EUV-FILAMENTS AND THEIR MASS LOADING

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ABSTRACT

It was found recently (Heinzel et al., 2001; Schmieder et al., 2003a) that solar filaments observed in EUV lines by SOHO/CDS are much more extended than their Hα counterparts. This was explained by a large difference between the hydrogen Lyman-continuum and Hα opacities. Two different MHD models were suggested to explain the EUV-filament extensions: the model based on parasite polarities (Aulanier & Schmieder, 2002) and the model with twisted flux tubes (Anzer & Heinzel, 2003). The latter model can explain our recent findings that at least some parts of the EUV-filament extensions are located relatively high in the corona. These heights can be computed using a new spectroscopic model of EUV-filaments. The mass which is loaded into the EUV-filament extensions is then estimated on the basis of non-LTE transfer calculations. The total filament mass is larger than that derived for the Hα filament itself and this may have consequences for the structure and mass loading of CMEs whenever they form from such filaments - this may answer the question how the extended CME structures can form from rather narrow Hα filaments. We summarize the basic properties of EUV-filaments, present their spectroscopic analysis and give some estimates for mass loading. We then discuss possible relations between EUV-filaments and CMEs, in particular the problems of their masses.

Key words: EUV-filaments; CMEs; Mass Loading.

1. INTRODUCTION

Solar filaments represent an important trace of the Sun’s activity and thus their understanding is one of the principal goals of the solar physics. On one side they are often connected to eruptive flares (Svestka et al., 1992), on the other they may accompany Coronal Mass Ejections (CME) playing a significant role in their mass loading (see reviews in Schmieder et al. (2000)). Filaments have been studied for decades using mostly Hα filograms. Their physical conditions were determined using the optical, infrared and UV line spectra. In particular new UV and EUV observations have been collected since 1996 by Coronal Diagnostics Spectrometer (CDS) and Solar Ultraviolet Measurements of Emitted Radiation (SUMER) onboard the Solar and Heliospheric Observatory - SOHO. Filaments observed in transition-region (TR) and coronal lines which have the wavelength below the hydrogen Lyman-continuum head (912 Å) appear as dark structures on the solar disk. When seen on the limb as a prominence, they also appear dark in coronal lines but bright in cooler lines. Dark filaments or prominence structures observed in UV are generally ascribed to absorption of the UV-line radiation by the hydrogen Lyman continuum which is supposed to be opaque enough in cool plasmas (Schmähl & Orrall, 1976). For prominences seen on the limb, this mechanism was investigated recently by Kucera et al. (1998). In Schmieder et al. (1999) one can find a coalignment between a dark prominence observed in EUV by CDS and the cool Hα structures which also supports the absorption scenario. For filaments, Drago et al. (2001) have shown that in lines below 912 Å they appear dark while in lines above 912 Å they are invisible. This is again a strong evidence of the absorption by Lyman continuum. Note also that dark filaments are frequently seen on synoptic images from SOHO/EIT (Extreme-Ultraviolet Imaging Telescope) and images from TRACE (Transition-Region And Coronal Explorer). However, they correspond to lines having the wavelength below 227 Å (HeI ionization edge) where He I and He II resonance continua dominate the absorption (see e.g. Mein et al., 2001).

In this paper we summarize recent UV and EUV observations of filaments made by SOHO and show several new results which arose from them. In particular we try to make an estimate of the filament mass which seems to be important for the understanding of CMEs.
Figure 1. CDS images of 5 May 2000 EUV-filament. Overlaid contours correspond to the Hα filament observed by THEMIS. SUMER observations were obtained with the slit position indicated in the Si XII raster image. From Heinzel et al. (2001).

