Vertical magnetic flux tube expansion in the solar atmosphere from the photosphere to the corona. A motivational letter

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Abstract
The solar atmosphere is of great interest for plasma physicists due to the wealth of different plasma processes and phenomena which can be studied here in detail and not reproduced in a laboratory. Among those interesting phenomena are magneto-hydrodynamic waves, their generation, propagation, and finally damping and absorption of their energy. These waves are not only of interest from an abstract point of view for understanding our nature and physical universe but they also constitute a major possible contributor to the so-called coronal (and/or chromospheric) heating problem.
Vertical magnetic flux tubes are an important wave and energy guide connecting the lower atmosphere with the higher one. Due to the decrease of the plasma pressure in the surrounding atmosphere, these flux elements start to expand. The resulting question which we wish to investigate in more detail in this work is, how fast are the magnetic elements really expanding and what consequences might this have?

Keywords: MHD waves, flux tubes, solar magnetic fields, numerical simulations

1. INTRODUCTION

The solar atmosphere is highly structured by magnetic fields which cause a manifold of different physical processes and phenomena. E.g., starting in the photosphere we can clearly identify and differentiate between the granulation pattern, the manifestation of the uprising and sinking convective plasma cells, versus the network regions in between the granules. Among other processes, like magnetic flux emergence from the subsurface, convection sweeps magnetic field into these network regions and leads thus to magnetic field agglomerations which are then often visible as strong (kG range) magnetic flux tubes (see e.g. Utz et al. 2013 [1], Riethmüller et al. 2014 [2]).

Leaving this surface layer, into the photosphere, and going even higher up into the chromosphere these flux tubes expand and form finally somewhere in the middle chromosphere the so-called magnetic canopy layer. A wealth of interesting phenomena are happening here starting from fibrils and spicules which are mass flows from the lower atmosphere to the higher one, via acoustic shock wave absorption, seen e.g. as intensity brightenings in the chromosphere, to MHD wave processes (e.g., Wedemeyer et al. 2009 [3]).

Different types of MHD waves can be generated in the photosphere due to the interaction of small-scale magnetic fields with the granulation flows. Among them are kink and sausage modes as well as purely Alvénic torsional modes (Jess et al. 2009 [4], Stangalini et al. 2013 [5]). All of these waves travel up into the higher atmosphere where interesting phenomena such as mode conversion – the changing of the type of mode from one to the other – as well as absorption, refraction and reflection of waves can happen (e.g. Grant et al 2015 [6] and references therein).

It becomes immediately clear that for all of this phenomena it is very important to know how the magnetic fields are structured in the atmosphere and how they are expanding with height in the atmosphere. Especially for the wave processes it is important to know how the plasma beta – the ratio between gas pressure to magnetic pressure – changes with height as this defines how and where mode conversion and other effects can take place. In this contribution we will try to motivate this aspect even more and try to approach the problem from the point of numerical modelling.

2. CONSTRUCTION OF THE BACKGROUND MODEL

In this work, we make use of the numerical code MPI-AMRVAC which stands for Message Passing Interface – Adaptive Mesh Refinement Versatile Advection Code (e.g. Porth et al 2014 [7]). This code is now hosted and maintained at the Centre for mathematical Plasma Astrophysics at KU Leuven and can be freely downloaded from:

"http://homes.esat.kuleuven.be/~keppens/".

The code can be used to treat HD, MHD and relativistic MHD problems. Thus different physical modules are available to handle these classes of problems. The user can also choose between different numerical schemes to integrate the set of equations as well as different methods for divergence B cleaning, flux and slope limiters and so on.

For our problem we use the ideal, non-isothermal full energy equation treating MHD module with a Lax Friedrich scheme for integrating the equations.

