Irradiance Effects of Small-Scale Magnetic Fields on the Sun

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Small-scale magnetic fields affect the solar luminosity mainly on long time scales. To understand their contribution to solar luminosity variations we must know and understand the contribution of a typical small-scale magnetic feature. In this review I briefly outline our theoretical understanding of the processes leading to the enhancement (or reduction) of the brightness of flux tubes. I also present a brief overview of our observational knowledge.

1. Introduction

Observations show that whereas sunspots dominate solar luminosity variations on a timescale of days to months it is the bright faculae which dictate the variation of the global solar luminosity on time scales approaching the period of the solar cycle (Willson & Hudson 1988; Foukal & Lean 1988; Fröhlich 1994). It is equally well established that faculae are composed of small-scale magnetic features (see the reviews by Stenflo 1989; Solanki 1993). Consequently, in order to understand long term solar irradiance variations we must study and understand the brightness and energy balance of small-scale magnetic features. For the purposes of brightness variations small-scale magnetic features may be divided into two classes.

a) *Flux tubes*: These are magnetic flux concentrations having a field strength of a kG or more in the middle and lower photosphere (e.g.; Stenflo 1973; Rabin 1992; Rüedi *et al.* 1992). The magnetic energy density of such features is sufficiently high to dominate over the thermal and kinetic energy of the internal gas at and above the visible solar surface. This implies that the magnetic field significantly affects the way that radiation is channelled through the solar surface. The most successful description of these strong-field elements is provided by the flux-tube model (briefly described in Sect. 2) and in the following we will refer to such features simply as flux tubes. Note that a dominant fraction of the non-sunspot magnetic flux seen in the daily Kitt Peak magnetograms is in the form of small flux tubes.

b) *Weak field features*: They are composed of less concentrated fields, with field strengths below one kG throughout the photosphere (Rüedi *et al.* 1992). The thermal and kinetic energy densities are larger than or equal to the magnetic energy density. Therefore we expect such magnetic fields to affect the solar luminosity only slightly, at most. The necessary measurements have, however, never been carried out.

In the following I shall consider only flux tubes, since we know too little about the brightness or the irradiance effects of weak field features.

2. Luminosity changes due to small-scale magnetic features: Theory

A considerable number of MHD models of magnetic flux tubes and sheets exist in the literature. Of interest here are those which include an energy equation that adequately takes into account at least some of the important effects. Such models have been constructed by, e.g., Spruit (1976, 1977); Deinzer *et al.* (1984a,b); Herbold *et al.* (1984); Kalkofen *et al.* (1986); Knölker *et al.* (1988); Knölker & Schüssler (1988); Hasan (1988);

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Grossmann-Doerth *et al.* (1989)i; Nordlund & Stein (1989); Steiner (1990); Pizzo *et al.* (1993a,b) and Fabiani Bendicho *et al.* (1993). Unfortunately, no model exists which adequately includes all the relevant energetics.
There are four main effects which determine the final luminosity of a flux tube:

1. The magnetic field inhibits convection, so that heat transport from below is reduced. Consequently the flux tube is cooled.
2. The magnetic pressure causes a gas pressure deficit within the flux tube, so that its $\tau = 1$ level is lowered (Wilson depression). Radiation flows in through the walls of the flux tube above the Wilson depression, which heats the flux tube near its $\tau = 1$ level and cools its surroundings (due to radiation losses into the flux tube).
3. Radiation from the 'hot walls' and the bottom of the flux tube heats the middle and upper photosphere within the tube, and partly also in its near surroundings.
4. Mechanical energy, e.g. in the form of waves, is transported upwards along the field lines to heat the upper photosphere and chromosphere. The waves are thought to be excited by the buffeting of the flux tubes through granules.

The importance of effects 2, 3, and 4 decreases as the size of the flux tube increases. The important quantity determining the brightness of magnetic features is the ratio of horizontal size to the Wilson depression. For larger horizontal size more magnetic flux is blocked, while for a larger Wilson depression the surface area of the flux tube and its temperature are increased, allowing more radiation to escape. Since the Wilson depression changes only slowly with changing flux tube size, it is mainly the horizontal extent of flux tubes which determines their brightness.