Figure 2. Correlation between $\tau_0$ for Hα and $\tau_{912}$ for 11 values of temperature (top curve: 6000 K; the step is 500 K). Right: Same correlation shown for T = 8000 K and the microturbulence variation from 3 to 10 km s$^{-1}$. From Heinzel et al. (2001).
2. NATURE OF EUV-FILAMENTS

Solar filaments observed in EUV lines below 912 Å are dark against the disk and we call these structures 'EUV-filaments'. Quite recently, Heinzel et al. (2001) and Schmieder et al. (2003a) found that EUV-filaments can be much more extended than their Hα counterparts - an example is shown in Fig. 1 where we see a filament observed on 5 May 2000. Extended dark structures are well detected in the O \textsc{v} (629.73 Å) TR line and in three coronal lines of Mg \textsc{x} (624.94 Å), Si \textsc{xii} (520.60 Å) and Ca \textsc{x} (557.77 Å). Overlaid on these images are contours of the Hα filament as observed by THEMIS. The width of the EUV-filament is several times larger than the width of the Hα part. Heinzel et al. (2001) have explained this behaviour by a large difference between Lyman-continuum and Hα opacity. This then means that those parts of the filament which are outside the Hα contour are practically transparent in Hα but still rather opaque in the Lyman continuum. The theoretical correlation between Hα and Lyman-continuum opacities was presented in Heinzel et al. (2001) (see Fig. 2) and is based on an extensive grid of non-LTE filament models developed in Tziotiou et al. (2001). From Fig. 2 one can see that the ratio between Lyman-continuum and Hα optical thickness can reach two orders of magnitude (this is based on the assumption of complete redistribution in Lyman lines, in reality the partial-redistribution calculations show that this ratio is somewhat lower, at least in the central parts of the filament visible in Hα - see Schmieder et al. (2003a)).

3. SPECTROSCOPIC MODEL

In order to estimate the altitudes where the EUV-filaments are located, Heinzel et al. (2003) have suggested a new spectroscopic model which allows the determination of the bottom and top heights of the EUV-filament using simultaneous observations in at least two coronal lines. This model was successfully applied to SOHO/CDS observations which provide 2D rasters of the filament area in selected EUV lines. Moreover, complementary observations of EUV-filaments in TR lines like O \textsc{v} (CDS) and O \textsc{vi} (SUMER) allow to determine the hydrogen Lyman-continuum optical thickness which is an important parameter in the spectroscopic model. We will now detail the model and show some examples how it can be applied to SOHO observations.

3.1. Determination of EUV-filament Altitudes

Fig. 3 shows a sketch of the model, the individual quantities have the following meaning:
- \( h_1 \) - height of the bottom of the Hα part (all heights are measured from the solar surface)
- \( h_2 \) - height of the top of the Hα part
- \( h_3 \) - height of the bottom of the EUV part
- \( h_4 \) - height of the top of the EUV part

\[ \Delta h = h_4 - h_3 \]

\[ I_{qs} \] - quiet-Sun disk intensity, measured in the neighborhood of the filament

\[ I_{bg} \] - intensity of radiation incident at the bottom surface of the EUV part (background intensity)

\[ I_{fii} \] - intensity of the EUV-filament

\[ I_{fg} \] - intensity measured at the darkest points within the Hα filament body (foreground intensity)

\[ I_b \] - coronal intensity emitted along the height \( \Delta h \) of the EUV part.

Here Hα means the main filament body as seen in the Hα line, EUV is its lateral EUV extension. The Hα parts are also seen in EUV lines as the darkest areas.

We define the function \( f(h) \)

\[ f(h) = \int_0^h \epsilon(h') \, dh' / I_{qs}, \]  

\[ \epsilon(h') \] is the height-dependent EUV-line volume emissivity. Note that at the surface \( f(0) = 0 \) and at very large heights \( f(h) \) approaches unity.

\[ I_{qs} = \int_0^\infty \epsilon(h') \, dh'. \]  

The basic idea of the spectroscopic model is to use at least two coronal lines which have different scale heights. Because the coronal-line emissivity extends far into the corona (depending on the actual scale height), we can consistently take into account both absorption and volume-blocking effects. The latter, newly introduced in Heinzel et al. (2003), is due to the presence of the cool EUV-filament plasma which blocks a certain coronal volume otherwise occupied by a hot coronal plasma emitting the EUV lines. For two coronal lines we can then write two equations describing the absorption and volume-blocking and their solution gives us the two unknown quantities \( h_3 \) and \( h_4 \). These equations have the form
\[ I_{fla} = I_{q4} [1 - f(h_5)] + I_{q5} f(h_5) \exp(-\tau_\lambda). \] (3)

