SMALL-SCALE PHYSICS OF CONVECTION AND MAGNETIC FIELDS

S.K. SOLANKI

Institute of Astronomy, ETH-Zentrum, CH-8092 Zurich, Switzerland

ABSTRACT

An overview is given of our current knowledge of the properties and the physics of small-scale magnetic features, magnetoconvection and convection. This review concentrates on the theoretical aspects. Some examples are given of features or processes which require very high spatial resolution to be observed.

Keywords: Solar granular convection — Solar magnetoconvection — Solar magnetic fields.

1. INTRODUCTION

The present review covers a very broad range of topics. It is therefore unavoidable that each individual topic is touched on very briefly and that a strong selection of topics has had to be made. Following the title I concentrate on the small-scale end of the solar spatial scale and on the physical aspects (i.e. on the theoretical side of things). Fortunately, the topics covered here have been extensively reviewed in the last few years. The following is a sample of recent reviews in which many more details are to be found. For reviews on solar granular convection see Muller (1989), Stein et al. (1989), Title et al. (1990), Spruit et al. (1990) and Cattaneo (1992). For more details on magnetoconvection see Hurlburt & Weiss (1987), Hughes & Proctor (1988), Nordlund & Stein (1989, 1990) and Weiss (1989). Small-scale magnetic fields have been reviewed by Schüssler (1986, 1987, 1990), Solanki (1987a,b, 1990, 1992), Stenflo (1986, 1989), Spruit et al. (1982) and Steiner (1992).

2. CONVECTION

Many 2-D and 3-D models of convection under roughly solar conditions exist. Most such models lead to a better understanding of the physics, but cannot be compared with observations since they lack one or the other important ingredient. Examples of models which are of particular relevance to the observed sun are those of Stein & Nordlund (1989) and Stein et al. (1989), and those of Steffen at al. (1989) and Steffen & Freytag (1991). The former models are three dimensional and come closest to fulfilling all the major requirements for the modelling of granulation. One of their main shortcomings is the limited amount of small-scale structures in the models. For example, Lites et al. (1989) find more fine-scale detail in high-resolution observations than in the 3-D models. The primary reason for the missing power at small scales is the relatively high numerical viscosity. Steffen & Freytag (1991) use another numerical scheme which is free of numerical viscosity. Although only 3-D models, like those of Nordlund & Stein, can give any reliable information at all on the topology of the flow, the models of Steffen and co-workers are better at resolving small-scale phenomena, such as shocks.

In the following I briefly describe two selected recent results of modelling solar convection at the granular scale.

2.1. Topology of the granular flow

The topology of the flow changes completely with depth. At the solar surface the downflows form a closed network that is dark in the continuum (Fig. 1), while just 1-2 Mm below this level the downflows are concentrated into isolated filaments. Thus granules are *not* vertically closed cells. Stein & Nordlund (1989) propose that the downflowing filaments keep merging together at increasing depth, thus producing ever larger horizontal scales which correspond to a steady increase of the horizontal 'cell' size with depth. Their idea is sketched in Fig. 2, which shows the tree-like structure produced by the filaments. The cutaways are meant to suggest that the process keeps repeating itself at different scales. Cattaneo et al. (1989) note from their 3-D models of compressible convection that the flow possesses topological symmetry with depth (downflows form a closed network at the surface, while upflows do the same at depth), but not geometrical symmetry (upflows are always gentle, downflows are always strong).

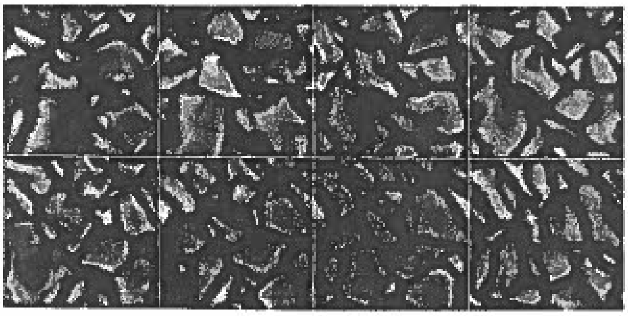


Fig. 1 Total radiation intensity at the surface (corresponding roughly to the continuum intensity) of a 3-D simulation of normal granulation. Each frame corresponds to a time 4 minutes later than the previous one. The horizontal size of the computational box is 6 × 6 Mm. From Nordlund & Stein (1989).

2.2. Supersonic convection

For a sufficiently large Rayleigh number (which is proportional to the superadiabatic gradient) the convective flow can become supersonic in parts of the computational domain (Cattaneo et al. 1990,

---

Proceedings of an ESA Workshop on Solar Physics and Astrophysics at Interferometric Resolution, Paris 17-19 February 1992.

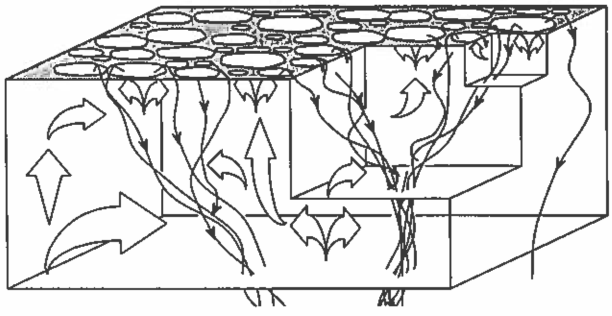


Fig. 2 Flowlines schematically showing the merging of downdrafts on successively larger scales. The box cut-outs illustrate how the same process can occur at different scales. From Spruit et al. (1990).