Theory predicts that small flux tubes (smaller than 200–300 km in diameter) appear bright all over the solar disc, in both the continuum and in spectral lines. They are surrounded by a dark ring. Somewhat larger tubes are predicted to appear dark in the continuum at disc centre, but bright near the limb. They may appear bright in spectral lines as well. Such tubes are also surrounded by a dark ring. Very large flux tubes (pores, sunspots) are predicted to be dark everywhere on the solar disc, in both the continuum and photospheric spectral lines.

3. Luminosity changes due to small-scale magnetic features: Observations

Basically two types of observations are of interest:

a) Contrast measurements: These are narrow- or broad-band measurements of the intensity of magnetic features relative to the quiet Sun intensity.

b) Spectropolarimetric measurements: Stokes V profiles (spectral profiles in net circularly polarized light) are measured and the temperature stratification of the magnetic features is determined therefrom.

3.1. *Contrast measurements*

The basic idea is to measure the intensity of the 'magnetic feature', I_m, and of the average quiet Sun, I_q, and therewith to construct the contrast δ:

$$\delta = I_m/I_q - 1$$

One major advantage of this approach is its simplicity. Thus a large body of data has been collected (for reviews see: Akimov *et al.* 1987; Solanki 1993). Another advantage

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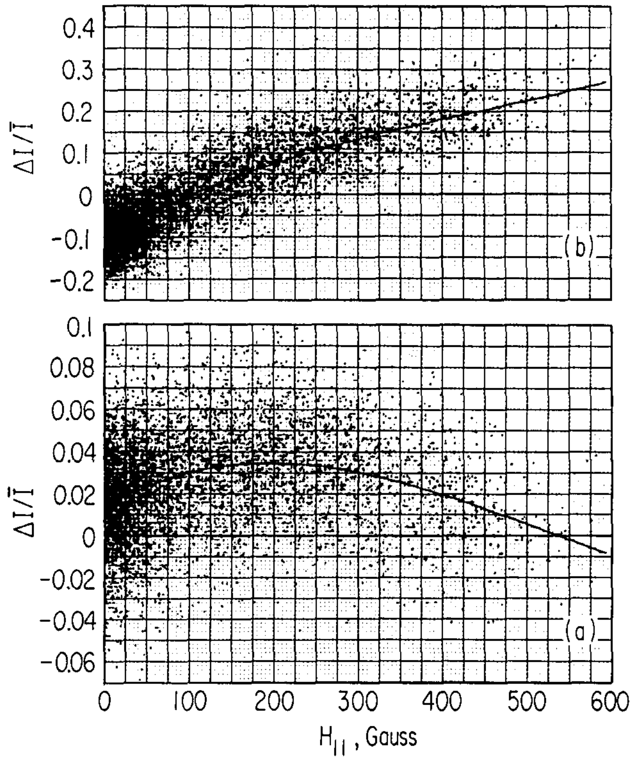

FIGURE 1. Contrast $\Delta I/\langle I\rangle$ vs. spatially averaged field strength, $\langle B\rangle$, where $\langle I\rangle$ is the average brightness of the whole observed image and differs somewhat from I_q. a) Continuum, b) line core of Fe I 5250Å. The solid curves are polynomial least-squares fits (adapted from Frazier 1971).

is that in this manner the effect of the magnetic feature on its surroundings, for example the production of a dark ring around the flux tube, is automatically taken into account.

The main problem is that the measured δ depends on many factors, which makes its interpretation and the comparison between different observations difficult. There are four main parameters on which δ depends.

a) *Spatially averaged field strength* $\langle B\rangle$: δ initially increases with increasing $\langle B\rangle$, before decreasing again and finally turning negative. This happens at much smaller $\langle B\rangle$ for the continuum than for spectral lines (Figure 1). Sheeley & Engvold (1970); Frazier (1971, 1978); Simon & Zirker (1974); Mehltretter (1974); Frazier & Stenflo (1978); Foukal & Fowler (1984); Title *et al.* (1990, 1992); Moran et al. (1992); Topka et al. (1993) give further examples.

b) *Limb distance*: The continuum contrast δ_c increases rapidly towards the limb (e.g. Waldmeier 1949; Rogerson 1961; Schmahl 1967; Livshits 1968; Chapman 1970; Frazier 1971; Muller 1975; Ingersoll & Chapman 1975; Hirayama 1978; Chapman & Klabunde 1982; Libbrecht & Kuhn 1984, 1985; Akimov *et al.* 1982, 1987; Lawrence 1988; Auffret & Muller 1991), while δ in line cores varies much less rapidly. Figure 2 illustrates the centre to limb variation of δ at different λ (from Foukal *et al.* 1991).