We see that the relative filament to quiet-Sun intensity depends only on \( \tau_\lambda \) and the function \( f(h) \). \( \tau_\lambda \) is the optical thickness of the Lyman continuum at the wavelength position of a given coronal line and \( f(h) \) also depends on the line used. We then take

\[ f(h) = 1 - \exp(-h/H), \] (4)

where \( H \) is the scale height of the coronal-line emissivity. This formula follows from Equation 1 with the emissivity taken from Equation A4 in Heinzel et al. (2003). The first term on the r.h.s. of Equation 3 corresponds to the coronal radiation above the EUV part and the second term is \( I_{q5} \) attenuated by the absorption. Note that for coronal lines

\[ I_{q5} = I_{q5} f(h_5) + I_h + I_{q5} [1 - f(h_5)], \] (5)

where the first term represents \( I_{q5} \), \( I_h \) is the coronal emission blocked by the presence of the cool plasma extending between the heights \( h_3 \) and \( h_4 \) (this volume-blocking is taken into account in Equation 3) and the last term represents a foreground emission above the EUV-filament extension. \( \tau_\lambda \) is easily obtained from \( \tau_{912} \) using the well-known \( \lambda^3 \) dependence of the hydrogen Lyman-continuum absorption cross-section (e.g. Mihalas, 1978)

\[ \frac{\tau_\lambda}{\tau_{912}} = \frac{\lambda^3}{(912)^3}. \] (6)

EUV-filament heights \( h_3 \) and \( h_4 \) are then computed iteratively as described in detail by Heinzel et al. (2003). For one selected CDS pixel in the 5 May 2000 filament raster, Heinzel et al. (2003) have determined \( h_3 \) and \( h_4 \) depending on \( \tau_{912} \) which was taken as a free parameter. The result is shown in Fig. 4. We see that for larger \( \tau_\lambda \) the volume-blocking effect becomes less important.

4. 3D-TOPOLOGY FROM SOHO OBSERVATIONS

Using the spectroscopic model described above, Schwartz et al. (2003a,b) computed the heights \( h_3 \) and \( h_4 \) for the whole EUV-filament as observed on 15 October 1999 (note that this filament was not located close to the solar-disk center and thus the projection effects had to be taken into account). CDS raster images of this filament in \( \text{O}_v \), \( \text{Mg}{\text{x}} \) and \( \text{Si}{\text{xii}} \) lines are shown in Schwartz et al. (2003a,b). Here in Fig. 5 we reproduce only the CDS raster obtained in the \( \text{Mg}{\text{x}} \) line. The white contours indicate the location of the \( \text{H} \alpha \) filament (three rather small patches) and the vertical line shows the position of the SUMER slit.

Figure 4. EUV-filament model. The upper full line shows variations of \( h_4 \), the lower one corresponds to \( h_3 \). The dashed line is drawn at the height \( h_2 \). From Heinzel et al. (2003).

Figure 5. SOHO/CDS observations of the filament on 15 October 1999, in \( \text{Mg}{\text{x}} \) line. Boundaries of the EUV-filament are drawn as dashed lines, the white contours show the location of the \( \text{H} \alpha \) filament as observed by VTT on Tenerife. The vertical bar is the SUMER slit position. From Schwartz et al. (2003a,b).
The whole EUV-filament is bounded by the dashed line. We define the location of the EUV-filament by taking a certain level of image contrast relative to a mean 'quiet-Sun' area. A more rigorous way of determining the EUV-filament contours is to use two rasters simultaneously obtained in two similar TR lines, where one has the wavelength below 912 Å and the other one above 912 Å. An example of such a line pair is O V (CDS) and O VI 1031.91 Å (SUMER). In Fig. 6 we show a cut through the filament along which the intensities of these two lines are plotted (this cut corresponds to the SUMER slit position as indicated in Fig. 5). We see that while the O VI line exhibits similar intensity variations along the whole cut, the O V line is significantly depressed in the region of the EUV-filament. This confirms the behaviour described by Drago et al. (2001) who found that EUV-filaments are invisible in TR lines above 912 Å. Note that the dashed-line boundaries in Fig. 5 determined from contrast considerations agree quite well with the behaviour of O V - O VI line pair along the SUMER slit position. This confirms that the EUV-filament boundary previously determined is realistic at this position.

