Magnetic straws in the solar atmosphere

Multi-wavelength observations, interpretations and speculations

M.R. Haas

Abstract

Observations are done on several positions on the solar disk, varying from disk center to the limb of the Sun, using the Dutch Open Telescope on La Palma. Four different wavelength bands are compared to each other and to older observations. The observed features, called straws because of their elongated, thin appearance in Ca II H linecenter as well as Hα linewing, are investigated and compared to each other and to cartoon models. The lack of cospatial and cotemporal observations in Ca II H linecenter and Hα linewing made it impossible to draw any hard conlcusions. Therefore several possibilities are kept open and suggestions for further research are made.

1 Introduction

In October 2004 there was a possibility for four students to go to La Palma and to observe with the Dutch Open Telescope (see Rutten et al. (2004)). As originally planned the new Hα camera should be used to find out what the possibilities of this camera were to observe several features in the solar atmosphere. Next to that, the speckle cluster (used to speckle reconstruct the images in almost real time) should have been finished and working to gather whichever data we liked. Unfortunatley the new camera was just placed and gave its first results, but the speckle cluster was not finished yet. Therefore we were banned to older observations concerning the specific topic we had chosen before.

Originally I was interested in magnetic bright points; bright features in the intergranular lanes, seen as well in Ca II H as in the G-band. Their relation with the magnetic field is not doubted (see Berger & Title (2001)). They appeared to live in patches. Seperate bright points live on timescales of minutes, while these patches appeared to exist for mesogranular timescales. To get better statistics on these patches, longer time series were needed (the original timeseries were only 42 minutes long, slightly below mesogranular timescales). For an overview on this research, see the thesis of Mabula Haverkamp (2004). Longer timeseries could unfortunately not be made and speckle-reconstructed before the end of this small research, so another topic had to be found.

The attention was caught by solar limb observations taken on June 18$^{\text{th}}$, 2003. The total set of observations consisted of 4 cotemporal and cospatial timeseries of 15 minutes on five different positions on the solar disk ($\cos\theta = \mu =$ 0.34, 0.48, 0.62, 0.74, 0.98) in four wavelength bands (Ca II H, G-band and blue and red continuum). In the Ca II H series the filter switched between linecenter and linewing (1.35 Å off) alternatively.

2 Observations

2.1 Dutch Open Telescope observations

A snapshot of three positions on the solar disk can be found in Figure 1. The appearance in G-band is most probably understood and explained by comparison with simulations by Keller et al. (2004) and Carlsson et al. (2004), by means of the hot wall model first proposed by Spruit (1976). Facular elements, as these bright points are called when viewed towards the limb, in G-band have shape factors (length divided by width) around unity, see Adjabshirizadeh & Koutchmy (2002). In Ca II H linecenter however, we can see 'straws' of several arcseconds long, originating from these bright points when we are looking at the limb of the solar disk. These straws always point more or less limbward from the bright point they originate from and their shapefactor is obviously far from 1. A larger image of Ca II H linecenter can be seen in Figure 2. In the wing these straws are absent,