The first step in constructing our model consists in setting up a background solar atmosphere reaching from the photosphere to the corona. For that purpose, we simplify the solar atmosphere in such a way that we consider for the temperature profile a 5 regions atmosphere. Starting from an isothermal 5400 K photosphere to a first transition to a chromosphere with a temperature of 4700 K. The transition is modelled via a hyperbolic tangent. Then we have an isothermal chromosphere before we reach the transition to the corona, again modelled by a hyperbolic tangent, before we finally have an isothermal corona at 1 MK (Eq. 1).

$$T(h) = T_{pho} - \frac{(T_{pho} - T_{chr})}{2} * \left(1 + \tanh\left(\frac{h - h_{chr}}{w_{tpc}}\right)\right) + \frac{(T_{cor} - T_{chr})}{2} * \left(1 + \tanh\left(\frac{h - h_{cor}}{w_{tcc}}\right)\right) \quad \text{Eq.1}$$

The temperature profile of this quiet background atmosphere as well as a cut through our magnetic element are shown in Fig. 1, where the magenta colored lines belong to the background atmosphere and the pink lines to the cut through the magnetic element.

In a next step the atmospheric density profiles can be derived by evaluating the hydrostatic pressure equation together with the ideal gas law which leads to a slightly modified barometric density/pressure formula as the temperature of the atmosphere is not constant (isothermal) and changes with height. In a final step the pressure profile can be calculated via the ideal gas law.

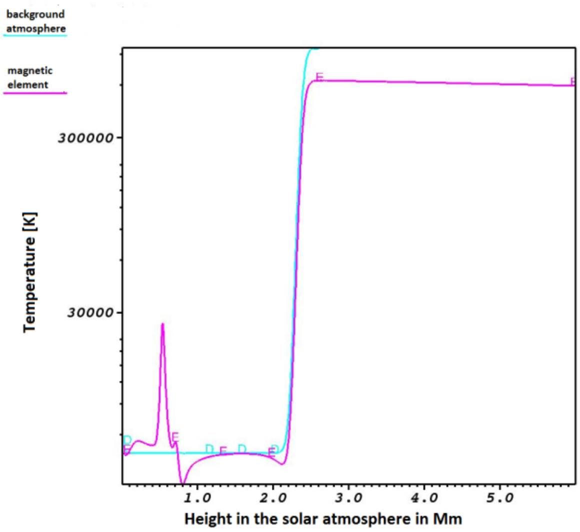

Figure 1. The chosen vertical temperature profile of the quiet non magnetic field atmosphere (shown in magenta) and a vertical cut through the magnetic element (pink color).

Figure 2 shows the pressure and finally Fig. 3 the density profile for the quiet background atmosphere as well as for the magnetic flux element. Interestingly we can see that the magnetic element shows an increased temperature in the chromosphere, which can be

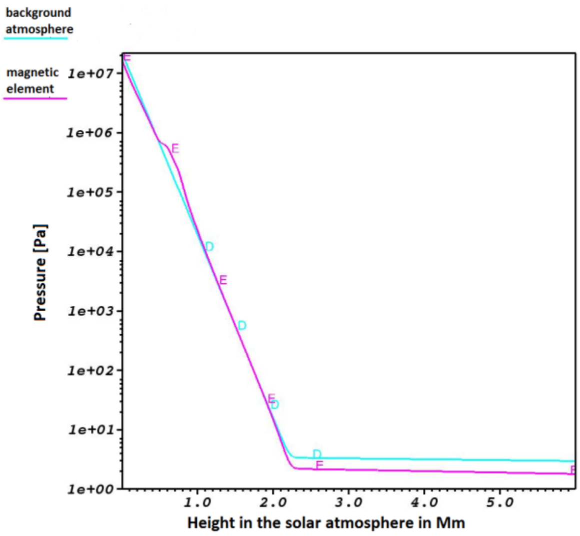

Figure 2. Similar to Fig. 1 but the vertical distribution of the pressure within the quiet non-magnetic atmosphere and a flux element is shown.

probably observed as CaII-H brightening. This hot layer is followed by some temperature minimum and higher pressure layer. Finally, the density distribution reveals two interesting, but quite simple to interpret facts. First the magnetic atmosphere shows a density decrease in the chromosphere where the canopy layer forms (strong horizontal fields) and secondly there is a strong drop of density in the transition region where the temperature rises to a million degrees. The second finding results from the hydrostatic equilibrium.

