SELF-CONSISTENT MODELS FOR SMALL PHOTOSPHERIC FLUX TUBES

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We give a short summary of some results of a numerical study of magnetic field concentrations in the solar photosphere and upper convection zone. We have developed a 2D time dependent code for the full MHD equations (momentum equation, equation of continuity, induction equation for infinite conductivity and energy equation) in slab geometry for a compressible medium. A Finite-Element-technique is used. Convective energy transport is described by the mixing-length formalism while the diffusion approximation is employed for radiation. We parametrize the inhibition of convective heat flow by the magnetic field and calculate the material functions (opacity, adiabatic temperature gradient, specific heat) self-consistently. Here we present a nearly static flux tube model with a magnetic flux of $\sim 10^{18}$ mx, a depth of 1000 km and a photospheric diameter of $\sim$ 300 km as the result of a dynamical calculation. The influx of heat within the flux tube at the bottom of the layer is reduced to 0.2 of the normal value. The mass distribution is a linear function of the flux function A: $dm(A)/dA$ = const. Fig. 1 shows the model: Isodensities (a), fieldlines (b), isotherms (c) and lines of constant continuum optical depth (d) are given. The "Wilson depression" (height difference between $\tau = 1$ within and outside the tube) is $\sim$ 150 km and the maximum horizontal temperature deficit is $\sim$ 3000 K. Field strengths as function of x for three different depths and as function of depth along the symmetry axis are shown in (e) and (f), respectively. Note the sharp edge of the tube.

We have used the 2D radiative transfer code of Mihalas, Auer and Mihalas (1978, Astrophys. J. 220, 1001) for LTE diagnostics of the radiation field. The emergent intensity is found by integrating along rays through the multicomponent source function. Fig. 2 shows the centre-to-limb-variation (CLV) of the continuum intensity emerging at different horizontal positions while Fig. 3 gives the x-dependence of the intensity for different aspect angles (see figure captions for more information). Fig. 4 displays line profiles for the magnetically unchanged ($g < 0.1$) line Ti I λ5222.7 for $\mu = 1$. and different horizontal positions. The thick curve shows the horizontally averaged