Malagoli et al. 1990). It is mainly the horizontal velocities which become supersonic. In the simulations of Cattaneo et al. (1990) the transition from the subsonic to the supersonic regime is smooth and happens between the upflowing centre and the downflowing edges of a convective cell. The deceleration near the downflowing lanes is sudden, leading to the formation of shocks. An example of supersonic convection, including the presence of multiple shocks is shown in Fig. 3. In particular, the Mach number plot, if considered in conjunction with the velocity field, is very instructive. Peak Mach numbers in this particular simulation lie above 2. Non-adiabatic effects (e.g. radiative cooling) play an important role in supersonic convection. They lower the temperature, and thus the sound speed, in the topmost convective layers. This enables the horizontal flows in the upper layers, accelerated by horizontal pressure gradients, to easily become supersonic. Steffen & Freytag (1991) find shocks forming also in models which simulate the solar atmosphere much more closely than the model of Cattaneo et al. (1990). The shocks produce very strong gradients, which can only be resolved with a much higher spatial resolution than achievable with current instrumentation or observational techniques.

3. MAGNETOCONVECTION

Convection and magnetic fields interact with each other in an often complex and non-trivial manner. Easiest to treat are the extreme cases of a very strong or a very weak magnetic field. In the former case the nature of the convection is changed by the magnetic field, it is suppressed and may, for sufficiently strong fields, be completely quenched, while the magnetic field remains basically unaffected. In the latter case the magnetic field follows the dictates of the convection more or less passively. This invariably leads to a segregation of the field and the convection (see below). For fields of intermediate strength some form of convection can usually take place, but it is generally modified, for example into oscillatory convection (as compared to 'normal' overturning convection, e.g. Hurlburt & Weiss 1987, Weiss 1989). Conversely, the convection also affects the structure of the magnetic field. In particular, the magnetic field is not allowed to reach a static equilibrium.

A not too strong, initially homogeneous field is concentrated into a small volume by the convection. At those positions where the field is strong the convection becomes weak and vice versa, so that the field is effectively expelled to the boundaries of the convective cells. The new configuration minimizes interference between convection and the magnetic field and minimizes the energy of the system (Parker 1984). This so-called flux expulsion process (Parker 1963, Weiss 1966, Galloway et al. 1977, Galloway & Weiss 1981, Hurlburt and Toomre 1988) enhances the field strength to roughly a value of $B_{\mathrm{eq}} = \sqrt{4\pi\rho}\, v$, which implies equipartition between magnetic and kinetic energy. In the real world of granules and supergranules flux is expelled to the boundaries of supergranules (Meyer et al. 1979, Schmidt et al. 1985) and of granules (Nordlund 1983, Schmidt et al. 1985, Nordlund and Stein 1989), if the spatially averaged magnetic flux density is not too large. As the amount of flux in the computational domain increases the field starts to react onto the convection and changes its properties. This change in convective properties has been observed. The simulations of Nordlund and Stein (1989, 1990) reproduce many of the observations (see also Fig. 4): These include the concentration of flux into the intergranular lanes (observed by Title et al. 1987),

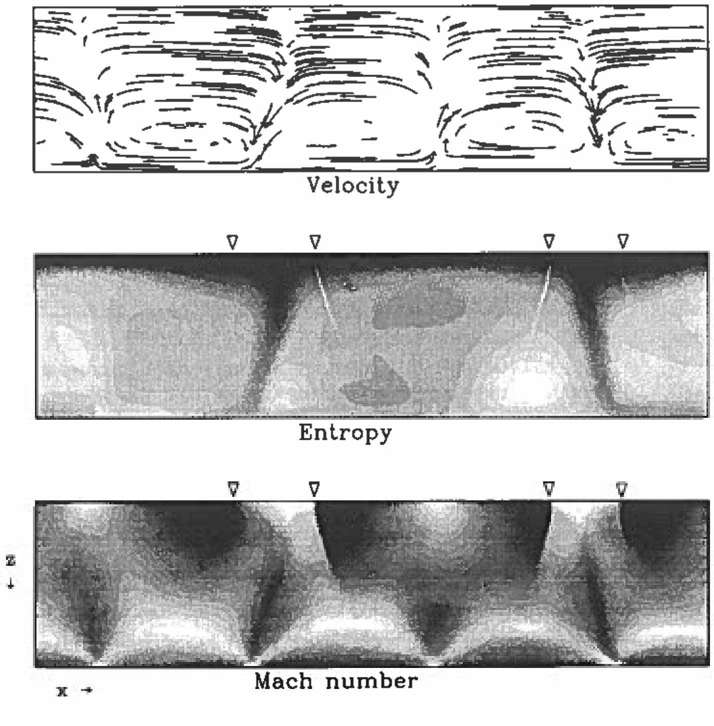


Fig. 3 The velocity field, entropy distribution and Mach number field at one instant in time throughout the two-dimensional computational domain for supersonic convection. The triangles indicate the positions of the shocks along the upper boundary. In the entropy distribution, low entropy material is displayed as dark grey. In the Mach number field the grey scale is reversed, so that darker regions correspond to a higher Mach number. From Cattaneo et al. (1990).

reduction of the continuum contrast between up- and downflowing gas (deduced by Brandt & Solanki 1989), so that the familiar granular pattern becomes almost unrecognizable (see Spruit et al. 1990, Title 1992) and finally the increase of granular lifetimes (observed by Title et al. 1989). The enhanced lifetimes may have to do with the network formed by the semirigid field lines, which do not allow exploding granules, a major source of granule death, to develop.