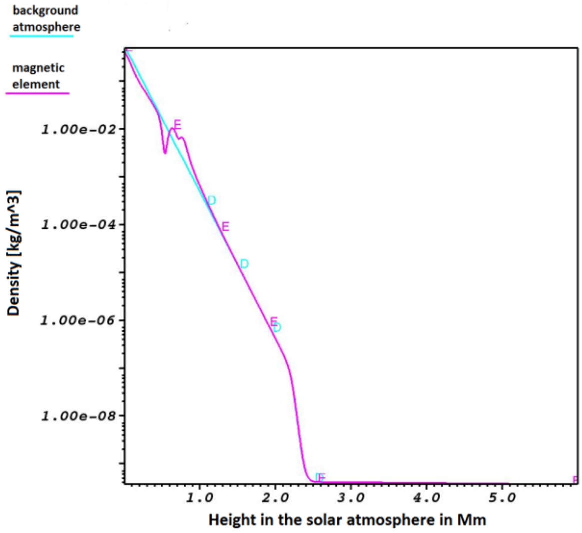

Figure 3. Similar to Fig. 1 but the vertical distribution of the density within the quiet non-magnetic atmosphere and a flux element is shown.

3. MODELLING OF MAGNETIC FLUX TUBES

Now we wish to turn to the problem of how to insert a magnetic flux tube in our atmosphere. A usual approach is given by Shelyag et al. (2010)[8] where a divergence free magnetic field configuration can be created via a given magnetic field strength profile in the centre of the flux tube and an expansion function of how the magnetic field should diverge with height (for more details see the previously cited work).

We have chosen a more general approach as we have a certain shape and configuration of flux tubes already in mind, i.e. we would like to have a preferential shape of the flux tube, similar to an inverted bottle, of which we unfortunately do not know the exact vertical field strength profile through the centre of the flux tube.

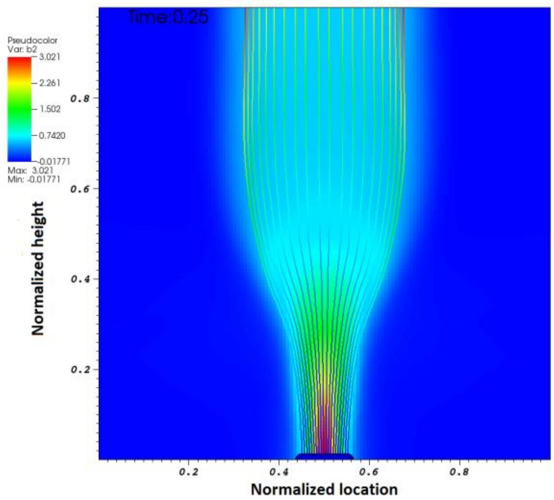

Figure 4. A typical magnetic flux tube is shown, opening from the photosphere to the higher layers. The shown quantity is the vertical magnetic field strength in arbitrary units.

In our case we start with the assumption that a likely horizontal cut through the magnetic flux tube will yield a cross sectional vertical field strength distribution similar to a Gaussian curve. The second assumption is