J. O. Stenflo (ed.), Solar and Magnetic Fields: Origins and Coronal Effects, 67–71.

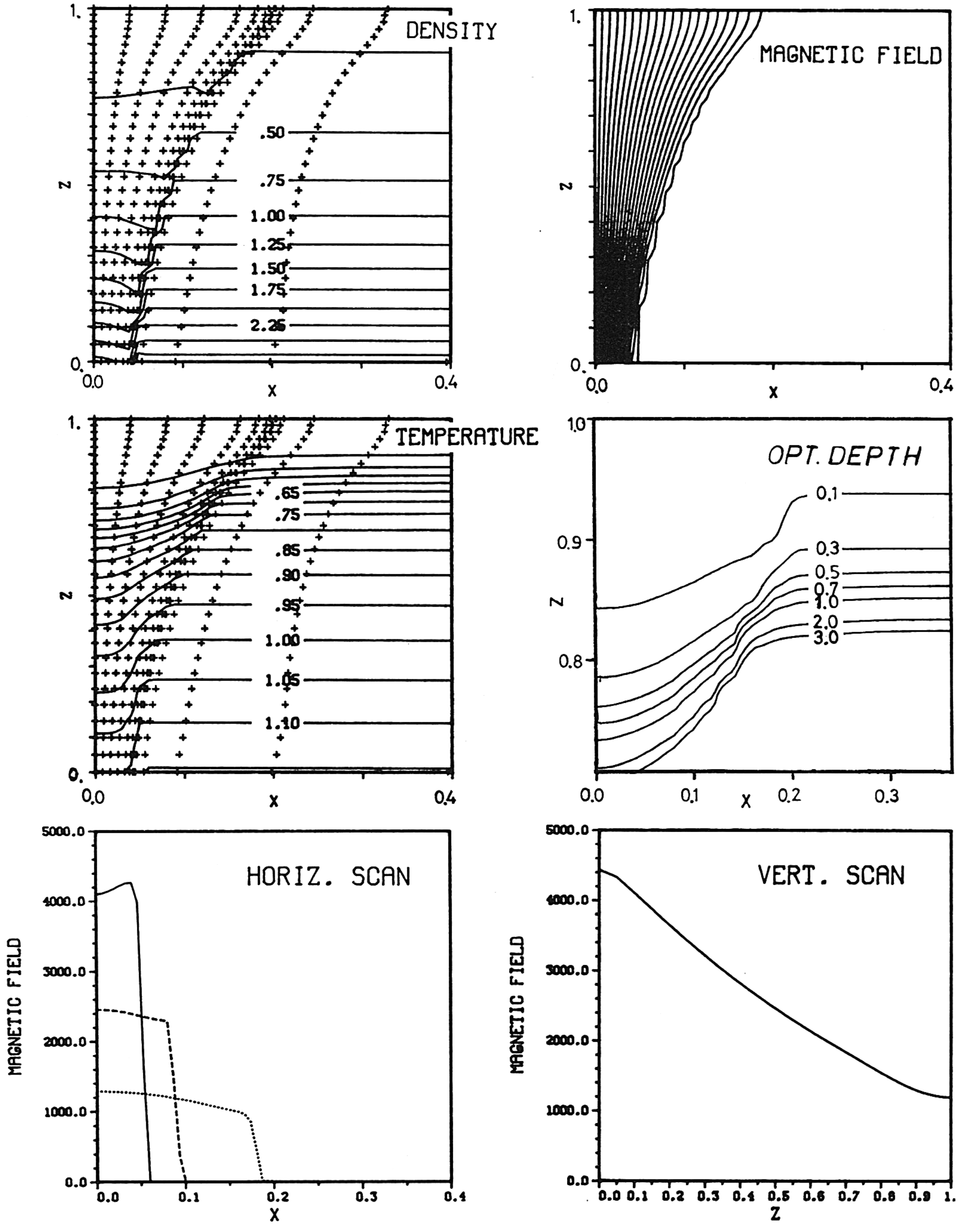

Fig. 1: Isodensities (a), fieldlines (b), isotherms (c) and lines of constant continuum optical depth (d) for the flux tube model. The horizontal scale has been expanded in (a) - (c). The length scale is 1000 km. (e) and (f) give the field strength as a function of x for different depths and as a function of z along the symmetry axis (x = 0).

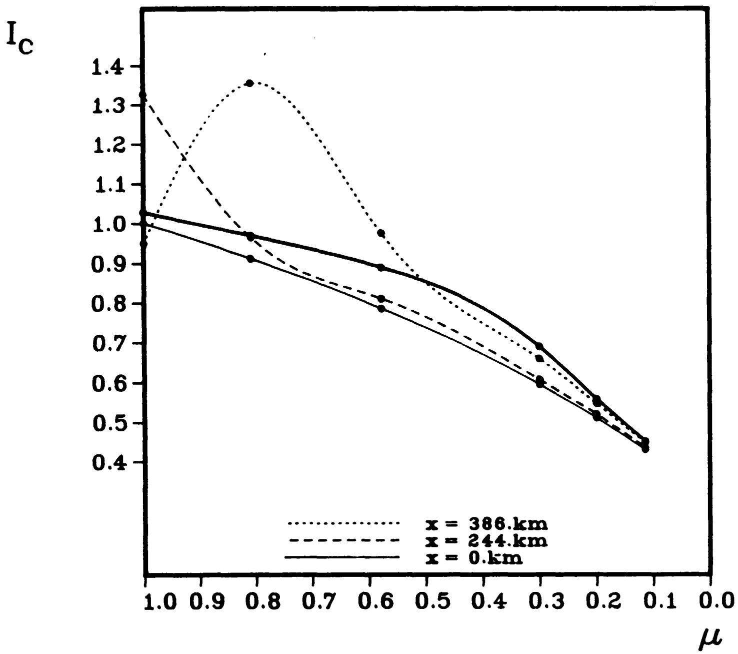

Fig. 2: CLV of the continuum intensity emerging at different horizontal positions. x = 0 km: undisturbed photosphere; x = 244 km: "hot ring" near the boundary of the tube; x = 386 km: centre of the tube. The thick line gives the CLV of the horizontally averaged intensity, i.e. the observed intensity at finite resolution. The tube appears slightly brighter ($\sim$ 3 %) than the undisturbed photosphere at the centre of the disc (μ = 1) and the intensity contrast increases towards the limb with a maximum of 17 % for $\mu \sim 0.4$ and decreases afterward.