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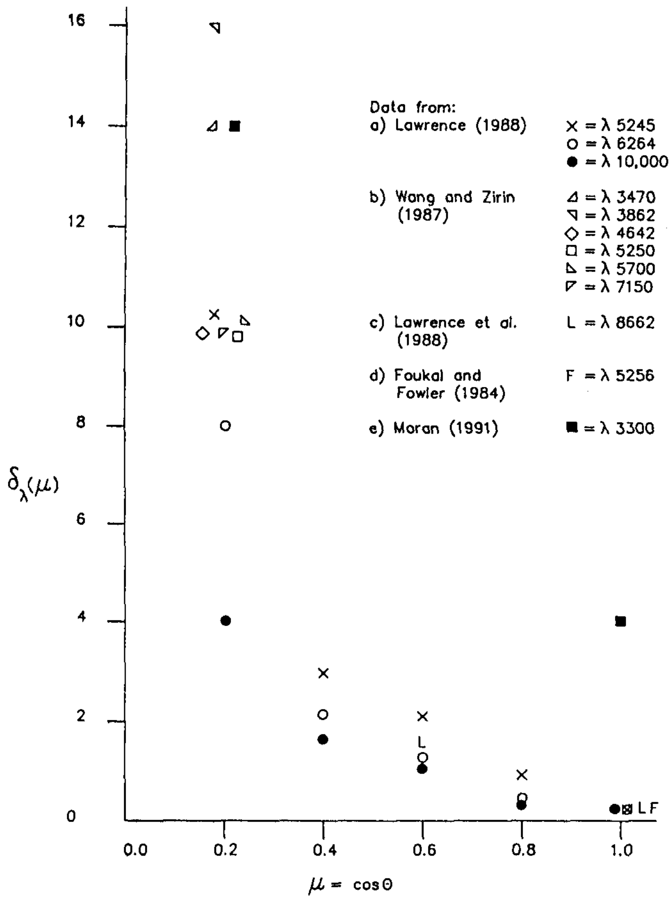

FIGURE 2. Measured values of the broad-band contrast, δ (in %), at different wavelengths vs. $\mu = \cos\vartheta$, where ϑ is the heliocentric angle. The data are from various sources (adapted from Foukal *et al.* 1991).

c) *Wavelength* λ: δ decreases strongly from the UV to the IR (cf. Figure 2) due to two effects. Firstly, the Planck function has a larger temperature sensitivity in the UV, so that the intensity reacts more strongly to a given temperature perturbation. Secondly, the density of spectral lines decreases with λ and spectral lines show larger contrasts than the continuum. Consequently, the exact wavelength and width of the passband may strongly affect the results. The wavelength dependence of δ has been widely studied (e.g. Frazier 1978; Chapman & McGuire 1977; Wang & Zirin 1987; Moran *et al.* 1992).

d) *Spatial resolution*: Higher spatial resolution usually leads to higher $|\delta|$ values (e.g., Mehltretter 1974; Koutchmy 1977; Muller & Keil 1983; Auffret & Muller 1991; Keller 1992). Thus Auffret & Muller (1991) find δ values (around 5750 Å) up to 25% at disc centre ($\mu = 1$). Keller (1992) even finds values ranging up to 30% in the true continuum near 5250 Å. Compare this with Figure 2. Note, however, that the highest δ values (1.8–2.0) have often been obtained in bandpasses containing strong, temperature sensitive lines and do not reflect white-light contrasts.

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The above list on the one hand illustrates the wide variety of brightness signatures produced by small flux tubes. On the other hand it also demonstrates that different contrast measurements often cannot be directly compared to each other. A consistent set of measurements under good seeing conditions at many λ and μ values is required. It is important to measure $\langle B \rangle$ simultaneously.

3.2. *Spectropolarimetric measurements*

The procedure for determining contrasts from spectropolarimetric measurements is as follows: 1.) A number of spectral lines are recorded in polarized light. 2.) Clean diagnostics (e.g. line ratios) are identified. 3.) Models are constructed which ideally reproduce all diagnostics. The end products are the simultaneously determined magnetic, velocity and thermal stratifications within the magnetic feature. Using these, continuum or line contrasts may be derived.