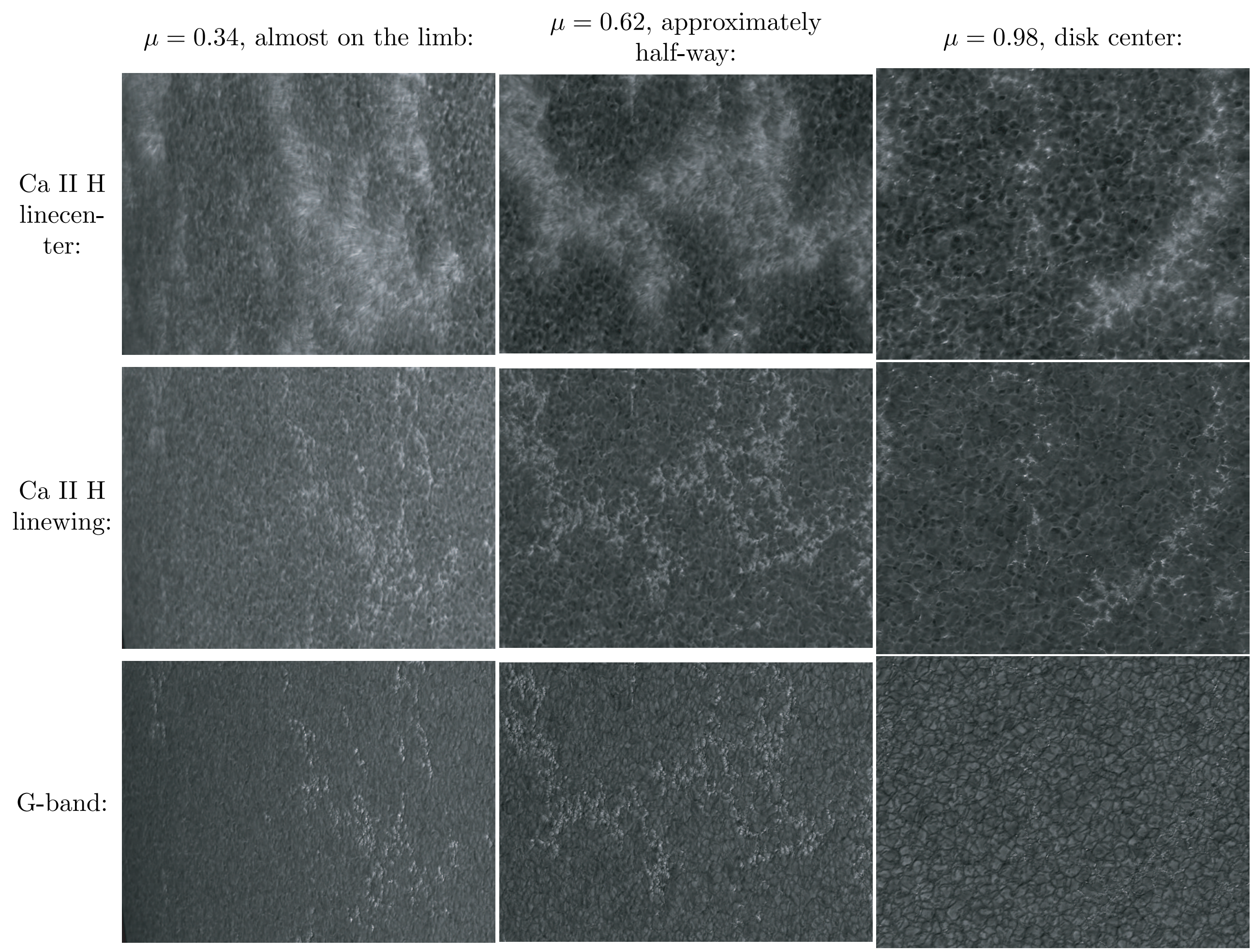

Figure 1: Nine images taken on the solar disk at three different μ position. The left columnn is at $\mu = 0.34$, which contains the solar limb. The middle column is approximately halfway the disk at $\mu = .62$. The last column is taken at disk center. The upper row is taken with Ca II H filter at line center, while the second row is centered at 1.35 Å offset in the Ca II H filter. The last row is taken in G-band.

