Session III

“PHOTOSPHERIC PHENOMENA: RESULTS”

SOLAR AND STELLAR MAGNETIC FLUX TUBES

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Abstract. The magnetic field of the Sun is mainly concentrated into intense magnetic flux tubes having field strengths of the order of 1 kG. In this paper an overview is given of the thermal and magnetic properties of these flux tubes, which are known to exhibit a large range in size, from the smallest magnetic elements to sunspots. Differences and similarities between the largest and smallest features are stressed. Some thoughts are also presented on how the properties of magnetic flux tubes are expected to scale from the solar case to that of solar-like stars. For example, it is pointed out that on giants and supergiants turbulent pressure may dominate over gas pressure as the main confining agent of the magnetic field. Arguments are also presented in favour of a highly complex magnetic geometry on very active stars. Thus the very large starspots seen in Doppler images probably are conglomerates of smaller (but possibly still sizable) spots.

1. Introduction

On the surface of the sun, and from all evidence also on other late-type stars, most of the magnetic energy is stored within discrete features best described by flux tubes: A flux tube is a set of field lines bounded by a topologically simple surface generally modelled by a current sheet. The flux tubes we see on the sun and expect to see on stars are such bundles of field lines passing more or less vertically through the solar surface. The release of part of the stored magnetic energy leads to coronal heating and to flares. Flux tubes also channel energy into the upper atmosphere in the form of waves and hence lie at the heart of stellar magnetic activity. In the context of these proceedings flux tubes count among the main causes of surface structure on cool stars. Large flux tubes give rise to sun- or

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starspots (complex structures with a dark, inner umbra and a less dark, outer penumbra), intermediate sized flux tubes show up as pores (naked umbrae), and small flux tubes appear as bright magnetic elements forming faculae (or plages in chromospheric layers).

Flux tubes can have a complex internal structure and are described by a whole row of different physical parameters. Here I consider only three basic parameters: size, magnetic field strength and brightness (or, equivalently, temperature). Note that each parameter is a strong function of height and the last two also depend on horizontal position inside the flux tube, at least for the larger ones.

Since it is only on the sun that we have *direct* evidence that magnetic fields exist in the form of flux tubes and that these play such a dominant role, a substantial part of this paper will be devoted to solar flux tubes.

2. Flux Tube Sizes

On the sun magnetic flux tubes come in a great variety of sizes ranging from small magnetic elements at (and in many cases probably below) the measurement threshold of ≈ 200 km (e.g. Keller 1992) to the largest sunspots with equivalent diameters of approximately 80'000 km (e.g. Brants & Zwaan 1982). Thus flux-tube areas cover a range of more than 5 orders of magnitude. The range of sizes often increases with the level of solar activity, so that by analogy we expect more active stars to have a greater range of sizes. Starspots larger than the largest sunspots are expected on more active stars; their presence is indicated by light-curve variations and Doppler imaging. The solar analogy suggests, however, that small flux tubes forming plages are also present on such stars.

At any given time there are always many more small flux tubes than large flux tubes on the solar surface. Bogdan et al. (1988) found the distribution of sunspot *umbral* areas shown in Fig. 1. Note that the area of the complete sunspot (umbra plus penumbra) is usually 3 to 5 times larger than the umbral area. The points not coincident with the fit were thought to be unreliable in the measurements and were not considered further by these authors. The data points are well fit by a log-normal distribution. The relative number of small sunspots decreases again below some critical size, because smaller flux tubes appear as pores or magnetic elements. Nevertheless, the number of small flux tubes keeps increasing with decreasing size (but see Wang et al. 1995). So far no firm evidence for a lower limit to flux tube size exists although there are observational indications that below a certain size the physical nature of solar flux tubes changes.

In a solar active region the ratio of the area covered by large relative to that covered by small flux tubes is a strong function of the total magnetic

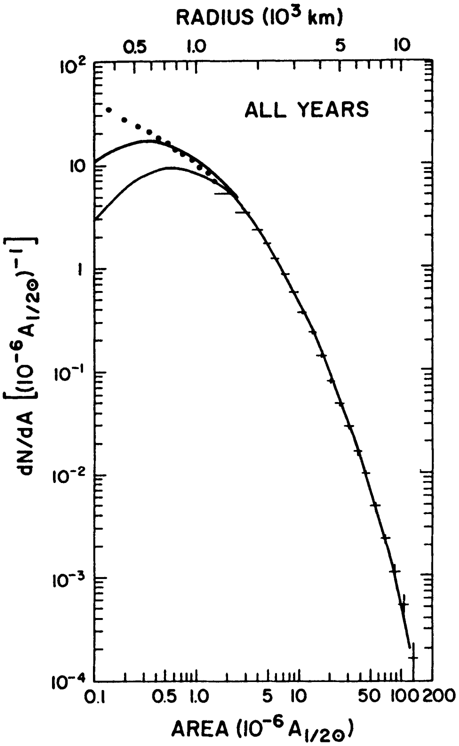

Figure 1. Observed size spectrum of sunspot umbrae for a set of 24615 umbrae (crosses). In addition, physically meaningless, smaller sizes are also plotted (filled circles; meaningless due to the similarity of the size to the spatial resolution of the observations). Two log-normal fits (upper and lower limits) are also shown (from Bogdan et al. 1988 by permission).