We may count among the advantages of this approach that its results are (to first order) spatial resolution and wavelength independent. In addition, $\langle B \rangle$ is automatically determined with high accuracy. Disadvantages are that some model dependence always remains and considerable effort must generally be invested to obtain good models, which limits the number of relevant investigations. Also, current diagnostics mainly give information on the magnetic features alone and not so much on their surroundings which are also important for the net radiation budget. Here I concentrate on two results of spectropolarimetric observations.

Dependence of temperature on $\langle B \rangle$: The temperature in the lower photosphere, and consequently the continuum intensity I_c, depends strongly on $\langle B \rangle$ (e.g. Frazier 1978; Hirayama 1978; Solanki & Stenflo 1984, 1985; Solanki 1986; Zayer *et al.* 1990; Solanki & Brigljević 1992).

$$\begin{aligned} \text{Small } \langle B \rangle \lesssim 100 \text{ G} \quad &\rightarrow \quad \delta_c\,(5000\text{Å}) \;\approx 5\% \text{ to } 30\% \,, \\ \text{Larger } \langle B \rangle \approx 200 - 350 \text{ G} \quad &\rightarrow \quad \delta_c\,(5000\text{Å}) \;\approx -5\% \text{ to } -20\% \,. \end{aligned}$$

Also, as $\langle B \rangle$ increases, so does the average diameter d of the magnetic features. The dependence on $\langle B \rangle$ is most probably a result of this dependence of d on $\langle B \rangle$ (e.g. Keller 1992; Grossmann-Doerth *et al.* 1994). $\langle B \rangle$ is, however, the more convenient quantity to measure. The δ_c inferred from spectropolarimetric observations is at least in good qualitative agreement with direct δ_c measurements.

Height dependence of the temperature: In the deeper layers the temperature in the flux tube is lower than in the surroundings at the same height, while in the upper photosphere and the chromosphere the opposite is the case (Keller *et al.* 1990; Bruls & Solanki 1992). At equal optical depth the flux tubes may be hotter or cooler than their surroundings near $\tau_c = 1$, but in the middle and upper photosphere the flux tubes are invariably hotter (e.g. Stenflo 1975; Chapman 1979; Solanki 1986; Walton 1987; Keller *et al.* 1990; Solanki *et al.* 1991). In particular, the chromospheric temperature rise starts $200 - 300$ km deeper within small-scale magnetic features than in the quiet Sun (Bruls & Solanki 1992; cf. Ayers *et al.* 1986; Chapman 1981). This leads to considerably enhanced Ca II H and K emission. The temperature stratification of small flux tubes is plotted in Figure 3.

4. Conclusions

The basic parameter determining the brightness of small-scale magnetic features is their size. Since the average size of the magnetic features increases with increasing $\langle B \rangle$ or

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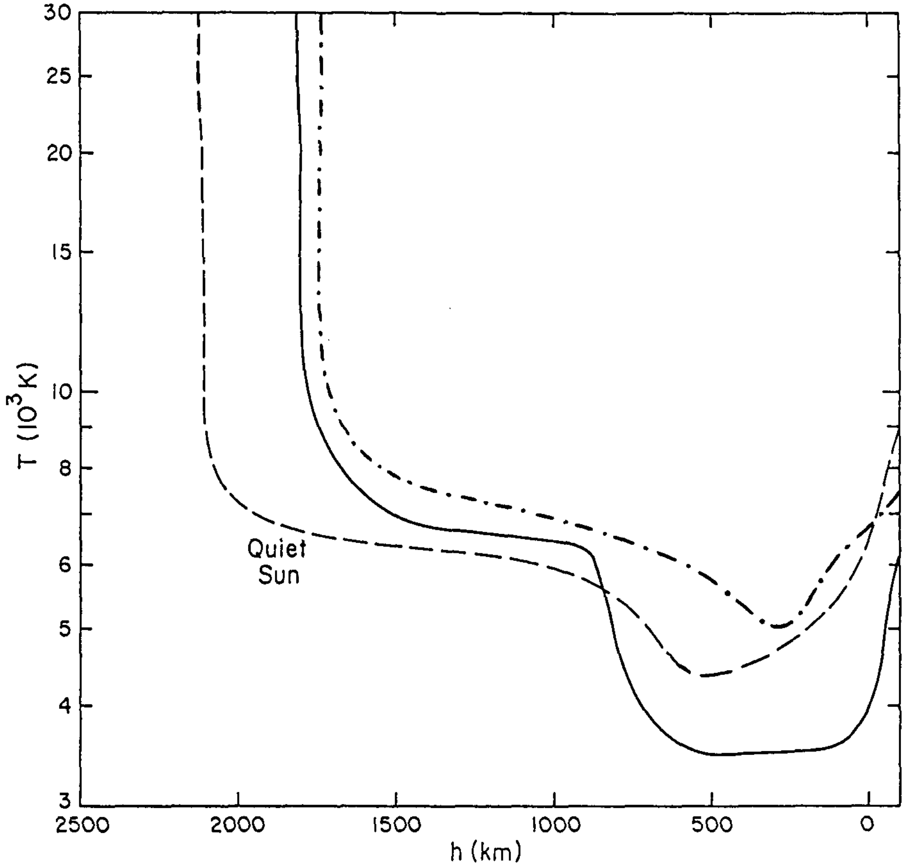