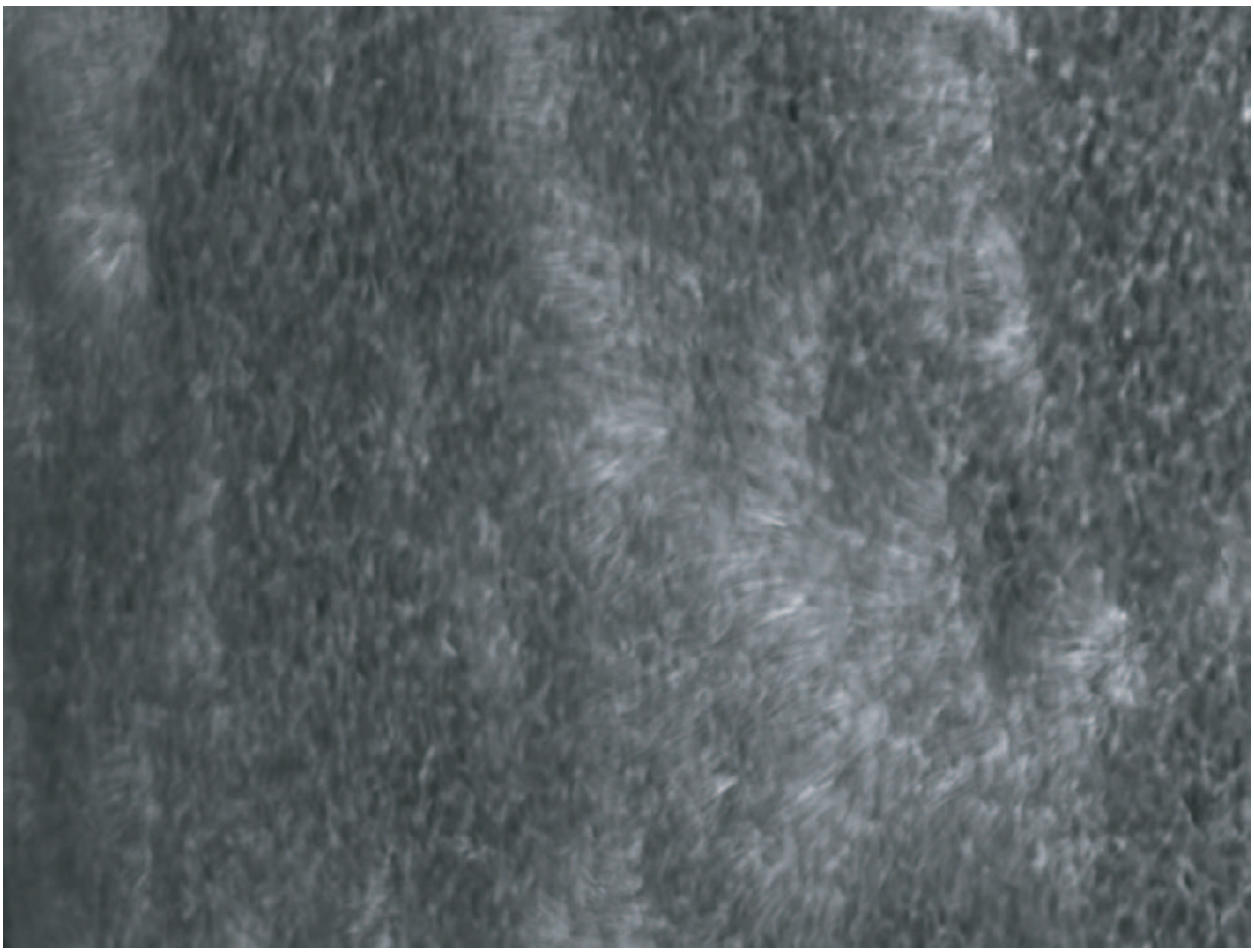

Figure 2: A magnification of the upper left panel of Figure 1. Here the mentioned straws can be easily recognized.

just as in the other observed wavelength bands.

The straws are likely to be optically thin. When a background image (Ca II H linewing images, taken 25 seconds after the linecenter image) is subtracted (after proper normalization, i.e. when the reversed granulation pattern is just removed) you see only straws on the image, indicating that the background was visible through the straws. This is illustrated in Figure 3.

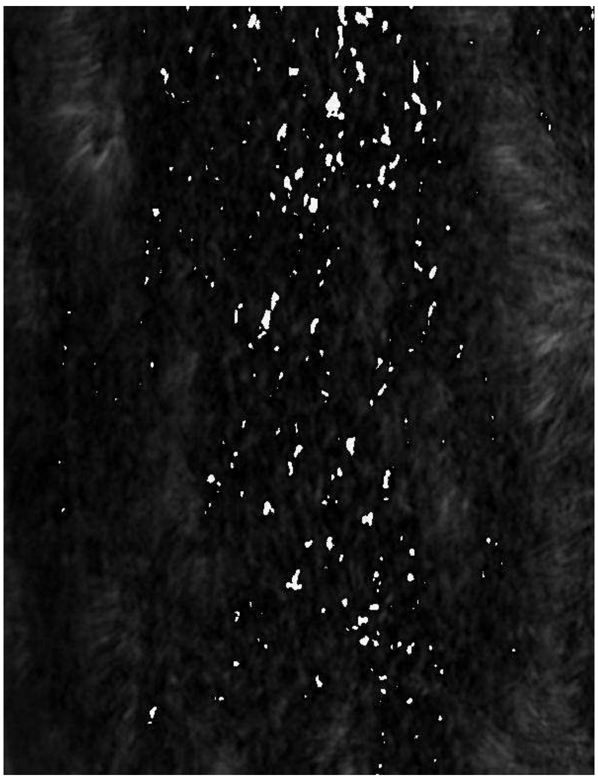

Figure 3: A background subtracted image of Ca II H line center. As background a linewing image with proper normalization is used. From this image it becomes clear that the straws must be optically thin.