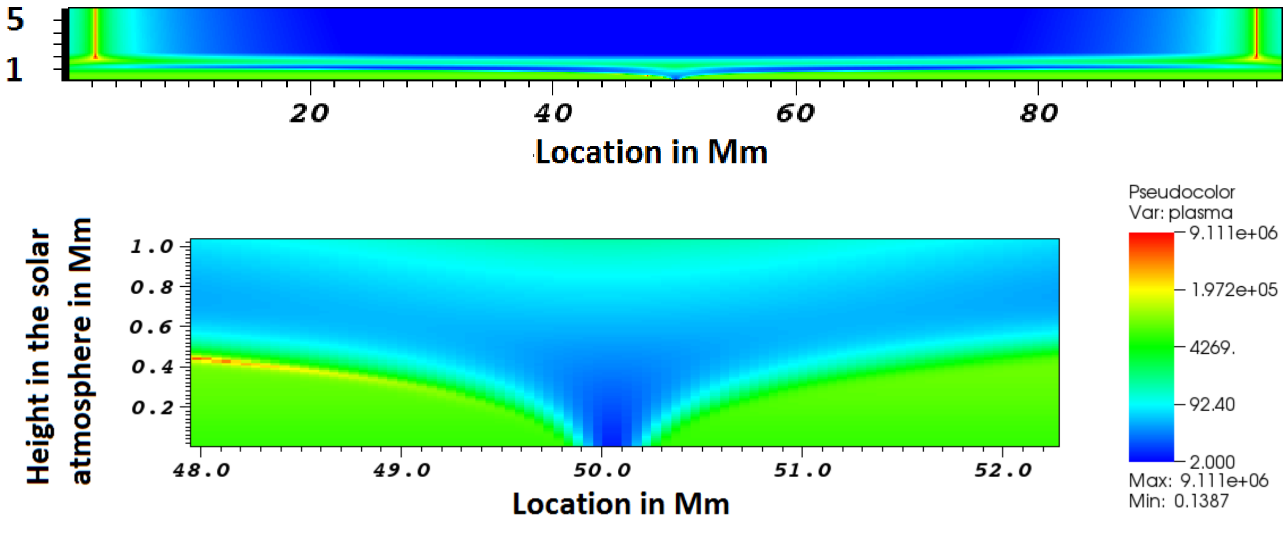

Figure 5. A strongly expanding vertical magnetic flux tube; clearly the large expansion contradicts the picture of a slim vertical magnetic flux tube which could be modelled in first order by a cylindrical homogenous magnetic field configuration. Shown is the plasma beta distribution ranging for this model from 2 to ~10^6 (from blue to red; from strong magnetic fields to field free regions).

that the flux tube will broaden due to the decreasing gas pressure and become again purely vertical in the higher atmosphere (corona). To model such a "slender" flux tube we change the sigma in the previous horizontal cut modelled by a Gaussian distribution with height. The functional change in height will be given again by a hyperbolic tangent. In this way we can create the vertical magnetic field strength. For the horizontal magnetic field strength, we directly integrate the div B = 0 condition in each horizontal cut with the boundary condition that the horizontal magnetic field should be 0 in the centre of the magnetic flux tube.

For a particular set of parameters this procedure will yield a flux tube as depicted in Fig. 4.

The question arising is, is this a good model for a vertically stratified solar magnetic flux tube?

4. DISCUSSION OF THE OPENING/EXPANSION OF MAGNETIC FLUX TUBES

While Fig. 4 corresponds nicely to what we might have in mind about solar vertical magnetic flux tubes, the question is, if it fits to reality.

There are more or less two observational constraints: a) from measurements of the small-scale magnetic fields in the Sun we know that typical field strengths are up to the kG regime, with some authors claiming that it is a requirement for such elements to have at least 1 kG [2]. b) on the other hand our theoretical understanding and indirect measurements of the solar coronal magnetic field indicates that within the corona the magnetic field should have dropped to only a few Gauss.

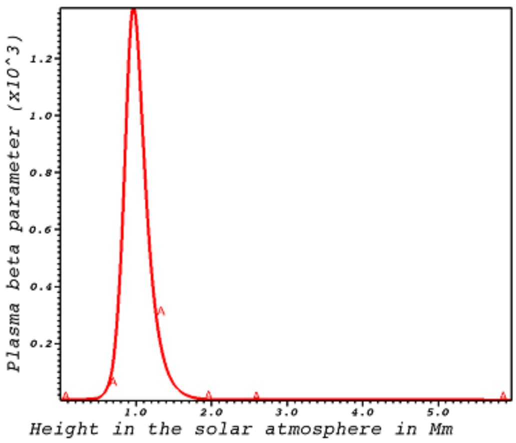

Figure 6. The distribution of the plasma beta parameter inside the central magnetic flux element of Fig. 8. In this case a highly plasma dominated chromosphere is forming due to the rapid expansion.

This said it means that, at least for 2D, we need expansion factors of the flux tubes between 100 to 1000 to decrease the magnetic field from the kG regime to just a few Gauss. Moreover, this must happen over a very limited range in height (roughly 2000 km – from the photosphere to the corona). Having this in mind we would end up with a flux tube which would look more like Fig. 5.

This is clearly not what we have in mind when we talk about a slender solar vertical magnetic flux tube. So how can we solve the contradiction between the expansion and the requisite of somehow keeping a slim shape on the other hand?