Let me briefly mention a final, but important twist to the interaction between convection and the magnetic field, the convective collapse process. The magnetic field concentrated by flux expulsion is generally not completely convectively stable. If the convection in such a magnetic patch starts as a downflow (the probability for this is enhanced by the fact that the magnetic patches are situated in the granular downflow lanes), it can become a runaway, leading to a further compression of the field, i.e. to an enhancement of the field strength (e.g., Parker 1978, Webb & Roberts 1978, Spruit 1979, Hasan 1984, 1985, cf. Schüssler 1990). The convective collapse is thought to be responsible for the measured kG field strengths (e.g. Stenflo 1973, Zayer et al. 1990, Rabin 1992, Rüedi et al. 1992), but see also Thomas (1990) who cites siphon flows as another source of field strength enhancement. Convective collapse calculations have so far been restricted to a single spatial dimension. The need for 2-D and eventually 3-D simulations is acute.

The filamentation produced by magnetoconvection in general and convective collapse in particular leads to the formation of very small-scale features, which it will require extremely high spatial resolution to resolve observationally

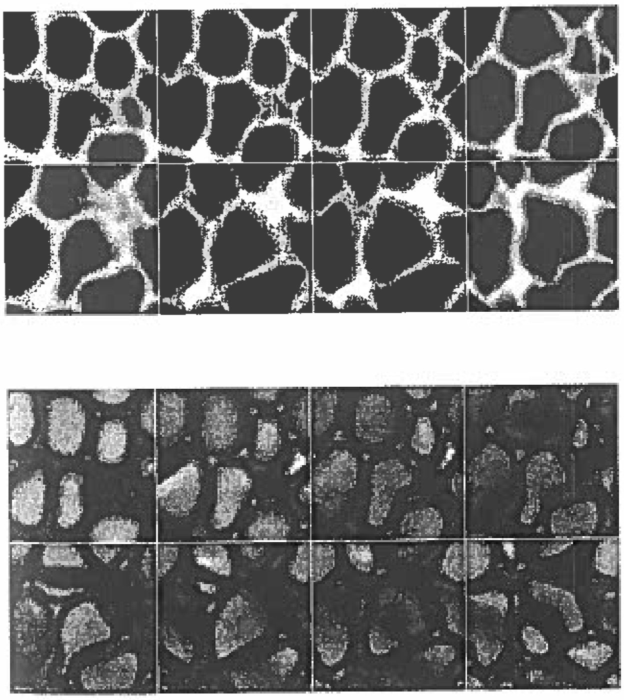


Fig. 4. Upper panel: The magnetic flux density at the solar surface as a function of time. White corresponds to a field strength above 1500 G. The time intervall between each panel is 4 solar minutes. The horizontal size is 3 Mm. Lower panel: The total radiation intensity at the surface as a function of time, for the same simulation as shown in the upper panel. Note the "filled in" intergranular lanes. From Nordlund & Stein (1989).

4. MAGNETIC FIELDS

4.1. Basic structure

The structure of the magnetic field evolves with height. In the different layers of the solar atmosphere it (the magnetic field) can be represented by three basic structures: Flux tubes, canopies and loops. In the solar interiour and the photosphere the field is best described by flux tubes (or in some cases possibly flux slabs). A flux tube is a bundle of magnetic field lines with a distinct and topologically simple surface to the non-magnetic gas. Since flux tubes are in approximate pressure balance with their surroundings they expand with height as the gas pressure decreases. For simplicity, in the following I usually refer to both flux tubes and slabs as flux tubes. In the chromosphere the flux tubes expand very rapidly, so that the field forms a magnetic canopy, i.e. an almost horizontal field overlying non-magnetic gas. Finally, in the corona, and according to some researchers in the transition region as well, the magnetic structure is dominated by loops or arcades. Loops are best understood as curved flux tubes, which emerge at one point on the solar surface and return to it at an other point. Similarly, arcades can be described as curved flux slabs. According to other researchers the transition region is structured by straight magnetic flux tubes. To my mind it is still unclear whether the fine-scale emission structures seen in the transition region and corona really outline the field, as is generally assumed. The magnetic field itself may be much more homogeneous than the emission structures (i.e. thermal and density structures) that are observed. The structure of these solar magnetic features and their interrelationship is sketched in Fig. 5.

4.2. Photospheric flux tubes

Due to the often small scale of the flux tubes (much smaller than the granules), no comprehensive 3-D models of photospheric flux tubes have yet been constructed. In particular, since even better spatial resolution, required to treat the sharp current sheets at the magnetic boundaries, must be combined with avery large number of grid points, to simultaneously treat the granules surrounding the magnetic features. Most of the many 1-D and 2-D models, although valuable guides to the physical processes taking place in small flux tubes, cannot be quantitatively compared with observations. The main exceptions are the models of the Freiburg group and of Steiner and co-workers.