For the EUV-filament one can then compute the values of γ₁₂. The result for γ₁₂=5 is shown in Fig. 7. These maps have been interpolated between pixels where we could obtain a solution for our spectroscopic model (see below).

The height maps computed for other γ₁₂ (3 and 7) can be seen in Schwartz et al. (2003b) (this volume), while Schwartz et al. (2003a) show these maps in color which allows a better visibility of the 3D topology.

The maps in Fig. 7 show several interesting features. First, we see that the EUV-filament of 15 October 1999 is located at rather large heights, its top reaches altitudes larger than 70000 km. The surface of h₃ looks more structured compared to that of h₄. This can be explained by the fact that for a given variation of Mg X and Si XII line intensities, h₃ varies much more than h₄ (see Heinzel et al., 2003 and Schwartz et al., 2003a). Finally, as we show below, the solution depends on the scale heights used and also on the level of the quiet-Sun intensity. Therefore, it may happen that even outside the EUV filament, solutions exist if there are detected some dark features and if the scale heights and actual value of the quiet-Sun intensity favours such solutions. In other words, the spectroscopic model doesn’t prove the existence of an EUV-filament at a given position in the CDS raster, but rather gives a reasonable estimate of heights at points which are supposed to belong to EUV-filament.

4.1. Solution Space Depending on Scale Heights

As mentioned above the height maps in Fig. 7 were interpolated between those CDS pixels where the spectroscopic models gave us a solution. In fact, as already shown in Heinzel et al. (2003), for a given pair of the line scale heights one obtains a specific area of solutions which is rather narrow. For the case of the 15 October 1999 filament this is shown in Fig. 8. The scale heights obtained for that case are \( H(\text{Mg X}) = 32000 \text{ km} \) and \( H(\text{Si XII}) = 46075 \text{ km} \). The medium-gray area in the plot of relative intensities is rather narrow compared to the range of the observed intensities (black points in Fig. 8). As a result we find solutions only in some CDS raster pixels and to get smooth height variations in our maps we used the interpolation between such pixels. This, however, doesn’t mean that there is no solution in such 'black' pixels. Schwartz et al. (2003a) have investigated this problem in a great detail and found that in fact by varying the range of the line scale heights one can get a much wider area of solutions - see the other two solutions in Fig. 8 (light and dark gray strips). This indicates that that the coronal line scale heights are very probably non-uniform over the whole EUV-filament. Note that the EUV-filament intensities plotted as dark points in Fig. 8 were normalized to measured quiet-Sun intensity and thus their actual position in the plot depends on the way how this intensity was determined.
5. MHD MODELS OF EUV-FILAMENTS

The observational evidence that EUV-filaments are typically a factor 5 – 10 wider than the corresponding Hα filaments is very important for any theoretical attempt to model the equilibrium of these cool structures in the solar corona. The basic problem is the very small scale height of such a cool plasma. The narrow width of the Hα filaments follows quite naturally in all the magnetic equilibrium models from the observed temperatures of 6000 – 10000 K and a field geometry with shallow dips. The temperature of the EUV material has not been determined observationally up to now. But there exists a rather strong constraint: there must be enough neutral hydrogen in these regions to produce the absorption in the EUV lines below 912 Å. From this constraint an upper limit for the temperature can be found. The temperature should certainly not exceed 20000 K in order to avoid a complete ionization. In this case the scale height could be a factor 2 – 3 larger than that in the Hα counterpart. But this is by far not enough to explain the very large widths of the EUV-filaments.

This implies that simple arcade-like magnetic field configurations cannot explain the EUV-filaments. The only reasonable possibility seems to assume many individual magnetic dips which are spread over the entire region of the arcade. Then if a large fraction - or all - of the dips are filled with cool material one can produce the required extended absorbing region. This will imply that such types of magnetic field configurations have to be necessarily very complex. Therefore no simple analytical models can be expected. Two models of this kind have been proposed recently: the constant α force-free field model by Aulanier & Schmieder (2002) and the twisted flux tube model of Anzer & Heinzle (2003).