Some of the straws originating from very crowded bright point fields seem to be very elongated, sometimes over lengthscales of 10.000 kilometers. This probably is an optical illusion: we just see several straws behind each other, projected on the disk.

New observations with the DOT in Hα become available. Not yet on the solar limb, but already cospatial and cotemporal with Ca II H (and other wavelength bands). Careful inspection of Ca II H disk center observations do also show very little signs of the straws, indicating that they are indeed not perfectly vertical, but very close to that. Blinking Hα images with Ca II H seems to show that at the place of these little straws on disk center, also elongated structures in Hα linewing originate. In Hα linecenter you see nothing, because there are too many structures above it, obscuring the deeper layers.

2.2 Mt Wilson and NSO Hα observations

Figure 4: Hα linewing image taken at NSO, Sacramento Peak. The arrows point at what people call dark mottles. The dark straws as they appear in Hα are very clear. Image taken from Foukal (1990).

In Hα observations in the line wing (from approximately 0.2Å to at least 0.7Å in both wings) we can see structures which look more or less the same, besides some important differences. Observations are taken from Title (1966) at the Mt Wilson Solar Observatory and Foukal (1990) at National Solar Observatory, Sacramento Peak, see Figure 4. High resolutions images show structures like we see in Ca II H linecenter, but here they are dark (in absorption against their background), a little bit shorter and more bent over than in Ca II H.

Because all straws are pointing limbward we can say they are mostly vertical. Deviations from that are larger in Hα (to approximately 30 degrees, determined by eye by guessing how far they bend over towards the sides) than in Ca II H (to approximately 15 degrees, determined in the same manner). These deviations can be explained as an effect of the polarity of the fluxtubes. They all have the same polarity, and therefore they exert a repulsive force on each other.

3 Open questions

We want a model that describes the solar atmosphere at the height around the formation of Ca II H linecenter and Hα linewing (a height of approximately 200 km, see Foukal (1990)). The structures we see on the high resolution images are clearly magnetic in nature. Why do we only see the near vertical field lines? The magnetic field has no reason to be mostly vertical on the formation height of the lines discussed, see Steiner (1994) and Foukal (1990). Also we see the structures in both filters as mostly linear features while fluxtubes are thought to expand with height, see Ballegooijen et al. (1998).

We want to know what the relation is between the observed structures in Hα and Ca II H linecenter. Are these really the same structures? If they are the same structures we also want to explain the observed differences between them. Besides it might be very useful to explore the relations between the straws and other magnetic features observed in the lower solar atmosphere like spicules (see Beckers (1968)), mottles (see Loughhead (1974)) and fibrils (see Marsh (1976)).

4 Models and speculations

Here I will present short reviews of the explanation of observations in the past, as well as speculations about the new observations. Several distinct models will be presented and compared. In all cases, advantages and disadvantages will be explained.

4.1 Older Hα observations

With older observations I mean the observations in Hα, made at the NSO and at Mt Wilson. Because the features were dark in both wings of Hα, it is unlikely that it should be explained by means of a Dopplershift. This would mean that matter in the straws is simultaneously moving towards us and from us. This would only be an explanation if the observed red- and blueshifts can be caused by the gyrational motion of the gas around the magnetic field lines (then it would be moving towards us at one side of the field line and from us at the other side). Matter is after all supposed to move along field lines, not perpendicular to it. Therefore in vertical fluxtubes on the limb of the Sun there is supposed to be almost no movement in our line of sight.

Another reason for the objects to be dark is optically thick scattering. If there is enough matter in the Hα straws you can see them in absorption against their background. It is obvious that the sourcefunction should in that case be lower than the source function of the background. If it is optically thick this means that the content of these straws must be cold (at least colder than the emitting background). This is the observation favoured by the original authors, see Foukal (1990) and Title (1966).