Models calculated by the Freiburg group (Deinzer et al. 1984a, b, Knölker et al. 1988, Knölker & Schüssler 1988, Grossmann-Doerth et al. 1989) are the most comprehensive models of small-scale photospheric flux tubes (or rather slabs). They are based on solutions of the 2-D compressible magnetohydrodynamic equations (in slab geometry), are time dependent, include multidimensional grey radiative transfer (including rays outside the plane of symmetry) and a realistic equation state (with partial ionisation effects taken into account). Fig. 6 shows the distribution of various quantities in a cut through one of their models. The four frames show curves of equal density, field lines, isotherms and velocity arrows. The thick curve in the temperature plot is the $\tau = 1$ surface. The plots illustrate the following basic effects: A large gas density deficit in the flux tube (caused by horizontal pressure balance and the corresponding gas pressure deficit in the flux tube), the presence of a current sheet at the flux tube boundary (this is not a necessary ingredient of the models, but is supported by the observations of Zayer et al. 1989), the formation of a convection cell around the flux tube (it is one of the results of the radial inflow of radiation into the flux tube), a strong cooling of the

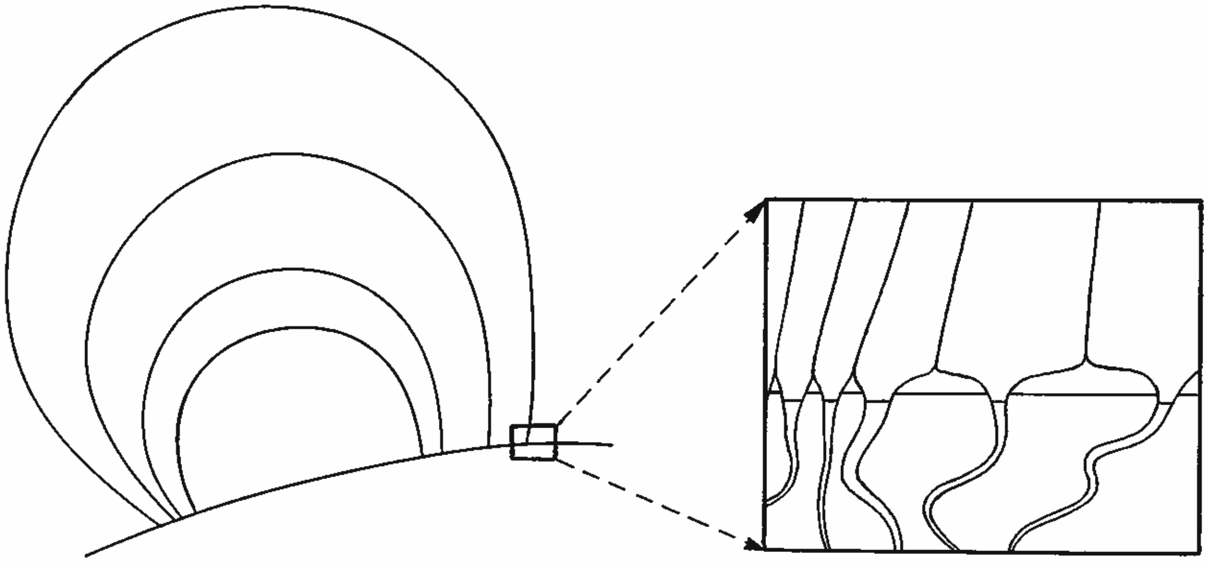


Fig. 5. A sketch of the 3 main classes of magnetic structure in the solar atmosphere. Left: Large loops extending through the transition region and well into the corona. Smaller loops also exist, but have not been plotted. The blow-up of the rectangular region at the footpoint of the larger loop illustrates that the footpoint of this loop is made up of small flux tubes (in the convection zone and the photosphere) which form low-lying canopies in the chromosphere. Note that flux tubes are also present outside the boundary of the visible loop.

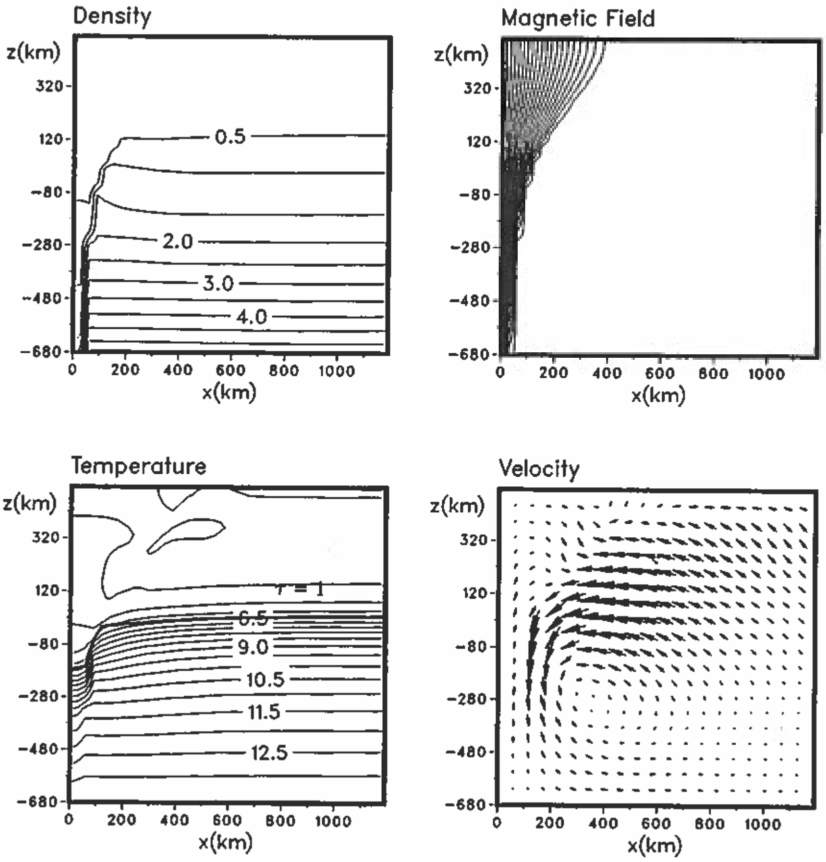


Fig. 6. Structure of a recent model of the Freiburg group (Grossmann-Doerth, U., Knölker, M., Schüssler, M., Weisshaar, E.), a magnetic flux slab with a diameter of 200 km at the $\tau = 1$ level. **a.** Lines of constant density, **b.** magnetic field lines, **c.** lines of constant temperature, **d.** velocity field: the length of the arrows indicates the velocity at that point. Maximum velocity is larger than 3 km s^{-1}. Courtesy of M. Schüssler.