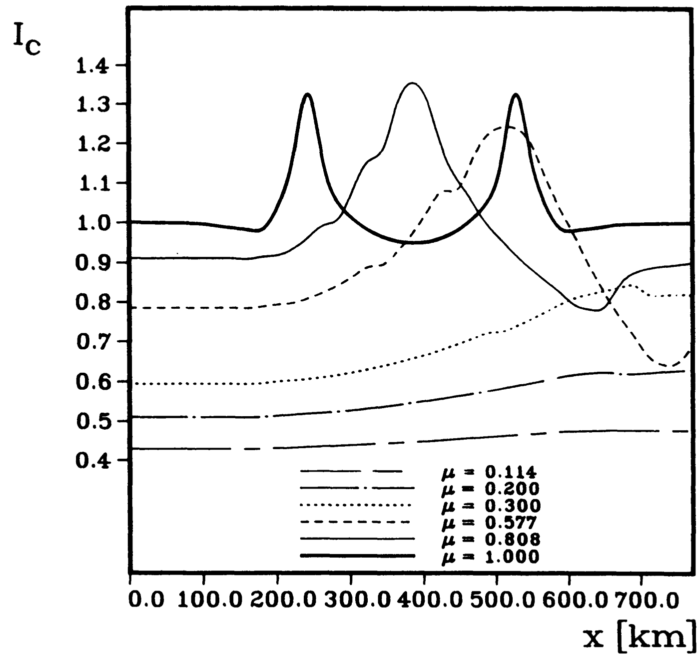

Fig. 3: x-dependence of the intensity for different aspect angles. The curve for μ = 1 shows that the intensity enhancement at disc center comes from the "bending walls" which lead to a bright ring at the periphery of the tube. When viewed under an angle $\mu < 1$, only the opposite wall can be seen and we find only a single intensity maximum. Furthermore, the maximum decreases because the ray has to penetrate the edge of the structure and reaches $\tau = 1$ at a smaller temperature for decreasing μ.