In Hα also mottles are observed. Discussions about dark and bright mottles can be found in Heinzel & Schmieder (1994). In mottles usually upflows of matter are observed (Tziotziou, personal correspondence and Tziotziou et al. (2003)). In magnetic fluxtubes the matter is expected to move upwards with a higher temperature. Gas outside the tube is expected to be a bit cooler and flowing down, see Briand & Solanki (1998).

4.2 Ca II H linecenter

As the calcium straws concern the observations with the DOT, these were the first ones encountered and discussed. The question arised why these features look the way they look. They are bright and do not expand upward. Furthermore they are probably optically thin.

To be bright against their background they either have a higher sourcefunction than the background and their surroundings or it is just an extra contribution to the intensity emerging from the background.

As modelling an observation in Ca II H linecenter asks for highly NLTE simulations, no reliable simulations are done yet. The question of the fluxtubes being evacuated (as is the case in lower photosphere) in the higher chromosphere is not yet brought to a final answer. Structures like these are expected to be in pressure equilibrium with their surroundings. This does not necessarily mean that the tube is evacuated above the lower photosphere. Inside a fluxtube the enhanced magnetic field exerts a certain magnetic pressure and the gas has a certain gas pressure. Outside the tube there only is gas pressure, so the gas pressure in the tube is supposed to be smaller than outside the tube. Because gas pressure depends on temperature and gas density it is possible to get pressure equilibrium in three different ways: make both the temperature and the density lower than in the surroundings, make the temperature considerably lower, in order to allow for the density to be slightly *higher* than in the surroundings or vice versa.

There are several ways in which we can satisfy one or more of the constraints of these fluxtube models. A low temperature at large height is gained when the material comes from below and crosses the temperature minimum. A higher temperature can be obtained if downflowing gas is assumed, from higher up in the chromosphere, or even from the corona. There are other ways of heating the material inside a fluxtube, by means of radiative transfer perpendicular to the line of sight, or by waves moving up from the footpoint. The density and optical thickness of course are related. With a high gas density high opacities can be created, but also relatively small opacities are still possible. Also with a low gas density, both a high and a low opacity are still possible.

4.3 Relations between Hα and Ca II H observations

To me it is very clear that both the Hα and Ca II H straws are different appearances of both the same physical objects. Likely they are even the same structures as spicules and mottles (although these last may correspond with irregularly high mass fluxes through the fluxtube). If they indeed are the same, which I will assume from now on, then their different aspects should of course not contradict each other.

In Figure 5 a cartoon representation of the fluxtubes is given, together with the main features that might be important for explaining the different appearances of bright points. In both Ca II H and G-band we see bright points. It is not clear whether the Ca II H bright points are caused by the hot wall effect, as are the G-band bright points. Also the bright points in Ca II H linecenter at the center of the disk can be an effect of the line of sight integration that causes the straws, but the fact that we do see the bright points in Ca II H linewing indicates that the hot wall effect may play a role too. It is obvious that the Hα straws are not caused by this effect.

If we assume that there must be upflow of material in the fluxtubes you see in Hα, then it is not possible to heat the calcium straws by means of a downflow from above, where the material is hotter. If the intensities in both wavelengths are formed at the same physical location this is very obvious. If Hα is higher up in the atmosphere then different flow directions are highly unlikely too, because we never see any sign of a transition region between those. If there would be a transition region the inflow of matter in the fluxtubes must be large and coming from an unseen source. On the other hand it is also very improbable that the fluxtubes are evacuated when looking in calcium, but have a higher density than their surroundings in Hα.