flux or plage area, as shown in Fig. 2, which is based on a table by Foukal et al. (1996); cf. Foukal (1993). This ratio, a measure of the number of large flux tubes relative to small, increases rapidly with increasing size of the active region. If we extrapolate this empirical relationship linearly, then we find that already for active regions covering only 3% of a solar, respectively stellar hemisphere the spot area should become comparable to the plage area.[1] This implies that the *average size* of flux tubes increases with increasing magnetic flux emerging on the solar surface in a localized area. The size of an active region is a measure of the magnetic flux transported to the surface by the large underlying flux tube produced by the solar/stellar

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[1] Given the notorious uncertainty of extrapolations it appears wise to warn that a linear function may not be appropriate. It does, however, possess the enticing advantage of simplicity.

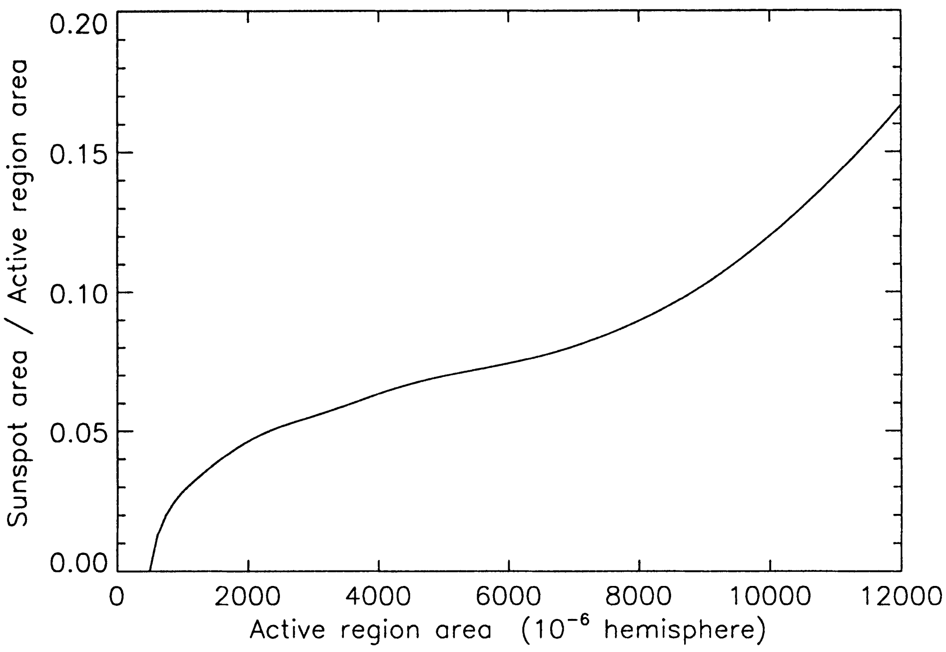

Figure 2. **Ratio of the surface area within an active region covered by sunspots relative to the total area of the active region vs. the total active region area.**

dynamo located at the base of the convection zone. MHD calculations (e.g. Schüssler et al. 1996) suggest that for the more rapidly rotating and active stars the flux tubes can carry much larger amounts of magnetic flux to the stellar surface from the overshoot layer than their solar counterparts, so that the active regions on these stars should be much larger too. An extrapolation of Fig. 2 implies that on these stars the area covered by starspots may approach or exceed that covered by faculae.

The average flux-tube size also appears to increase with increasing magnetic filling factor (Grossmann-Doerth et al. 1994, compare also the results of Spruit & Zwaan 1981 with those of Muller & Keil 1983).

It has been suggested that due to the interchange instability the range of flux-tube sizes may not be continuous (Parker 1975; Meyer et al. 1977; Schüssler 1984). Consequently fewer flux tubes may be present in an intermediate size range of a few hundred km, although whirl flows may be able to stabilize all flux tubes (Bünte et al. 1993). The stellar implications of this instability have been investigated by Bünte & Saar (1993).