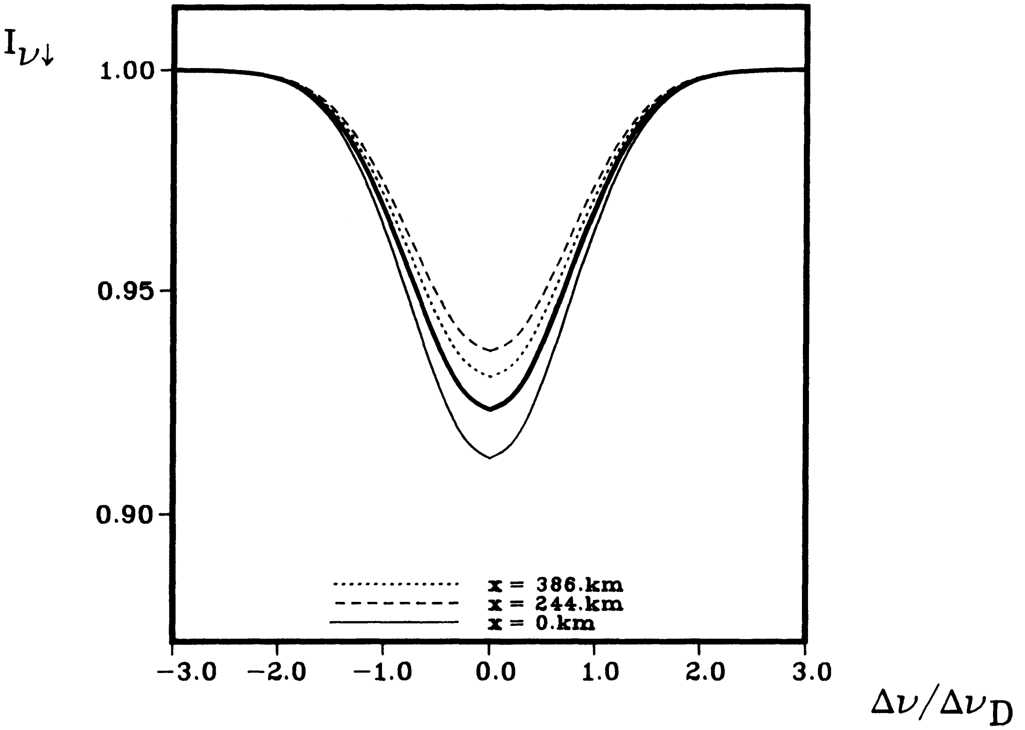

Fig. 4: Line profiles for Ti I λ5222.7 for $\mu = 1$ and different x positions. The thick line is the horizontally averaged profile

profile. By comparison with the profile for the undisturbed photosphere (x = 0. km) we notice that the line is weakened. This "line gap" is enhanced by the slightly larger continuum for the averaged case, which leads to a total intensity enhancement of 4 % in the line core. This is a rather low value and points to the necessity of non-thermal heating for the explanation of the observed line gaps.

ACKNOWLEDGEMENTS

We are grateful to Drs. F. Kneer and E. Wiehr for helpful discussions and to Dr. H. Schleicher for putting some of his routines at our disposal. This work has been supported by the Deutsche Forschungsgemeinschaft (DFG).

https://doi.org/10.1017/S0074180900029739 Published online by Cambridge University Press

DISCUSSION

GARCIA DE LA ROSA: (1) Is there any observation of the bright ring that you mentioned? (2) Where do you think the size limit between large (dark) and thin (bright) fluxtubes is? Dr. Spruit suggested $\sim$ 0.8 arcsec, but we have observations at -1 Å from the Hα line center on the emergence of spot groups, which show bright features eventually converging to form dark pores, but these have diameters larger than 2 arcsec.

SCHÜSSLER: (1) Dr. Tarbell will comment on this. (2) Our results are compatible with the value given by Dr. Spruit.

TARBELL: My group at Lockheed has filtergrams in temperature-sensitive lines and magnetograms with a resolution of 0.5 arcsec or better. In pores which are clearly resolved (1–3 arcsec diameters), the entire structure is dark in continuum wavelengths, but at the line center we see a dark core with a bright ring around it. In smaller but still resolved fluxtubes ("knots" with 0.5–1.5 arcsec diameters), the contrast is neutral in the continuum and shows a neutral core with a bright ring at line center. In the smallest magnetic elements which are probably not fully resolved, we often see an offset between the bright dot at line center and the magnetic point, as your models indicate for an inclined line of sight. These offsets are sometimes seen at disk center but are more common at offset disk positions. Thus there is good qualitative agreement with your models, and we look forward to more detailed comparisons when your results have been published.

SPRUIT: Your solutions for a small tube have an almost constant field strength across the tube. To what extent is this a result of the lower boundary condition assumed?

SCHÜSSLER: It is a result of the initial mass distribution as a function of the vector potential, which does not change during the calculation due to infinite conductivity. We are currently performing calculations for other mass distributions.

SPRUIT: So it is an effect of the initial conditions?

SCHÜSSLER: Yes.

KOUTCHMY: You showed several nice pictures giving the detailed distribution of the magnetic lines of force and the distribution of the downward velocity field over the whole fluxtube. It seems to me that there are motions *across* the field lines. Is that true?

SCHÜSSLER: No. We have infinite conductivity and no flow across field lines. These are carried bodily with the fluid.

ROBERTS: Have you considered the timescale for the convective collapse process and how it compares with available linear thin tube results?

SCHÜSSLER: We have not yet considered the convective collapse realistically, because we have been mainly interested in static models which evolve. Preliminary dynamical calculations we have done show that the surface-layer structure of the tube (depths $\lesssim$ 300 km) settles to a steady state within a few sound-travel times, i.e., a few minutes.