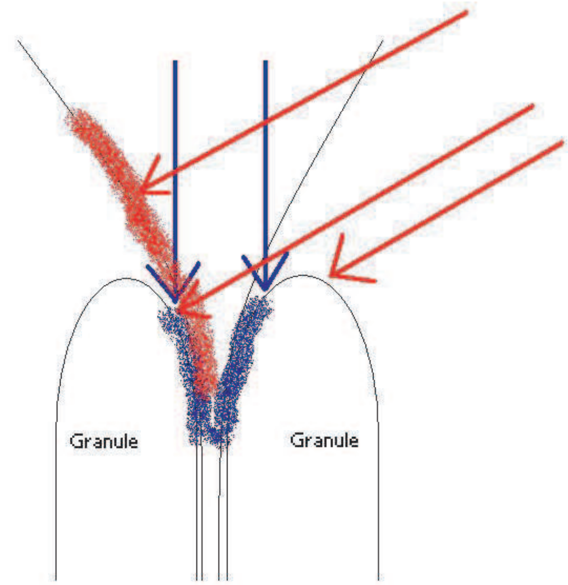

Figure 5: Cartoon model of the appearance of magnetic fluxtubes in the lower solar atmosphere. The granules are separated by an intergranular lane. The fluxtube is forced to live inside that lane. The blue arrows represent the line of sight at disk center, the red ones towards the limb. The shaded regions of both the colors indicate what is seen *in projection* from both viewing angles. The straw that is seen from the limb for Ca II H linecenter is the result of an integration along the line of sight (in the region inside the fluxtube, not outside), which we do not see in G-band because of the lack of 'hot wall'. From disk center the emission in Ca II H is also an integration along the line of sight (i.e. in the fluxtube), so it looks very much like a hot wall, as in G-band. One should not forget that scattering is also very important for this radiation.

In both wavelengths we see thin, non-expanding, straws. It's already mentioned that this is strange, because one expects fluxtubes to expand with height, if they are sticking out of the surface more or less vertically. The fact that we do not see that is a problem. An explanation could be the fact that we only see the central line, because the integration of intensity along the line of sight is moste effective there (the line of sight has the longest path through the tube).

4.4 Twisted magnetic field lines

Another possibillity is that fluxtubes in general are twisted, as illustrated in Figure 6. This would be contradicting the cartoon in Figure 5 and the general view of fluxtubes (like in Steiner (1994)). In modeling the magnetic field one usually assumes fluxtubes to be there and to consist of vertical field lines next to each other. If on the contrary they would be assumed to be twisted around one another, simulations will most likely show non-expanding fluxtubes. A reason for this is the magnetic tension: field lines cannot easily be stretched. In order to let a fluxtube consisting of twisted field lines expand, one needs to either stretch the field lines or make them longer by pulling them down from above. In the latter case, a driving force is needed to expand the tube, which is absent. Therefore twisted field lines will explain thin fluxtubes.

The difference in spread of inclination (Hα being more bend over than Ca II H) can possibly be explained by a difference in height in solar atmosphere. If the tubes exert repulsive forces on each other, you really expect the straws to bend away from each other from their footpoints, which are close together. Therefore a higher spread in inclination can be expected higher up in the atmosphere, concluding that the radiation of the internetwork in Hα linewing might possibly be created at greater height.

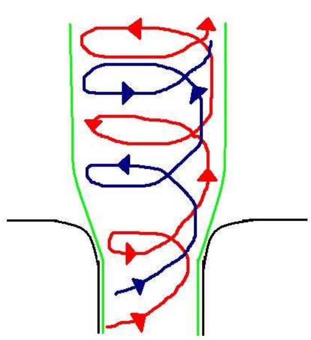

Figure 6: Cartoon model of fluxtubes consisting of twisted filed lines. The areas in balck represent two granules. In the intergranular lane in between, two field lines are drawn (blue and red). The direction of the magnetic field is indicated by the arrows. As long as the fluxtube is confined in the intergranular lane, its size is determined by the size of the intergranular lane. As soon as ite reaches the photosphere the tube (the green line represents its envelope) can expand. This expansion is limited by the magnetic tension. Therefore, the magnetic fields in this case will not expand as far as in the case indicated in Figure 5.

5 Summary of past observations

In this section I will present a summary of the situation I personally prefer now. Of course this is not ultimate truth, but to me it seems to be the most reliable picture, which explains all observed features relatively well. For every element in the summary I will give a motivition of why I think it works that way. In the next section I will give suggestions for further research to the magnetic straws in order to eventually find out how the magnetic field, the gas and the radiation fields behave in the solar atmosphere.