deeper geometrical layers of the flux tube (due to the suppression of convective energy transport within the magnetic feature) and a heating of the upper layers (the hot and bright bottom and walls of the flux tube illuminate the upper flux tube photosphere rather strongly). Note that although the temperature at equal geometrical height is reduced in the flux tube below the $\tau_{\mathrm{quiet\ sun}} = 1$ level, the density deficit leads to a considerable lowering of the $\tau = 1$ level within the flux tube. The net result is that one sees deeper and hotter levels, making the flux tube appear bright.

The models of Steiner et al. (1986), Steiner & Pizzo (1989) and particularly Steiner & Stenflo (1990) are also two dimensional (but assume axial symmetry), include non-grey 2-D radiative transfer (in an axially symmetric geometry), are static (i.e. they do not include convection). Departures from greyness in the radiative transfer are treated with the opacity distribution functions of Kurucz (1979), i.e. they take into account roughly a million spectral lines. These models have similar thermal and magnetic properties as those of the Freiburg group. Due to the better treatment of convection the Freiburg-group models are superiour in the deeper photospheric layers, but due to the superiour treatment of radiation the models of Steiner are better in the upper photospheric layers.

4.3. Comparison of flux tube models with observations

The above model calculations produce good qualititative agreement with a number of observed phenomena. Quantitative comparisons give good agreement in some cases, but disagreement in others. Below I list some examples of qualitative comparison with observations.

1. For not too large flux tubes, the temperature as a function of the optical depth τ in the magnetic element, $T(\tau)$, is larger than the temperature at equal optical depth in the quiet sun. Qualitative agreement is found with the empirically derived models of Solanki (1986) and Keller et al. (1990), but there are still quantitative differences, which may partly be due to shortcomings in the empirical models.
2. The magnetic field strength stratification (particularly of the Steiner & Stenflo 1990 models) agrees very well with the observations. Differences near the upper boundary of the computational domain of the Freiburg models have to do with their choice of boundary conditions.
3. The downflow surrounding the model flux tubes of the Freiburg group (driven by the heat influx into the flux tubes from their surroundings) automatically leads to Stokes V profiles with a blue-red asymmetry having the sign and approximate magnitude observed by Solanki & Stenflo (1984, 1985). The theoretical models also produce an inversion of the sign of the asymmetry near the solar limb, as observed by Stenflo et al. (1987) and Pantellini et al. (1988). The fact that the flux tubes are always concentrated in downflow regions is also in good agreement with observations (Title et al. 1987, Solanki 1989).
4. Velocities within the flux tubes are oscillatory in nature. They do not lead to any significant shift of the Stokes V zero-crossing wavelength, in agreement with the observations of Stenflo & Harvey (1985), Solanki (1986), etc. These velocities do lead to a broadening of the V profiles, again in agreement with observations (Solanki 1986).
5. Tests carried out by the Freiburg group show that the centre to limb variation (CLV) of the continuum contrast of a single model flux tube or flux slab does not reproduce the observed continuum contrast. Only the superposition of many flux tubes or slabs (ordered to mimic a random distribution) leads to the correct CLV of the contrast if all magnetic features are assumed to be the same size (Spruit 1976 achieved similar agreement by combining the CLV of the continuum contrast of individual flux tubes of different sizes).

Finally, let me note that very high spatial resolution is required to observationally determine the true properties of magnetic flux tubes. An illustraive example is shown in Fig. 7: The true continuum contrast at $\mu = 1$ (disk centre) of a flux tube with a diameter of 100 km can be a factor of 7–8 larger than the measured value, even at a spatial resolution of approximately 0.3″ (Knölker, private communication).