3. Magnetic Fields

Measurements of magnetic fields in solar magnetic flux tubes received a tremendous boost from recent advances in IR detector technology. Field strengths can now be measured with relative accuracies of 2% using 1.56 μm lines (e.g. Rüedi et al. 1992). Consider first smaller flux tubes, i.e. magnetic elements. In active regions we find that most of the flux is in the form of kG flux tubes, with a small amount of flux in weaker-field elements (Rüedi et al. 1992; Rabin 1992a,b; see Solanki 1993, 1995; Stenflo 1994 for an overview). For a given magnetic filling factor (larger than some minimum value) the field strength appears to be almost unique. The magnetic filling factor represents the magnetic-field covered fraction of the surface within the observational spatial resolution element. The rest of the resolution element is generally thought to be field-free. For very small filling factors, i.e. principally in the quiet sun, a substantial amount of the flux appears to reside in intrinsically weaker fields (Keller et al. 1995; Solanki et al. 1996).

Little is known about the internal magnetic structure of elements, although there is observational evidence that it may be rather simple (Zayer et al. 1989; Rüedi et al. 1992). Sunspots by contrast show both large- and small-scale internal structure of magnetic field strength (cf. Thomas & Weiss 1992). The main trend is for the field strength to decrease from its maximum value in the darkest part of the umbra (2000–3600 G) to the outer edge of the penumbra, where it lies between 700–1000 G (e.g., Adam 1990; Lites & Skumanich 1990; McPherson et al. 1992; Solanki et al. 1992; Lites et al. 1993). The maximum umbral field strength increases with increasing umbral size (e.g., Brants & Zwaan 1982; Kopp & Rabin 1992), but little is known about the size dependence of the field strength at the sunspot boundary. The field strength averaged over the whole sunspot, i.e. over the whole flux tube is relatively independent of size, being roughly 1200–1700 G. Since it is basically this quantity which is measured in magnetic elements we find, surprisingly perhaps, that solar magnetic flux tubes all have approximately the same measured field strengths (Solanki & Schmidt 1993). This equality is not as yet understood, so that we cannot apply it to non-solar cool stars without caution. It may, however, be a helpful tool for roughly estimating the amount of magnetic flux on active cool stars.

The theory of magnetic fields in flux tubes must explain different facets. Firstly, the field must be confined. On the sun the main confining force is provided by horizontal pressure gradients created by the partial evacuation of the flux tubes. If p_e is the external gas pressure, p_i the pressure within the flux tube and B the internal field strength, then

$$B^2/8\pi = p_e - p_i$$

must be satisfied at every height z. Typically $p_e/p_i \approx 4$ for small solar flux tubes in their photospheric layers, so that the ratio $8\pi p_i/B^2$, the so-called plasma β, is approximately 1/3. Since the gas pressure drops roughly exponentially with height, z, the field strength must also decrease with height. The conservation of magnetic flux thus forces the flux tube to expand with height, with its cross-sectional area varying as $1/B(z)$. The lower gas pressure within flux tubes implies that optical depth unity is reached at a deeper level than in the field-free gas. In sunspots this height difference, called the Wilson depression, is directly measurable.

Secondly, some process must concentrate the magnetic field to the high observed value after its emergence from the solar interior, since both observed and theoretically predicted field strengths at emergence lie well below the values observed in mature, stable flux tubes (see, e.g., Brants 1985; Moreno Insertis 1992). The required magnetic field concentration is produced by the convective instability acting in the initially weak-field magnetic feature. In simple terms a convective downflow within a weak-field feature partially evacuates it, thus lowering the gas pressure, which in turn causes gas to flow horizontally towards the features. The converging gas flow carries the embedded magnetic field lines with it, leading to an enhancement of the field (Parker 1978; Roberts & Webb 1978; Spruit 1979; Spruit & Zweibel 1979; Hasan 1984,1985). Recently the first comprehensive 2-D simulations of a convective collapse have been carried out (Steiner 1995), which confirm the simple 1-D prediction. Direct observational confirmation is still missing, however.

Can we extrapolate from the sun to other late-type stars? One easily determined quantity is the maximum field strength that can be confined by gas pressure at a given height, say the $\tau = 1$ level: $B_0 = \sqrt{8\pi p_e}$. Bünte & Saar (1993) determined the T_{eff} and $\log g$ dependence of B_0 shown in Fig. 3 for Kurucz (1991) models with 3500 K $\leq T_{\text{eff}} \leq$ 7000 K and $0.5 \leq \log g \leq 5.0$ (where T_{eff} is the effective temperature and g is gravitational acceleration). The inclination of the $B_0(T_{\text{eff}}, g)$ surface can be understood from the following considerations. As T_{eff} is lowered the main source of continuum opacity (due to the H^- ion) decreases. Consequently we see deeper layers with larger pressures, so that B_0 increases with decreasing temperature. As g is lowered we see less deep into the atmosphere: as the density scale height increases, both the geometrical and optical paths that light must traverse from a given pressure level to the observer increase. This