Figure 7. Height maps of the upper (hₙ) and lower (hₙ) boundaries of the EUV-filament derived for τ₉₁₂ = 5. These maps were computed using the model of Heinzel et al. (2003), for details see Schwartz et al. (2003a,b).

Figure 8. Areas in space of MgX versus SiXII line intensities where the spectroscopic model has solutions. These areas were computed for three combinations of the line scale heights. Tiny black points represent the line intensities of individual pixels of the CDS raster where we can identify the EUV-filament. From Schwartz et al. (2003a).
5.1. Model of Aulanier & Schmieder

Aulanier & Schmieder (2002) start from the observational aspect that the photospheric field associated with quiescent prominences is not strictly bipolar. In each of the two regions on both sides of the filament one has some background flux together with many small scale parasitic polarities. The flux distribution is therefore very irregular. The coronal field which results from such flux distributions will therefore automatically have many small scale magnetic dips. Aulanier & Schmieder (2002) took the photospheric flux distribution measured for the filament of 5 May 2000 which had a very extended EUV structure. They calculated force-free fields for different values of $\alpha$. They then compared the location of all these dips with the maps of the EUV-filament (see Fig. 9) and found a rather good spatial correlation. From this they concluded that if all magnetic dips are filled with a sufficient amount of cool material then such a model can explain the EUV-filaments. Note that these extended low-lying structures which are due to parasitic polarities form an outer part of the whole filament which was modelled in 3D and contains relatively high and thin Hα part in its central regions. This Hα part may contain some extra mass as discussed below.

5.2. Model of Anzer & Heinzelt

Anzer & Heinzelt (2003) took a different approach. They started from the field of a simple bipolar magnetic arcade and an Hα filament which is made up of many vertical threads. They further assumed that the arcade consists of many individual flux tubes. This kind of configuration does not have any dips outside of the Hα filament. But if one now applies a sufficiently large amount of twist to the individual flux tubes then all field lines of the tube will acquire dips away from the midplane of the arcade. These dips can extend far away from the Hα filament. For the case of an arcade with concentric circular field lines with radius $R$, height of apex $h$, a minor radius of the tube $r$ and number of twists $n$ these field lines will have dips up to a maximum distance $x_1$ from the midplane. For this case Anzer & Heinzelt (2003) found the relation

$$n \geq \frac{x_1}{\sqrt{R^2 - x_1^2}} \frac{R}{\pi r} \arccos\left(\frac{R - h}{R}\right).$$

(7)

Taking some representative values for the geometrical configuration of $R = 100000$ km, $h = 30000$ km and $r = 2000$ km one then obtains for the maximum width

$$x_1 \approx \frac{R}{\sqrt{n^2 + 170}}.$$ 

(8)

Therefore for large enough amounts of twist $n$, extended dip regions can be generated in this way. A

\[\text{Figure 9. Locations of magnetic dips in EUV-filament of 5 May 2000. The high altitude dips match the filament body and feet in Hα (top), the low-lying dips match the wide EUV-filament channel (bottom). From Aulanier and Schmieder (2002).}\]
limiting effect for this twisting process is the kink instability of slender flux tubes. This implies that \( r_1 \) will in practice always be a small fraction of \( R \); but half widths \( x_1 \) of the observed magnitude (70000 km) can be obtained in this way.

The difference between the two types of models arises from the different physical processes which are responsible for the formation of the dips. In the model of Aulanier & Schmieder (2002) the process is the appearance of small scale parasitic polarities. The model of Anzer & Heinzel (2003) is based upon the twisting of individual flux tubes. The configurations obtained in the two models differ significantly: in the first model all dips are very low. Aulanier & Schmieder (2002) found maximum heights around 4000 km (they also obtained some higher dips, but they are associated with the Hα filament and not the EUV extensions). The reason for these small heights is the fact that the vertical scale for the dips will be comparable to the horizontal line structure scale. In the second class of models the dips can occur at all heights of the arcade. There is only the aspect that very high rising flux tubes are very long and therefore less stable.