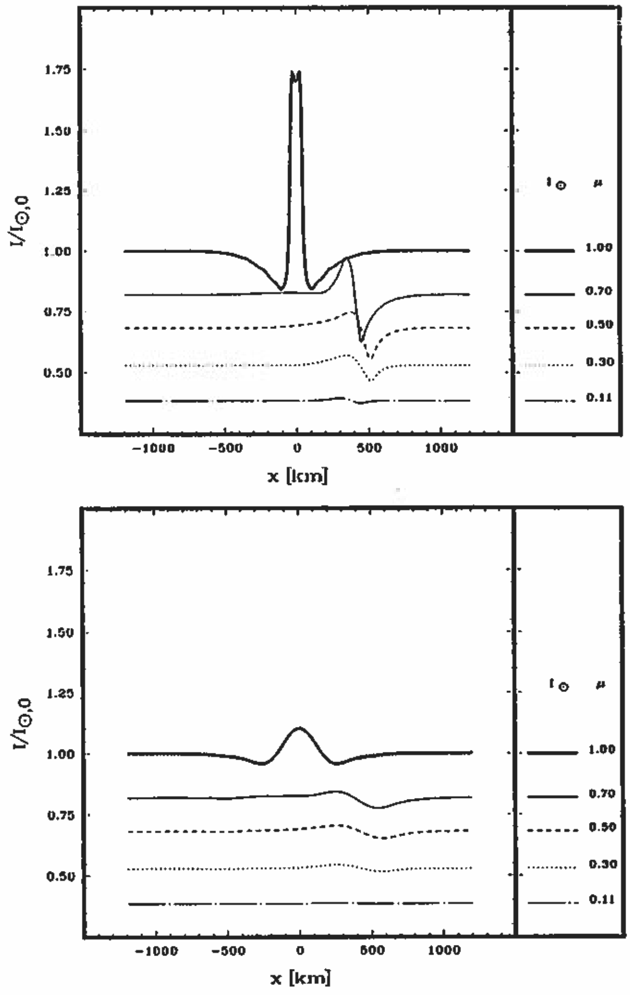


Fig. 7. The continuum intensity at different μ values of a small flux tube with a diameter of 100 km at the $\tau = 1$ level. **a.** Continuum intensity obtained directly from the model. **b.** Continuum intensity of the same model after being convolved with the modulation transfer function (MTF) of a 70 cm diameter telescope and the estimated MTF of seeing with an effective diameter of 40 cm. Courtesy of M. Knölker.

4.4. Photospheric and chromospheric canopies

Flux tubes expand with height. Over most of the height range the expansion of small flux tubes is relatively gentle. However, at a certain, critical height (determined mainly by the temperature difference between the magnetic and non-magnetic atmosphere) hot flux tubes embedded in a cool ambient medium can expand very rapidly, so that near that height the lower boundary of the field is almost horizontal, i.e. it forms a canopy (Solanki & Steiner 1990). If the temperature structure of the chromospheric models derived empirically by Ayres et al. (1986) from infrared CO and Ca II K observations is used, then small flux tubes form canopies in the lower chromosphere (Solanki & Steiner 1990, Solanki et al. 1991). Such a canopy base-height is consistent with the observations of Giovanelli (1980) and Giovanelli & Jones (1983) and the Hanle-effect based interpretations of Faurobert-Scholl (1992). The canopy models are also in qualitative agreement with a host of other observations, although there are still points of qualitative disagreement (Solanki et al. 1991).

Models of large flux tubes, like sunspots, also show canopy-like features (cf. e.g. the models of Pizzo 1986, 1990). The observations suggest that the base height of the superpenumbral canopy produced by sunspots lies in the photosphere (Giovanelli and Jones 1982, Solanki et al. 1992).

REFERENCES

Ayres, T.R., Testerman, L., Brault, J.W., 1986, *Astrophys. J.* **304**, 542

Cattaneo, F., 1992, in *Cool Stars, Stellar Systems and the Sun*, J. Bookbinder, M. Giampapa (Eds.), Publ. Astron. Soc. Pacific, Conf. Series, in press

Cattaneo, F., Hurlburt, N.E., Toomre, J., 1989, in *Solar and Stellar Granulation*, R.J. Rutten and G. Severino (Eds.), Reidel, Dordrecht, p 415

Cattaneo, F., Hurlburt, N.E., Toomre, J., 1990, *Astrophys. J.* **349**, L63

Deinzer, W., Hensler, G., Schüssler, M., Weisshaar, E., 1984a, *Astron. Astrophys.* **139**, 426

Deinzer, W., Hensler, G., Schüssler, M., Weisshaar, E., 1984b, *Astron. Astrophys.* **139**, 435

Faurobert-Scholl, M., 1992, *Astron. Astrophys.* in press

Galloway, D.J., Weiss, N.O., 1981, *Astrophys. J.* **243**, 945

Galloway, D.J., Proctor, M.R.E., Weiss, N.O., 1977, *Nature* **266**, 686

Giovanelli, R.G., 1980, *Solar Phys.* **68**, 49

Giovanelli, R.G., Jones, H.P., 1982, *Solar Phys.* **79**, 267

Grossmann-Doerth, U., Knölker, M., Schüssler, M., Weisshaar, E., 1989, in *Solar and Stellar Granulation*, R.J. Rutten and G. Severino (Eds.), Reidel, Dordrecht, 481

Hasan, S.S., 1984, *Astrophys. J.* **285**, 851

Hasan, S.S., 1985, *Astron. Astrophys.* **143**, 39

Hughes, D.W., Proctor, M.R.E., 1988, *Ann. Rev. Fluid Mech.* **20**, 187

Hurlburt, N.E., Toomre, J., 1988, *Astrophys. J.* **327**, 920

Hurlburt, N.E., Weiss, N.O., 1987, in *The Role of Fine-Scale Magnetic Fields on the Structure of the Solar Atmosphere*, E.-H. Schröter, M. Vázquez, A.A. Wyller (Eds.), p. 35

Jones, H.P., Giovanelli, R.G., 1983, *Solar Phys.* **87**, 37

Keller, C.U., Solanki, S.K., Steiner, O., Stenflo, J.O., 1990, *Astron. Astrophys.* **233**, 583

Knölker, M., Schüssler, M., 1988, *Astron. Astrophys.* **202**, 275

Knölker, M., Schüssler, M., Weisshaar E., 1988, *Astron. Astrophys.* **194**, 257

Kurucz, R.L., 1979, *Astrophys. J. Suppl. Ser.* **40**, 1

Lites, B.W., Nordlund, Å, Scharmer, G.B., 1989, in *Solar and Stellar Granulation*, R.J. Rutten and G. Severino (Eds.), Reidel, Dordrecht, p. 349

Malagoli, A., Cattaneo, F., Brumell, N.H., 1990, *Astrophys. J.* **361**, L33

Meyer, F., Schmidt, H.U., Simon, G.W., Weiss, N.O., 1979, *Astron. Astrophys.* **76**, 35