In the intergranular lanes the magnetic fluxtubes stick out of the solar surface. These footpoints are visible as bright points because of the 'hot wall' effect in G-band and Ca II H (and also, but less sharp in continuum bands) because there the pressure equilibrium demands a decrease in density with respect to the outside of the tube (presence of a magnetic field and the temperature inside and outside are equal). Continuing upwards the magnetic field lines inside the fluxtube are possibly twisted (then they do not expand, the tubes really are thin and that is why we see thin straws) or not twisted (in that case we only see the central part of the tube, because we here have the most effective line of sight integration). The matter moves up in these fluxtubes, either in straight lines (with gyration), or along the twisted field lines (gyration around a spiral) with effective speeds as measured in mottles. During this upward motion there is little or no interaction with the matter outside the tube and therefore the temperature is just marginally rising upward in the fluxtube (by means of radiative heating from the outside). In order to keep in pressure equilibrium with the surroundings the density in the tube needs to increase, which is obtained by slowing down the upward motion, for both twisted lines in the tubes or not (although the case of twisted field lines has a more or less constant magnetic field sterngth (and hence also pressure), whereas the expanding tube has a decreasing magnetic field strength).

Hα radiation is created a bit higher up, where the density in the tubes is just high enough to make the straws dark because of optically thick scattering. Ca II H linecenter is bright because of a little extra contribution to the radiation, so it clearly should be optically thin. The fact that we see only the near vertical ones is then explained by the fact that in the tubes that do not rise that far up the density does not change that much, so we will not see them.

6 Suggestions for future observations

It will be very useful to see the placement of the Hα straws compared to those in Ca II H. Cospatial and cotemporal DOT images on the limb will therefore be useful. Problems to be overcome will mostly consist of alignment problems. In the first place there are not very much structures that look the same in Hα and Ca II H. Most hopeful will probably be the reverse granulation pattern. Another problem arises from the fact that the formation height of the radiation coming from the granulation is not properly known. Therefore a difference in height will result in a misplacement in the direction of the limb of the Sun, because of projection effects. Valuable information about the height levels of the straws will thereby be lost, and constraints on the relative heights of both features will be weak.

If the images are properly aligned and compared, things about the relative placement of the two kinds of straws will become clear. This will show how strong the constraints on the density differences are. If the difference in height is large, lots of things are still possible, whereas a small difference in height (or even a (partial) overlap) has major consequences for the models.

Time behavior also is something that is worth spending time on. Trying to see gas movements up and down by feature tracking is something that gives very clear evidence of the gas motion being up- or downwards. One might also try to detect the 'waving' motion of the straws in order to say somthing about waves going up into the chromosphere and corona, eventually heating these regions.

Typical Hα features in the solar atmosphere (like mottles, spicules and fibrils) should be compared to movies in Ca II H linecenter to see if any of these object have counterparts in Ca II H. The more relations between events in Hα and Ca II H one finds, the more constraints can be put on relative placements of structures and to the physics going on in the solar atmosphere.

6.1 Observational aspects of twisted field lines

In order to test whether or not the twisted field line theory, as presented in this report, makes any sense, one will need good spatial resolution, in the order of magnitude of the width of intergranular lanes, for example the use of the DOT. Thereby quite narrow bandwidth tunable spectral filters, like the DOTs Ca II H filter, in which the tubes can be imaged in the blue as well as the red wing of the line. If gas is moving up along these twisted lines, it is forced to follow the field lines. It therefore will not move straight up, but it will move its way up along a spiral (like observed on larger scales by TRACE in X-rays).

On the fine scales of fluxtubes this might also be visible. If you look at a fluxtube from aside, and the gas spirals up, then you will see gas moving towards you on one edge of the tube, and gas moving away from you at the other side. A whole 'field' of straws, will all have the same polarity, and it is to be expected that all these fluxtubes are twisted in the same direction. Therefore, the image of the field in the red and blue wing will be slightly shifted (in the order of half a fluxtube-width, probably a little bit smaller than the width of intergranular lanes). Proper alignment of the images (based on the (reversed) granulation pattern) will therefore give you the opportunity to see this shift by blinking the red and blue wing images.

7 Conclusive remarks

It is also obvious that not only more observations are needed, but also simulations. NLTE simulations are needed to understand the physics that makes the straws bright in Ca II H linecenter. Also the magnetic field need to be modelled to check the possibillity of the twisted field lines as a reason for the straws to be that thin. Of course the explanation given to other features concerning the magnetic field should also be tested on compatibility with twisted field lines.

Only when full 3D NLTE radiative transfer and magnetohydrodynamic simulations are possible and reliable we will be able to fully understand the magnetic and radiative processes going on in the solar atmosphere.

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