These differences have severe consequences for the modelling of the EUV-filaments. Since in the parasitic polarity model the dips are low the outer filament parts can only extend from the solar surface to heights up to 4000 km according to Aulanier & Schmieder (2002). The dips in twisted flux tubes can reach to the top of the Hα filament (or even higher). Therefore the EUV-filament extension can be very high. The question of the filament height is very important for the modelling of coronal EUV lines. These lines are emitted over typical scale heights around 40000 km (Heinzel et al., 2003). Therefore any low lying cool structures cannot affect the coronal line emission. For this reason the parasitic polarity model will require an additional physical mechanism to produce the dark EUV features. A possible candidate for this is the existence of coronal voids. But since the shape of the EUV-filaments is almost identical for lines from the corona and from the transition region one would need a mechanism which conncets the low dips to the formation of voids. At present no such mechanism is known.

There is still another aspect related to low-lying dips. According to Fludra et al. (1999), the scale height of O V is a few thousands km, for O VI it will be more. If the low-lying dips were located below say 4000 km, they should cause a significant volume blocking to the TR line radiation and thus should be visible even when there is no absorption (O VI). But TR lines above 912 Å don’t show any dark features (Drago et al., 2001 and our Fig. 6). However, this idea will require further analysis, namely precise determination of the scale heights of TR lines.

On the other hand the twisted flux tube model can basically reproduce all the observed features. But since these models have to be fully three-dimensional and rather complex they have not been worked out in detail. Nevertheless it is found that EUV-filaments of the right width can be produced in this way.

6. MASS LOADING AND RELATION TO CME’S

One of the major goals of our analysis of the EUV-filaments is determination of the total mass loaded into EUV-filament extensions. This mass has to be compared with the mass of the main filament body visible in Hα. The total mass loaded into the whole filament then represents an important parameter in studies of Coronal Mass Ejections (CME). However, while the main filament body seen in Hα usually forms the bright core of a CME (when the filament erupts), the EUV extensions can be expelled only in the case when they are part of the destabilized magnetic arcade. This seems to be the case for the twisted flux tube model of Anzer and Heinzel (2003), while the parasitic-polarity EUV structures located at heights below 4000 km will remain away from the eruption and will not contribute to mass loading of a CME (Aulanier and Schmieder, 2002). In fact they will stay there and will be seen during and after the eruption inside the filament channel (Aulanier, private communication).

6.1. Hydrogen Density

In order to estimate the plasma density of both the Hα and EUV parts of a filament, one should perform rather complex non-LTE transfer computations as described in Schmieder et al. (2003a) where the MALI code of Heinzel et al. (1997) was used. For the filament of 5 May 2000, Schmieder et al. (2003a) used the SUMER observations of hydrogen Lyman lines and continuum plus Hα data from THEMIS to model the central cool parts of the filament seen in Hα. However, for EUV extensions no such modelling was done so far and some preliminary simulations indicate that EUV structures will be probably somewhat hotter and of lower density, in order to have rather low opacity in the Lyman continuum (see discussion in Heinzel et al., 2003). In this paper we show how the density can be roughly estimated, using an approximate formula based on extensive grids of non-LTE models of cool filament-like structures.

What is actually needed to compute the plasma density is the number density of hydrogen atoms and ions (protons). Then, assuming the helium abundance to be 0.1 relative to hydrogen, we can write for the plasma density

\[ \rho = 1.4 \times m_H n_H, \]

where \( m_H \) is the mass of the hydrogen atom and \( n_H \) is the density of neutral hydrogen atoms and protons (\( n_p \)), i.e. the total hydrogen density. Assuming that the helium is almost neutral in cool filament structures, we can use the charge conservation equation.
in the form \( n_e = n_z \), where \( n_z \) is the electron density. Most of neutral hydrogen is in the ground state, so that we can replace the neutral hydrogen by the density of hydrogen atoms in the ground state \( n_0 \). \( n_1 \) then directly follows from \( \tau_{912} \) and the geometrical thickness \( D \) (see Heinzel et al., 2001)

\[
n_1 = 1.6 \times 10^{17} \tau_{912} / D .
\]