Muller, R., 1989, in *Solar and Stellar Granulation*, R.J. Rutten and G. Severino (Eds.), Reidel, Dordrecht, p. 101

Nordlund, Å., 1983, in *Solar and Stellar Magnetic Fields: Origins and Coronal Effects*, J.O. Stenflo (Ed.), Reidel, Dordrecht, *IAU Symp.* **102**, 79

Nordlund, Å, Stein, R.F., 1989, in *Solar and Stellar Granulation*, R.J. Rutten, G. Severino (Eds.), Kluwer, Dordrecht, p. 453

Nordlund, Å, Stein, R.F., 1990, in *Solar Photosphere: Structure, Convection and Magnetic Fields*, J.O. Stenflo (Ed.), Kluwer, Dordrecht, *IAU Symp.* **138**, 191

Pantellini, F.G.E., Solanki, S.K., Stenflo, J.O., 1988, *Astron. Astrophys.* **189**, 263

Parker, E.N., 1963, *Astrophys. J.* **138**, 552

Parker, E.N., 1978, *Astrophys. J.* **221**, 368

Parker, E.N., 1984, *Astrophys. J.* **283**, 343

Pizzo, V.J., 1986, *Astrophys. J.* **302**, 785

Pizzo, V.J., 1990, *Astrophys. J.* **365**, 764

Rabin, D., 1992, *Astrophys. J.* **391**, in press

Rüedi, I., Solanki, S.K., Livingston, W., Stenflo, J.O., 1992, *Astron. Astrophys.* submitted

Schmidt, H.U., Simon, G.W., Weiss, N.O., 1985, *Astron. Astrophys.* **148**, 191.

Schüssler, M., 1986, in *Small Scale Magnetic Flux Concentrations in the Solar Photosphere*, W. Deinzer, M. Knölker, H.H. Voigt (Eds.), Vandenhoeck & Ruprecht, Göttingen, p. 103

Schüssler, M., 1987, in *The Role of Fine-Scale Magnetic Fields on the Structure of the Solar Atmosphere*, E.-H. Schröter, M. Vázquez, A.A. Wyller (Eds.), Cambridge University Press, p. 223

Schüssler, M., 1990, in *Solar Photosphere: Structure, Convection and Magnetic Fields*, J.O. Stenflo (Ed.), Kluwer, Dordrecht, *IAU Symp.* **138**, 161

Solanki, S.K., 1986, *Astron. Astrophys.* **168**, 311

Solanki, S.K., 1987a, in *The Role of Fine-Scale Magnetic Fields on the Structure of the Solar Atmosphere*, E.-H. Schröter, M. Vázquez, A.A. Wyller (Eds.), Cambridge University Press, p. 67

Solanki, S.K., 1987b, in *Proc. Tenth European Regional Astronomy Meeting of the IAU. Vol. 1: The Sun*, L. Hejna, M. Sobotka (Eds.), Publ. Astron. Inst. Czechoslovak Acad. Sci., p. 95

Solanki, S.K., 1989, *Astron. Astrophys.* **224**, 225

Solanki, S.K., 1990, in *Solar Photosphere: Structure, Convection and Magnetic Fields*, J.O Stenflo (Ed.), *IAU Symp.* **138**, 103

Solanki, S.K., 1992, in *Infrared Solar Physics*, D. Deming, D. Rabin (Eds.), Kluwer, Dordrecht, *IAU Symp.* **154**, in press

Solanki, S.K., Steiner, O., 1990, *Astron. Astrophys.* **234**, 519

Solanki, S.K., Stenflo, J.O., 1984, *Astron. Astrophys.* **140**, 185

Solanki, S.K., Stenflo, J.O., 1985, *Astron. Astrophys.* **148**, 123

Solanki, S.K., Steiner, O., Uitenbroek, H., 1991, *Astron. Astrophys.* **250**, 220

Solanki, S.K., Rüedi, I., Livingston, W., 1992, *Astron. Astrophys.* submitted

Spruit, H.C., 1976, *Solar Phys.* **50**, 269

Spruit, H.C., 1979, *Solar Phys.* **61**, 363

Spruit, H.C., Nordlund, Å, Title, A.M., 1990, *Ann. Rev. Astron. Astrophys.* **28**, 263

Spruit, H.C., Schüssler, M., Solanki, S.K., 1992, in *Solar Interior and Atmosphere*, A.N. Cox, W. Livingston, M.S. Matthews (Eds.), in press

Steffen, M., Freytag, B., 1991, *Reviews of Modern Astron.* **4**, 43

Steffen, M., Ludwig, H.-G., Krüß, A., 1989, *Astron. Astrophys.* **213**, 371

Stein, R., Nordlund, Å., 1989, *Astrophys. J.* **342**, L95

Stein, R., Nordlund, Å., Kuhn, J.R., 1989, in *Solar and Stellar Granulation*, R.J. Rutten and G. Severino (Eds.), Reidel, Dordrecht, p. 381

Steiner, O., 1992, in *Infrared Solar Physics*, D. Deming, D. Rabin (Eds.), Kluwer, Dordrecht, *IAU Symp.* **154**, in press

Steiner, O., Pizzo, V.J., 1989, *Astron. Astrophys.* **211**, 447

Steiner, O., Pneuman, G.W., Stenflo, J.O., 1986, *Astron. Astrophys.* **170**, 126

Steiner, O., Stenflo, J.O., 1990, in *Solar Photosphere: Structure, Convection and Magnetic Fields*, J.O. Stenflo (Ed.), Kluwer, Dordrecht, *IAU Symp.* **138**, 181