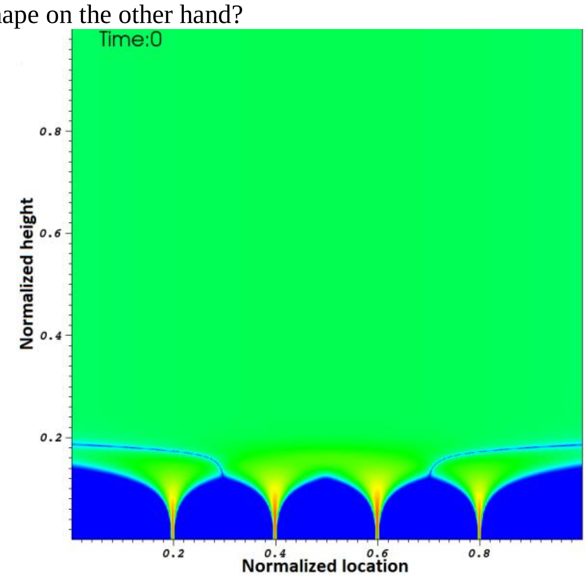

Figure 7. A possible solution to the problem of magnetic flux reduction in height. A multi-fluxtube atmosphere with different magnetic polarities can reduce, due to the superposition principle, the total magnetic field strength. The magnetic field strength scales logarithmically in this image in arbitrary units from 0 over 0.3 to 72 (blue over green to red color).

Besides this question, there is a second question, namely how fast should the flux tube open? If it expands very fast, the magnetic pressure can fall even faster than the gas pressure in the surrounding and thus the plasma beta parameter would yield a plasma dominated chromosphere $\beta > 1$, whereas if the expansion of the flux tube is slower with height, the gas

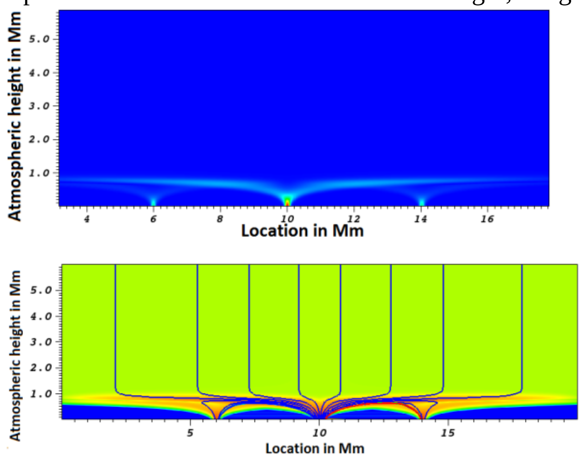

Figure 8. The currently employed flux tube set-up with a strong (~ 500 G) flux tube in the centre and two intranetwork weaker flux elements of opposite polarity on its side. The top plot shows the total magnetic field strength while the lower plot shows the same configuration and quantity but logarithmically plotted and field lines added.

pressure would drop faster and the chromosphere would be magnetic field dominated (e.g. Fig. 6, gives the plasma beta distribution for a cut through the centre line of the flux tube model from Fig. 8).

A possible solution for the first problem, which also yields most likely more realistic models, is to employ not a single flux tube, but to add neighbouring flux elements with opposite polarity to the main element. Such a model is also more realistic, as we know from recent Hinode observation that practically the whole solar surface is filled with magnetic elements (Lites et al. 2008 [9]). While we have the kG strong elements mostly situated within the magnetic network, there are practically everywhere else weak hG strong flux elements in the quiet internetwork regions.

Such magnetic fields can be likely modelled by weaker flux elements sitting in the internetwork regions. Such a modelling would give rise to Fig. 7 or the even more realistic model which is also currently employed by us for more detailed analysis and depicted in Fig. 8.

Due to the linearity of the MHD equations one can superimpose single flux elements on top of each other and the total magnetic field would be just the summation of the field components of the single flux tubes. Thus superimposing magnetic elements with opposite magnetic field strengths would lead to a cancellation of magnetic field and thus solve our problem of reducing the magnetic field strength without broadening the magnetic flux tube by unrealistic expansion factors.