(10)

Determination of the electron density is, however, more complicated. As a basis we can use the well-known relation between the electron density and the second-level hydrogen density \( n_2 \)

\[
n_e = C \sqrt{n_2} ,
\]

(11)

where the constant \( C = 2.6 \times 10^8 \) is taken from Mein et al. (2001) where this formula was used for filament-like structures. \( n_2 \) can be derived from the H\(\alpha \) line-center optical thickness \( \tau_0 \)

\[
n_2 = 10^8 \alpha(T) \tau_{912} \Delta \nu_D / D ,
\]

(12)

where \( \Delta \nu_D = 1.96 \times 10^8 \sqrt{T} \) is the Doppler width of the H\(\alpha \) line and the parameter \( \alpha(T) \) is the temperature-dependent ratio between \( \tau_0 \) and \( \tau_{912} \). The latter can be estimated using the non-LTE grid of models as shown in Heinzel et al. (2001), where \( \tau_0 \) is defined in the Appendix. Combining all these formulas we get an approximate expression for total hydrogen density

\[
n_H \simeq 1.6 \times 10^{17} \tau_{912} / D + 2.6 \times 10^6 [\alpha(T) \Delta \nu_D \tau_{912} / D]^{1/2} .
\]

(13)

Note that all densities derived here are the mean densities averaged over the local thickness \( D \). This means that all vertical inhomogeneities are taken into account. In other words, we can simply multiply such densities by \( D \) to get real column densities, which is clear from the above equations.

### 6.2. Mass Loading Estimate for two Filaments

**Observed by SOHO**

We have studied in detail two filaments which exhibit considerable EUV extensions and now we estimate their mass loading.

#### 5 May 2000 Filament

The lateral EUV extensions of this filament are about 5-10 times wider than the central H\(\alpha \) part. We have used SOHO/SUMER observations of hydrogen Lyman lines and continuum together with H\(\alpha \) data from THEMIS in order to model the central cool parts of the filament (Schmieder et al., 2005a). The best-fit model gave us the following parameters for central parts of the H\(\alpha \) filament:

#### Table 1. EUV-filament mass loading for the 15 October 1999 filament. The mass \( M \) in grams has been computed for different values of \( \tau_{912} \).

<table>
<thead>
<tr>
<th>( \tau_{912} )</th>
<th>( M ) [g]</th>
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<tbody>
<tr>
<td>1.0</td>
<td>8.6 x 10^{14}</td>
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<tr>
<td>3.0</td>
<td>1.8 x 10^{15}</td>
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<tr>
<td>5.0</td>
<td>2.2 x 10^{15}</td>
</tr>
<tr>
<td>8.0</td>
<td>2.7 x 10^{15}</td>
</tr>
<tr>
<td>12.0</td>
<td>3.0 x 10^{15}</td>
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\( T = 8000 \) K, \( D = 5000 \) km, \( \tau_{912} = 70 \) (PRD-value), \( \tau_0 = 3.2 \) (PRD-value), central gas pressure \( p = 0.08 \) dyn cm\(^{-2} \), \( n_z = 2 \times 10^{11} \) cm\(^{-3} \). PRD means that the non-LTE model was computed with partial frequency redistribution in Lyman lines, while the grid shown in Heinzel et al. (2001) is based CRD approximation (complete frequency redistribution). The density of EUV-extensions was found to be an order of magnitude lower than the density of the H\(\alpha \) filament. However, with respect to the large extension of this EUV-filament, the total mass is estimated to be comparable for both parts.

#### 15 October 1999 Filament

For this filament we have reconstructed the whole 3D topology as described in Section 4 and thus we can estimate its total mass. Note that this particular filament is barely visible in H\(\alpha \), in Fig. 5 we see only a few very limited H\(\alpha \) structures. Therefore, the EUV-filament mass loading will most probably dominate the total filament mass. Using the approximate formulas given above, we have computed the plasma density at each pixel position of the CDS raster and then multiplied it by the pixel size and filament thickness shown in Fig. 7. This was done for several values of \( \tau_{912} \) and we show the results in Table 1.