Stenflo, J.O., 1973, *Solar Phys.* **32**, 41

Stenflo, J.O., 1986, in *Small Scale Magnetic Flux Concentrations and the Solar Photosphere*, W. Deinzer, M. Knölker, H.H. Voigt (Eds.), Vandenhoek & Ruprecht, Göttingen, p. 59

Stenflo, J.O., 1989, *Astron. Astrophys. Review* **1**, 3

Stenflo, J.O., Harvey, J.W., 1985, *Solar Phys.* **95**, 99

Stenflo, J.O., Solanki, S.K., Harvey, J.W., 1987, *Astron. Astrophys.* **171**, 305

Weiss, N.O., 1989, in *Solar and Stellar Granulation*, R.J. Rutten and G. Severino (Eds.), Reidel, Dordrecht, 471

Zayer, I., Solanki, S.K., Stenflo, J.O., 1989, *Astron. Astrophys.* **211**, 463

Zayer, I., Solanki, S.K., Stenflo, J.O., Keller, C.U., 1990, *Astron. Astrophys.* **239**, 356

Thomas, J.H., 1990, in *Physics of Magnetic Flux Ropes*, C.T. Russell, E.R. Priest, L.C. Lee (Eds.), Geophysical Monograph 58, American Geophys. Union, Washington, DC, p. 133

Title, A.M., Tarbell, T.D., Topka, K.P., 1987, *Astrophys. J.* **317**, 892

Title, A.M., Tarbell, T.D., Topka, K.P, Fergusen, S.H., Shine, R.A., and the SOUP Team, 1989, *Astrophys. J.* **336**, 475

Title, A.M., Shine, R.A., Tarbell, T.D., Topka, K.P., Scharmer, G.B., 1990, in *Solar Photosphere: Structure, Convection, Magnetic Fields*, J.O. Stenflo (Ed.), Kluwer, Dordrecht, *IAU Symp.* **138**, 49

Webb, A.R., Roberts, B., 1978, *Solar Phys.* **59**, 249

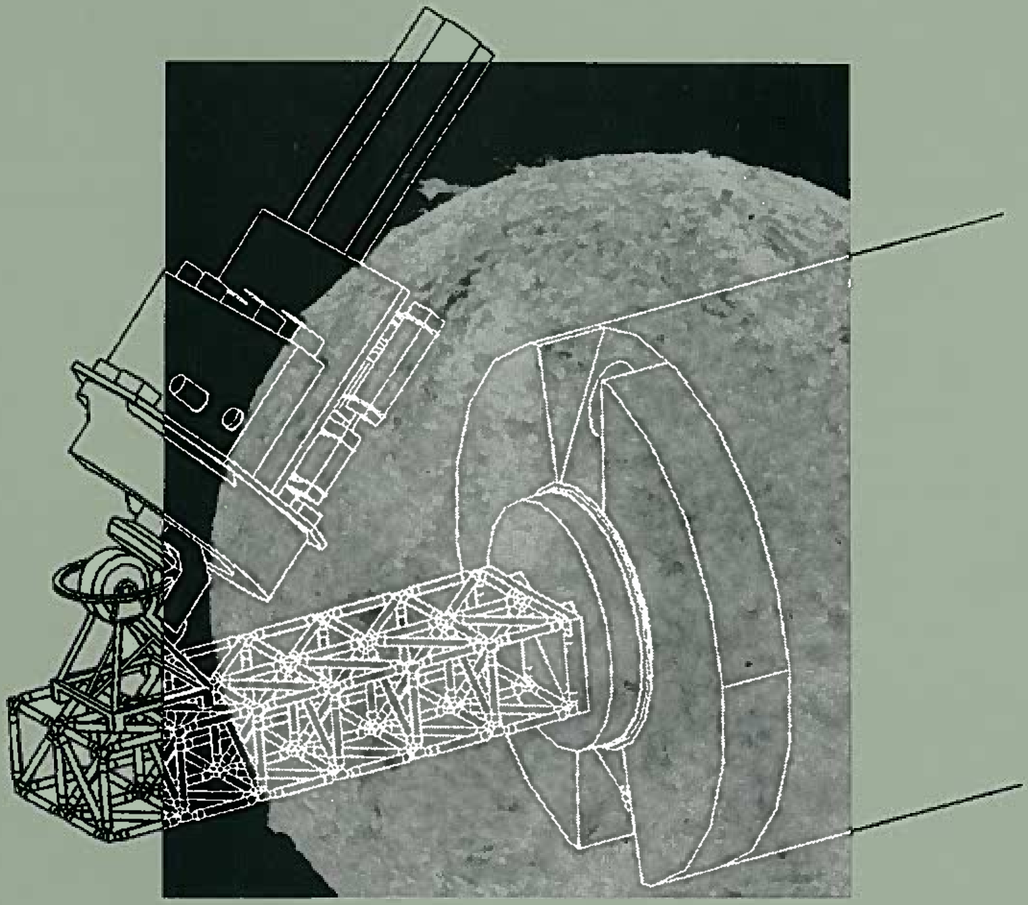
Weiss, N.O., 1966, *Proc. Roy. Soc. London, Ser.A* **293**, 310

esa SP-344

Solar Physics and Astrophysics at Interferometric Resolution

An international workshop to present SIMURIS
– Solar, Solar System and Stellar Interferometric Mission
for Ultrahigh-Resolution Imaging and Spectroscopy –

Paris, 17–19 February 1992



esa
european space agency