The second problem of how fast the flux tubes should expand can of course not be solved by such a "Gedankenexperiment". A better way to approach that problem is from the observational point of view.

This was recently done by the author and a team of co-workers in Utz et al. 2016. Here we took Hinode measurements of magnetic bright points in different filtergrams to inspect the size of the features in various heights. Due to the decreasing gas pressure outside of the magnetic flux tube the tubes start to expand. By measuring this expansion via the various sizes in different heights we were able to estimate the scale-height parameter within the photosphere for magnetic bright points (manifestations of kG strong magnetic flux tubes). The measured value of about 120 km agrees very well with theoretical predictions.

Besides of that we have shown that the expansion seems to be dependent on the size of the flux tube itself. In the paper we interpreted this fact as a statistical fingerprint of sausage type MHD waves.

To conclude this section: The opening of vertical magnetic flux tubes is an important but still ill investigated and posed problem of solar physics. While the decrease of magnetic flux with height can be achieved by superposing opposite polarity magnetic flux tubes, more observational research in the expansion of flux tubes with height is necessary. Especially the configuration in the chromosphere is not well known.

5. OUTLOOK AND FUTURE DIRECTIONS

After establishing a realistic magnetic field configuration for the solar atmosphere over quiet patches of the Sun, we wish to simulate MHD wave propagation in such an atmosphere.

By doing so we hope to address important questions like: a) when a certain spectrum of waves is generated in the photosphere, in what way does the atmosphere filter this spectrum; what is a realistic output spectrum on top of the magnetic field configuration in the corona; b) how and where do mode conversions from one type of MHD wave to another one occur? c) what are the absorption and/or heating rates due to the propagating

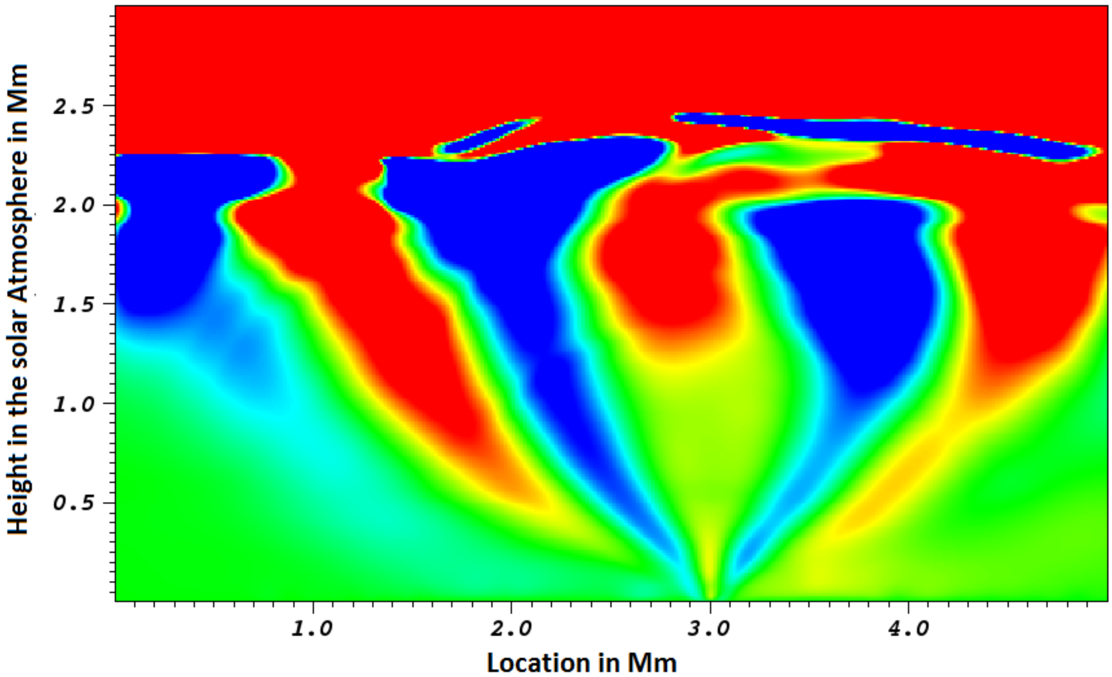

Figure 9. A first test run of horizontally driving a flux tube situated at 3 Mm while a second one situated at 2 Mm is not moving. Clearly a wavelike pattern evolves in the atmsophere which cannot easily penetrate into the corona. Shown is the horizontal velocity clipped to ±100 m/s (red/blue color).

waves? d) can waves trigger reconnection events? To what extent and how important would such effects be?

