t)$ of a typical EUV wave with $d_0 = 5443$, $t_0 = -217$ s, and $\delta = 0.662$ according to Eqs. (1), (2), and (4).

are then derived from the ideal MHD equations (a detailed derivation of the Eqs. (5)–(8) is found in the paper by Mann 1995). Here, the particle number density $N$, the velocities, that is, the propagation velocity of the wave $V$, the components of the streaming velocity $v_x$, $v_y$, and $v_z$, and the components of the magnetic field $b_x$, $b_y$, and $b_z$ are normalised to the undisturbed particle number density $N_0$, the Alfvén velocity $v_{A,0} = B_0/(4\pi\mu_0 m_p N_0)^{1/2}$ (m$^p$, proton mass), and ambient magnetic field $B_0$. The sound speed $c_{s,0}$ is given by $c_{s,0} = (\gamma k_B T_0/\mu_0 m_p)$, where $\gamma$ is the ratio of specific heats, $k_B$ is the Boltzmann’s constant, $T_0$ is the undisturbed temperature, and $\mu_0 = 0.6$ is the mean molecular weight (Priest 1982), respectively. Consequently, one finds $b_x = \cos \theta$. It should be emphasised that the propagation velocity $V$ does not explicitly depend on the spatial and temporal coordinates, but might be a function of $N$, $v_x$, $b_y$, and $b_z$. Equations (5)–(8) represent a homogeneous system of equations; its non-trivial solutions are

$$0 = b_y \frac{db_y}{dN} + b_z \frac{db_z}{dN} + \left( \frac{c_{s,0}^2}{v_{A,0}^2} \cdot N \right)^{-1} \cdot V^2 \cdot dN,$$

$$0 = \left( V^2 - \frac{b_y^2}{N} \right) \frac{db_y}{dN} - V^2 \cdot b_y \cdot dN,$$

$$0 = \left( V^2 - \frac{b_z^2}{N} \right) \frac{db_z}{dN} - V^2 \cdot b_z \cdot dN,$$

and

$$V = \sqrt{\left( \frac{c_{s,0}^2}{v_{A,0}^2} \right) \cdot N \cdot \left( 1 \pm \sqrt{1 - \frac{4c_{s,0}^2}{v_{A,0}^2} \cdot N^{-1}} \right)}$$

with $v_{A,x}^2 = b_x^2/N$, $v_{A,y}^2 = b_y^2/N$, $v_{A,z}^2 = b_z^2/N$, $v_{A,i}^2 = v_{A,x}^2 + v_{A,y}^2 + v_{A,z}^2 = (b_x^2 + b_y^2 + b_z^2)/N = b_0^2/N$, and $c_s^2 = (c_{s,0}^2/v_{A,0}^2)N^{-1}$. These equations represent the non-linear generalisation of the intermediate (or Alfvén) (see Eq. (9)), fast (see Eq. (10), plus sign), and slow (see Eq. (10), minus sign) modes in MHD. Because the wave is travelling along the $x$-axis, there are no disturbances of the $y$- and $z$-component of the streaming velocity, that is $v_y = 0$ and $v_z = 0$. Equations (5) and (6) result in a system of non-linear differential equations:

$$\frac{dv_y}{dN} = \frac{V}{N}$$

$$\frac{db}{dN} = \frac{V^2 - c_s^2}{b}$$

leading to $b(N) = N$ with the initial conditions. Finally, Eq. (10) can be written as

$$V = \sqrt{N + \frac{c_{s,0}^2}{v_{A,0}^2} \cdot N^{-1}}.$$
The EUV waves of class 1 travel outside active regions, where the magnetic field of the quiet Sun is mainly radially directed. Therefore, these EUV waves can be regarded as a manifestation of non-linear, fast magnetosonic MHD waves, which propagate nearly perpendicular to the ambient magnetic field. Their final speeds can therefore be identified by the fast magnetosonic speed \( v_{\text{fms},0} = (v_{A,0}^2 + c_s,0^2)^{1/2} \). The final velocity of a typical EUV wave is 275 km\( \text{s}^{-1} \). This value is taken for \( v_{\text{fms},0} \). It is assumed that the EUV waves travel at a height of 5 Mm above the photosphere along the solar surface. According to the one-fold Newkirk (1961) density model,

\[
N_e = N_0 \cdot 10^{3.22 R_0/p},
\]