FIGURE 3. Temperature T vs. height Z of a small flux tube (dot-dashed), of the quiet Sun (dashed) and a sunspot umbra (solid) (adapted from Avrett 1985).

magnetic filling factor, their average luminosity decreases with increasing $\langle B \rangle$. It follows that it is not sufficient to know the magnetic field averaged over the Sun to predict the solar irradiance variation. We must know the detailed distribution of the field. Thus solar irradiance need not peak simultaneously with the disc-integrated magnetic flux, even if the magnetic field is responsible for solar irradiance variations. For example, the B-field is more uniformly distributed in the falling phase of the solar cycle, so that at that time there may be more field in regions of small $\langle B \rangle$, which show a larger δ_c.

In the subphotospheric layers small magnetic features receive an excess of energy from their surroundings through radiation, through the excitation of internal motions (e.g. waves), and partly through storing energy in more complex magnetic geometries. This excess energy is:

- partly radiated away immediately at $\tau_c \approx 1$. This gives rise to a limb continuum enhancement from the flux-tube walls and, for small tubes, to a disc-centre continuum enhancement from the bottom of the flux tube.
- partly transported upwards to heat the middle and upper photosphere, which weakens

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most spectral lines, thus enhancing line emission. In addition, it further enhances continuum emission from flux tubes at the extreme limb.

- to a minor part transported still higher to heat the chromosphere and corona, enhancing Ca II H and K emission, X-ray and 11 cm radio flux and He I 10830 Å equivalent width.

Most of these proxies to solar irradiance are thus produced by channelling into the upper atmosphere of a minor amount of the excess energy flowing into magnetic features. The proxies thus have basically a common origin to the long-term irradiance variations themselves which are caused by the dominant part of this excess energy flux. The heating of the upper atmosphere, however, is a non-linear function of the magnetic flux, so that it is not a priori clear which particular indicator should be a good proxy of solar luminosity.

In addition to simply possessing a higher radiation flux than the quiet Sun, small flux tubes also redistribute the energy vertically in the atmosphere, transporting it to greater heights before allowing it to be radiated away. Therefore, the contribution of spectral lines to the total irradiance variations should not be neglected.

In summary, small-scale solar magnetic features affect the solar luminosity and even appear to dominate its evolution on the time scale of the solar activity cycle. Nevertheless there are sizable gaps in our understanding of how small-scale magnetic features influence the global luminosity. In order to understand the complex influence of the small-scale fields we must know both, the evolution of their distribution on the solar surface and the luminosity of individual features as a function of their position on the solar disc and of the local magnetic filling factor. The distribution and large-scale evolution of magnetic features is well documented by the daily Kitt Peak magnetograms. Our knowledge of individual magnetic features has also progressed substantially, but hardly any attempt has so far been made to combine these two subjects of study. I expect that a number of open questions regarding the mechanism by which small-scale magnetic features affect the global solar luminosity can be answered by carrying out this synthesis.

REFERENCES

AKIMOV, L.A., BELKINA, I.L. & DYATEL, N.P. 1982 Brightness of the photosphere and faculae at the limb based on eclipse observations. *Sov. Astron.* **26**, 334–340.

AKIMOV, L.A., BELKINA, I.L., DYATEL, N.P. & MARCHENKO, G.P. 1987 Contrast of faculae near the solar limb. *Sov. Astron.* **31**, 64–68.

AUFFRET, H. & MULLER, R. 1991 Center-to-limb variation of the network bright points. *Astron. Astrophys.* **246**, 264–279.