A first snapshot of a simulation with a horizontal driving of one flux tube situated at position 3 Mm on the x-axis can be seen in Fig. 9.

Another ongoing and promising part of the work is the generalisation to full 3D. A first step is the extension to 2.5D in the sense of magnetic sheets which can be generated by just filling a data cube with the same atmospheric 2D cut. A typical example for such an atmosphere can be seen in Figs. 10 and 11.

6. CONCLUSIONS AND REMARKS

The expansion of vertical magnetic flux tubes is to the best of our knowledge still not well constrained from observations. Some minimum requirements would be that a realistic model should reach kG field strengths in the photosphere and drop down with height too just a few Gauss in the corona. This cannot be done by simply opening the flux tube (at least in 2D) as it would yield unrealistic opening factors. Besides the theoretical framework for such a clearly non-vertical flux tube would break down. This is due to the fact that still lot of the current theoretical understanding is based on simplified cylindrical approaches or at least slim and slender flux tubes with low expansion factors.

A more realistic approach to the problem should involve not only a single flux tube by itself but also try to model the surrounding of the flux tube and thus include neighbouring weaker flux elements which are commonly found in the photosphere.

A detailed paper regarding the discussed points and more detailed results is under preparation and will be hopefully published in Utz et al. 2017 [11].

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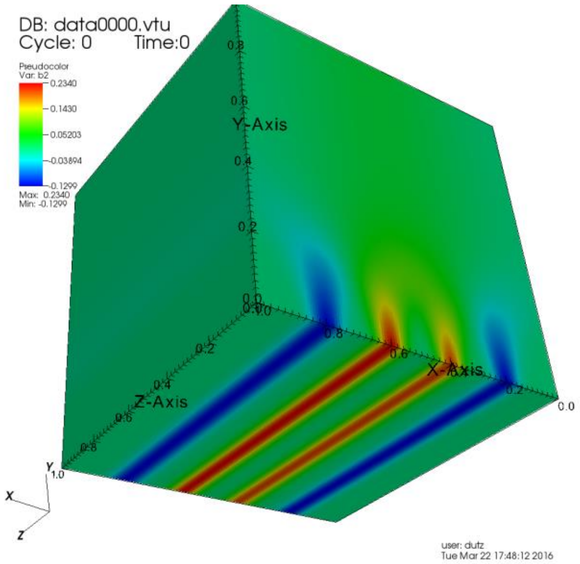

Figure 10. A first 2.5 D flux sheet set-up with two flux elements of one polarity in the centre and two elements of opposite polarity bordering this region. Shown is the vertical field strength in normalised units.

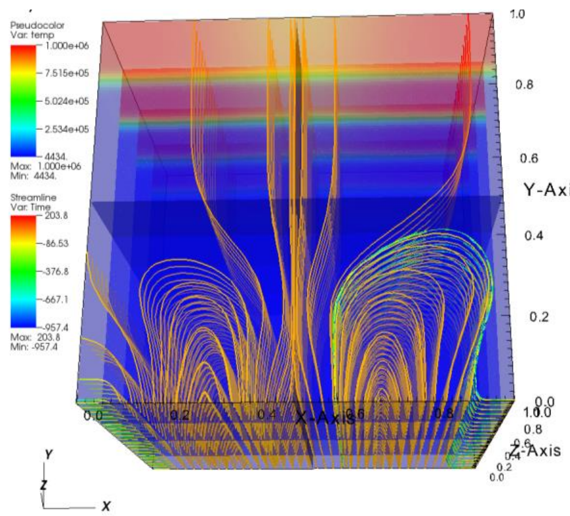

Figure 11. Same as Fig. 10 but for the temperature, and viewing under a different viewing angle; overplotted are the field lines. Clearly a flux tube element in the middle is formed with two low lying arcades to the side of the central element