#### 7. DISCUSSION AND CONCLUSIONS

In the previous section we have made an estimate of the mass loading into the whole filament of 5 May 2000 which consists of the main filament body seen in H\(\alpha \) and the EUV lateral extensions. Our conclusion for the case of this particular filament observed by SOHO is that the total mass loaded into the filament is about twice larger than the mass of the H\(\alpha \) part. This represents a significant enhancement of the total mass loaded into a CME in the case when such a filament erupts. One has to take into account that a typical H\(\alpha \) filament may contain a mass comparable to the mass of the corona. Therefore, it would be important to distinguish between the initially cool filament plasma which forms the core of most CMEs
and presumably a hot leading front which forms from erupted helmet streamers - see a representative example of such a CME in Plunkett et al. (2000) where a twisted core is nicely seen.

In the case of the 15 October 1999 filament we obtained the masses summarized in Table 1. They range from $10^{15}$ to few times $10^{15}$ g. The same range was reported by Webb (2000) for averaged CME masses. Similar estimates are also given by Sinnett (2000) who also makes a distinction between total CME mass and that of the ‘dense prominence’. In some cases the prominence mass dominates the CME, in others not. Prominence masses reported by Sinnett (2000) are in all cases below $10^{15}$ g, typically a few times $10^{14}$ g. However, a remark should be made here concerning these estimates which are based on white-light SOHO/LASCO (The Large Angle Spectroscopic Coronograph) images. The plasma density is estimated for fully ionized hydrogen, determining the electron density from Thomson scattering. This is plausible for the hot parts of CMEs. However, the related erupting prominence (bright core) must not be fully ionized since we can see it in some cases rather bright in Hα up to large distances from the limb - see an example in Plunkett et al. (2000). This would mean that the LASCO observations will underestimate the prominence mass in some cases.

In this work we have estimated the mass of EUV-filament extensions, i.e. of those parts of the filament which are not seen in Hα. However, it has to be noted that also the main filament body may contain some extra mass not visible in Hα. As shown by Aulanier and Schmieder (2002), the magneto-hydrostatic dips containing cool plasma visible in Hα have to be filled to about 5.6 pressure scale heights in order to reach low opacities in the Lyman continuum. This then means that each such hydrostatic dip will be about 50 % more massive than what one would expect from Hα diagnostics alone. However, there might be a problem with direct detection of this extra mass because the Hα dips will overlap in projection against the disk and thus the Lyman-continuum absorption will take place mainly in cool Hα plasma, contrary to what we observe in lateral EUV parts which are not visible in Hα. A plausible diagnostics of the total mass in these dips can be done using lines formed at low temperatures and having much larger opacity than Hα. Such lines are e.g. the hydrogen Lyman lines which were detected by SUMER for filaments studied here and which were analyzed by non-LTE radiative transfer methods in Schmieder et al. (2003). Since the diagnostics in the latter paper is based on these lines the mass of the central Hα filament should be more or less consistent within 50 % extras as suggested by Aulanier and Schmieder (2002).

To further continue these studies, new UV and EUV prominence and filament observations are required. Apart from CDS and SUMER, the EUV-filaments can be detected by EIT and TRACE. However, their appearance may differ from that in CDS rasters because the absorption will be weaker and thus the filaments will be less extended. This may explain why the EUV-filaments seen on the limb as dark prominences do not seem to be very extended, being more or less coaligned with bright He II prominence structures (there are some other effects which also decrease the visibility of EUV-filaments on the limb). On the other hand, synoptic observations of filaments passing over the solar disk can help us in understanding their true 3D topology. Schmieder et al. (2003b) report on TRACE observations of an EUV-filament close to the solar limb and derive from geometric considerations its altitude of 30000 km. New observations should also answer the question concerning the location of magnetic dips filled by cool plasma and thus discriminate between various MHD models of EUV-filaments.

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REFERENCES

Mihalas, D. 1978, Stellar Atmospheres, W. H. Freeman, San Francisco

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Schmieder, B., Yong Lin, Engvold, O. et al. 2003b, in preparation