AVRETT, E.H. 1981 Reference model atmosphere calculations: The Sunspot sunspot model. In *The Physics of Sunspots* (ed. L.E. Cram & J.H. Thomas). pp. 235–255. National Solar Obs., Sunspot, NM, USA.

AYRES, T.R., TESTERMAN, L. & BRAULT, J.W. 1986 Fourier transform spectrometer observations of solar carbon monoxide. II. Simultaneous cospatial measurements of the fundamental and first-overtone bands, and Ca II K, in quiet and active regions. *Astrophys. J.* **304**, 542–559.

BRULS, J.H.M.J. & SOLANKI, S.K. 1993 The chromospheric temperature rise in solar magnetic flux tubes. *Astron. Astrophys.* **273**, 293–303.

CHAPMAN, G.A. 1970 On the physical conditions in the photospheric network: An improved model of solar faculae. *Solar Phys.* **14**, 315–327.

CHAPMAN, G.A. 1979 New models of solar faculae. *Astrophys. J.* **232**, 923–928.

CHAPMAN, G.A. 1981 Active regions from the photosphere to the chromosphere. In *Solar Active Regions* (ed. F.Q. Orrall). pp. 43–82. Colorado University Press, Boulder, CO, USA.

https://doi.org/10.1017/S0252921100024726 Published online by Cambridge University Press

Chapman, G.A. & Klabunde, D.P. 1982 Measurements of the limb darkening of faculae near the solar limb. *Astrophys. J.* **261**, 387–395.

Chapman, G.A. & McGuire, T.E. 1977 The wavelength dependence of the facular excess brightness. *Astrophys. J.* **217**, 657–660.

Deinzer, W., Hensler, G., Schüssler, M. & Weisshaar, E. 1984 Model calculations of magnetic flux tubes I. Equations and method. *Astron. Astrophys.* **139**, 426–434.

Deinzer, W., Hensler, G., Schüssler, M. & Weisshaar, E. 1984 Model calculations of magnetic flux tubes II. Stationary results for solar magnetic elements. *Astron. Astrophys.* **139**, 435–449.

Fabiani Bendicho, P., Kneer, F. & Trujillo Bueno, J. 1992 On the photospheric temperature in small-scale magnetic flux concentrations. *Astron. Astrophys.* **264**, 229–235.

Foukal, P. & Fowler, L. 1984 A Photometric study of heat flow at the solar photosphere. *Astrophys. J.* **281**, 442–454.

Foukal, P. & Lean, J. 1988 Magnetic modulation of solar luminosity by photospheric activity. *Astrophys. J.* **328**, 347–357.

Foukal, P., Duvall, T. Jr. & Gillespie, B. 1981 Detection of a temperature deficit in magnetic faculae at the solar photosphere. *Astrophys. J.* **249**, 394–398.

Foukal, P., Harvey, K. & Hill, F. 1991 Do changes in the photospheric magnetic network cause the 11 year variation of total solar irradiance? *Astrophys. J.* **383**, L89–L92.

Frazier, E.N. 1971 Multi-channel magnetograph observations. III: faculae. *Solar Phys.* **21**, 42–53.

Frazier, E.N. 1978 Line profile families of faculae and pores. *Astron. Astrophys.* **64**, 351–358.

Frazier, E.N. & Stenflo, J.O. 1978 Magnetic, velocity and brightness structures in solar faculae. *Astron. Astrophys.* **70**, 789–799.

Fröhlich, C. 1994 Irradiance observations of the Sun. In *The Sun as a Variable Star: Solar and Stellar Irradiance Variations* (ed. J.M. Pap, C. Fröhlich, H.S. Hudson & S.K. Solanki). Cambridge Univ. Press, in press.

Grossmann-Doerth, U., Knölker, M., Schüssler, M. & Weisshaar, E. 1989 Models of magnetic flux sheets. In *Solar and Stellar Granulationx* (ed. R.J. Rutten & G. Severino). pp. 481–492. Kluwer, Dordrecht.

Grossmann-Doerth, U., Knölker, M., Schüssler, M. & Solanki, S.K. 1993 The deep layers of solar magnetic elements. *Astron. Astrophys.* in press.

Hasan, S.S. 1988 Energy transport in intense flux tubes on the Sun. I. Equilibrium atmosphere. *Astrophys. J.* **332**, 499–513.