with \( N_0 = 4.2 \times 10^4 \text{cm}^{-3} \) \((R_0, \text{radius of the Sun})\), an electron number density of \( N_e = 8.18 \times 10^{11} \text{cm}^{-3} \) is expected there. The one-fold Newkirk model describes the radial behaviour of the electron number density very well above quiet equatorial regions (Koutchmy 1994). It corresponds to a barometric height model with a temperature of 1.4 MK. A sound speed of \( c_s,0 = 179 \text{ km} \text{s}^{-1} \) is obtained for such a temperature. Then, an Alfven speed of 209 km\( \text{s}^{-1} \) is found by \( v_{A,0} = (v_{\text{fms},0}^2 - c_s,0^2)^{1/2} \). Assuming that the coronal plasma consists of electrons, protons, and double ionized helium, the full particle number density \( N \) is related to the electron number density \( N_e \) by \( N = 1.92N_e \) (Mann et al. 1999). A magnetic field of 3.0 G is found for the quiet Sun at a height of 5 Mm above the photosphere, which is consistent with the observations of the normal magnetic field \( B = v_{A,0} \cdot (4\pi m_p,1.92N_e)^{1/2} \) (with \( \mu = 0.6 \) as the mean molecular weight Priest 1982). This is a typical value for the magnetic field of the quiet Sun at the bottom of the corona (Mann et al. 1999; Klassen et al. 2000).

Waves of the fast magnetosonic mode are accompanied with a density enhancement. As discussed in Sect. 3, the particle number density and the velocity of the wave are strongly related with each other in the case of simple waves. Therefore, the evolution of the density has to be studied in order to investigate the evolution of the wave. The evolution of the density is described in an iterative manner: At time \( n \), the top of the wave is located at \( d_n \). There, it has a particle number density \( N_{\text{max},n} \). It therefore propagates with the velocity \( W(N_{\text{max},n})v_{A,0} \). After the time step \( \Delta t \), the top of the wave travels up to \( d_{n+1} = d_n + W(N_{\text{max},n})v_{A,0} \cdot \Delta t \). During this time step, the density at the top is diminished to \( N_{\text{max},n+1} \) according to

\[
N_{\text{max},n+1} = 1 + \frac{(N_{\text{max},n}-1)}{1 + \left( \frac{W(N_{\text{max},n})v_{A,0}}{\Delta t} \right)^2},
\]

with \( \alpha = 1 \) and 2 for a circular (or cylindrical) and spherical wave, respectively. This iteration is numerically treated with the choice of \( v_{A,0} = 209 \text{ km} \text{s}^{-1} \), \( d_{n+1} = 192 \text{ Mm} \) and \( \Delta t = 100 \text{ s} \). These parameters are typical for EUV waves, as seen in Fig. 1. The procedure is performed in the following way: Initially, a value of \( N_{\text{max},0} \) is chosen and the velocity \( W(N_{\text{max},0}) \) is calculated according to the numerical results leading to Fig. 2. Then, the value of \( N_{\text{max},i} \) is iteratively determined according to Eq. (16) and, subsequently, \( W(N_{\text{max},i}) \) is found, which is the velocity after 300 s of the evolution. The deceleration \( a_{300} \), which the wave experiences within the initial period of 300 s, is found by

\[
a_{300} = \frac{(W(N_{\text{max},i} = 300) - W(N_{\text{max},i = 10}))(v_{A,0})}{300 \text{ s}}.
\]

This procedure is done for \( N_{\text{max},i = 1} = 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, \) and 6.0. In this way, a relationship between the initial velocity \( v_{A,0} = 192 \text{ Mm} \) and \( a_{300} \) can be derived for the case of a circular (or cylindrical) \((\alpha = 1)\) and a spherical \((\alpha = 2)\) wave. The results are drawn in Fig. 3.

The approach of simple MHD waves can explain that a non-linear wave with a high initial velocity experiences a high initial deceleration. Thus, a large-amplitude EUV wave is decelerated during its evolution due to non-linear effects. In order to compare the theoretical results with observations of EUV waves, the initial velocities and decelerations measured for a sample of seven EUV waves are inserted in Fig. 3. This comparison shows that the evolution of a spherical \((\alpha = 2)\) simple MHD wave agrees well with the observations.

**5. Summary**

A characteristic feature of initially fast \((i.e., \geq 320 \text{ km} \text{s}^{-1})\) large-scale EUV waves propagating in the solar corona is their pronounced deceleration, where the magnitude of deceleration correlates with the speed. The measured kinematics of such waves (Warmuth & Mann 2011) are compared with the results of a non-linear MHD wave model describing the evolution of a so-called simple MHD wave (Mann 1995). We find that a spherical large-amplitude magnetosonic wave reproduces the observed
kinematics quite well. This provides further support for the interpretation of coronal EUV waves as fast-mode MHD waves.

References

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