Herbold, G., Ulmschneider, P., Spruit, H.C. & Rosner, R. 1985 Propagation of nonlinear radiatively damped longitudinal waves along magnetic flux tubes in the solar atmosphere. *Astron. Astrophys.* **145**, 157–169.

Hirayama, T. 1978 A model of solar faculae and their lifetime. *Publ. Astron. Soc. Japan* **30**, 337–352.

Ingersoll, A.P. & Chapman, G.A. 1975 Temperature variation with latitude in the upper solar photosphere: relevance to solar oblateness measurements and facular models. *Solar Phys.* **42**, 279–288.

Kalkofen, W., Rosner, R., Ferrari, A. & Massaglia, S. 1986 The equilibrium structure of thin magnetic flux tubes. II. *Astrophys. J.* **304**, 519–525.

Keller, C.U. 1992 Resolution of magnetic flux tubes on the Sun. *Nature* **359**, 307–308.

Keller, C.U., Solanki, S.K., Steiner, O. & Stenflo, J.O. 1990 Structure of solar magnetic fluxtubes from the inversion of stokes spectra at disk center. *Astron. Astrophys.* **233**, 583–597.

Knölker, M. & Schüssler, M. 1988 Model calculations of flux tubes. IV. Convective energy transport and the nature of intermediate size flux concentrations. *Astron. Astrophys.* **202**, 275–283.

Knölker, M., Schüssler, M. & Weisshaar, E. 1988 Model calculations of magnetic flux

https://doi.org/10.1017/S0252921100024726 Published online by Cambridge University Press

tubes III. Properties of solar magnetic elements. *Astron. Astrophys.* **194**, 257–267.

KOUTCHMY, S. 1977 Photospheric faculae: the contrasts at the center of the solar disk using filigree pictures. *Astron. Astrophys.* **61**, 397–404.

LAWRENCE, J.K. 1988 Multi-color photometric observations of facular contrasts. *Solar Phys.* **116**, 17–32.

LAWRENCE, J.K., CHAPMAN, G.A. & HERZOG, A.D. 1988 Photometric determination of facular contrasts near the solar disk center. *Astrophys. J.* **324**, 1184–1193.

LIBBRECHT, K.G. & KUHN, J.R. 1984 A new measurement of the facular contrast near the solar limb. *Astrophys. J.* **277**, 889–896.

LIBBRECHT, K.G. & KUHN, J.R. 1985 On the facular contrast near the solar limb. *Astrophys. J.* **299**, 1047–1050.

LIVSHITS, M.A. 1968 *Soln. Akt.* **3**, 78.

MEHLTRETTER, J.P. 1974 Observations of photospheric faculae at the center of the solar disk. *Solar Phys.* **38**, 43–57.

MORAN, T., FOUKAL, P. & RABIN, D. 1992 A photometric study of faculae and sunspots between 1.2 and 1.6 μm. *Solar Phys.* **142**, 35–46.

MULLER, R. 1975 A model of photospheric faculae deduced from white light high resolution pictures. *Solar Phys.* **45**, 105–114.

MULLER, R. & KEIL, S.L. 1983 The characteristic size and brightness of facular points in the quiet photosphere. *Solar Phys.* **87**, 243–250.

NORDLUND, Å& STEIN, R.F. 1989 Simulating magnetoconvection. In *Solar and Stellar Granulation* (ed. R.J. Rutten & G. Severino). pp. 453–470. Kluwer, Dordrecht.

PIZZO, V.J., MCGREGOR, K.B. & KUNASZ, P.B. 1993a A numerical simulation of two-dimensional radiative equilibrium in magnetostatic flux tubes. I. The model. *Astrophys. J.* **404**, 788–798.

PIZZO, V.J., MCGREGOR, K.B. & KUNASZ, P.B. 1993b A numerical simulation of two-dimensional radiative equilibrium in magnetostatic flux tubes. II. Computational results. *Astrophys. J.* **413**, 764–777.

RABIN, D. 1992 Spatially extended measurements of magnetic field strength in solar plages. *Astrophys. J.* **391**, 832–844.

ROGERSON, J.B. 1961 On photospheric faculae. *Astrophys. J.* **134**, 331–336.

RÜEDI, I., SOLANKI, S.K., LIVINGSTON, W. & STENFLO, J.O. 1992 Infrared lines as probes of solar magnetic features. III. Strong and weak magnetic fields in solar plages. *Astron. Astrophys.* **263**, 323–338.

SCHMAHL, G. 1967 Zum Zustand der photosphärischen Schichten von Sonnenfackeln. *Z. Astrophys.* **66**, 81–117.

SHEELEY, N.R.,JR. & ENGVOLD, O. 1970 Simultaneous measurements of magnetic fields and brightness fields using a 4-image spectroheliograph. *Solar Phys.* **12**, 69–83.

SIMON, G.W. & ZIRKER, J.B. 1974 A search for the footprints of solar magnetic fields. *Solar Phys.* **35**, 331–342.

SOLANKI, S.K. 1986 Velocities in solar magnetic fluxtubes. *Astron. Astrophys.* **168**, 311–329.

SOLANKI, S.K. 1993 Small-scale solar magnetic fields: An overview. *Space Sci. Rev.* **61**, 1–188.

SOLANKI, S.K. & BRIGLJEVIĆ, V. 1992 Continuum brightness of solar magnetic elements. *Astron. Astrophys.* **262**, L29–L32.

SOLANKI, S.K. & STENFLO, J.O. 1984 Properties of solar magnetic fluxtubes as revealed by Fe I lines. *Astron. Astrophys.* **140**, 185–198.

SOLANKI, S.K. & STENFLO, J.O. 1985 Models of solar magnetic fluxtubes: Constraints imposed by Fe I and II lines. *Astron. Astrophys.* **148**, 123–132.

SOLANKI, S.K., STEINER, O. & UITENBROEK, H. 1991 Two-dimensional models of the solar chromosphere. I. The Ca II K line as a diagnostic: 1.5-D radiative transfer. *Astron. Astrophys.* **250**, 220–234.

SPRUIT, H.C. 1976 Pressure equilibrium and energy balance of small photospheric fluxtubes.

https://doi.org/10.1017/S0252921100024726 Published online by Cambridge University Press

Solar Phys. **50**, 269–295.

SPRUIT, H.C. 1977 Heat flow near obstacles in the solar convection zone. *Solar Phys.* **55**, 3–34.

STEINER, O. 1990 Model calculations of solar magnetic fluxtubes and radiative transfer. *Ph.D. thesis*, No. 9292, ETH-Zürich.

STENFLO, J.O. 1973 Magnetic-field structure of the photospheric network. *Solar Phys.* **32**, 41–63.

STENFLO, J.O. 1975 A model of the supergranulation network and of active-region plages. *Solar Phys.* **42**, 79–105.

STENFLO, J.O. 1989 Small scale magnetic structures on the Sun. *Astron. Astrophys. Rev.* **1**, 3–48.

TITLE, A.M., TARBELL, T.D., TOPKA, K.P., CAUFFMAN, D., BALKE, C. & SCHARMER, G. 1990 Magnetic flux tubes and their relation to continuum and photospheric features. In *Phys. of Magn. Flux Ropes* (ed. C.T. Russell, E.R. Priest & L.C. Lee). pp. 171–179. Geophysical Monograph 58, American Geophys. Union, Washington, DC, USA.

TITLE, A.M., TOPKA, K.P., TARBELL, T.D., SCHMIDT, W., BALKE, C. & SCHARMER, G. 1992 On the differences between plage and quiet Sun in the solar photosphere. *Astrophys. J.* **393**, 782–794.

TOPKA, K.P., TARBELL, T.D. & TITLE, A.M. 1992 Properties of the smallest solar magnetic elements. I. Facular contrast near Sun center. *Astrophys. J.* **396**, 351–363.

WALDMEIER, M. 1949 Die Sichtbarkeitsfunktion der Sonnenfackeln. *Z. Astrophys.* **26**, 147–157.

WALTON, S.R. 1987 Flux tube models of solar plages. *Astrophys. J.* **312**, 909–929.

WANG, H. & ZIRIN, H. 1987 The contrast of faculae near the solar limb. *Solar Phys.* **110**, 281–293.

WILLSON, R.C. & HUDSON, H.S. 1988 Solar luminosity variations in solar cycle 21. *Nature* **332**, 810–812.

ZAYER, I., SOLANKI, S.K., STENFLO, J.O. & KELLER, C.U. 1990 Dependence of the properties of solar magnetic flux tubes on filling factor. II. Results of an inversion approach. *Astron. Astrophys.* **239**, 356–366.

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