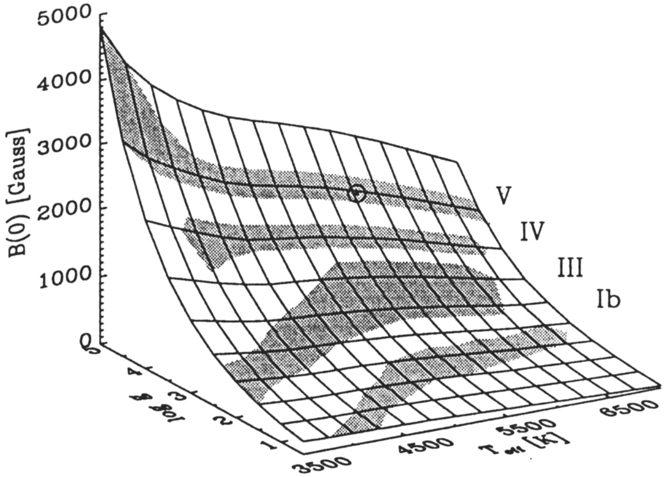

Figure 3. **The maximum surface magnetic field strength $B(0) = \sqrt{8\pi p_e(\tau^e_{5000} = 1)}$ (where τ^e_{5000} is the continuum optical depth at 5000Å in the external atmosphere) as a function of $\log g$ (= logarithmic gravitational acceleration) and $T_{\rm eff}$ (= effective temperature). Approximate positions of various stellar luminosity classes are shaded; ⊙ indicates the position of the sun. (From Bünte & Saar 1993 by permission).**

implies that the gas pressure and thereby B_0 at the $\tau = 1$ level decreases with decreasing g. One should not forget, however, that Fig. 3 can only be used as a rough indicator of the actual field strength of stellar flux tubes for the following reasons:

1. Figure 3 is based on the assumption of complete evacuation, whereas the true amount of evacuation depends on the efficiency of the convective collapse mechanism, which is not known for stars other than the sun. It depends on the superadiabaticity and the efficiency of radiative cooling. Further theoretical work is needed to estimate the expected field strengths. The assumption of complete evacuation may not be too bad for many dwarfs, as suggested by stellar magnetic field measurements based on the splitting of the unpolarized line profile (reviews by, e.g., Saar 1990, 1994; Solanki 1992), although infrared observations (e.g., Valenti et al. 1995; Saar & Linsky 1985; Saar 1996) are needed to reliably determine the field strengths (e.g., Rüedi et al. 1996).
2. For stars of luminosity classes I–III the kinetic energy density derived from measured macroturbulence velocities (Gray 1988, 1992) can become comparable to the internal energy density of the gas (represented by p_e). Thus the maximum achievable field strength is larger than indi-

cated by Fig. 4 for such stars. In Table 1 we list for $T_{\rm eff} = 5750$ K stars of luminosity classes Ib–V the maximum field strength due to pressure balance, $B_0 = \sqrt{8\pi p_0}$, and due to confinement by both pressure and kinetic forces $B_* = \sqrt{8\pi(p_0 + \rho_0 \cdot \xi_{\rm RT}^2/2)}$, where ρ_0 is the density at the stellar surface and $\xi_{\rm RT}$ is the radial-tangential turbulence velocity (Gray 1975). The ratio of the total energy in the magnetic field confined in these different manners, $(B_*/B_0)^2$, is also tabulated. As the table shows half or more of the magnetic energy density in flux tubes on giants and supergiants may be due to the confining effects of flows. Note, however, that magnetic fields confined dominantly by flows may well have rather different properties than gas-pressure confined flux tubes, e.g. lifetimes, height variations of the field strength, thermal structure (i.e. brightness) and the ability to produce a corona.

TABLE 1. Maximum field strengths on stars with $T_{\rm eff} = 5780$ K

Luminosity class	B_0 (G)	B_* (G)	$(B_*/B_0)^2$
Ib	310	530	2.9
II	450	680	2.3
III	640–910	830–1180	1.7
IV	1290	1510	1.3
V	1800	1910	1.1

Before moving on to discuss the thermal properties of flux tubes let me briefly present some thoughts on the Zeeman Doppler images (ZDI) of HR 1099 presented by Donati (1996). His ZDI are considerably more inhomogeneous than his (brightness) Doppler images, with various relatively small scale and complex features having radial (i.e. vertical), but also more horizontal fields. In addition, his spatially averaged field strengths are generally well below 400 G, even in starspots.

In order to interpret these observational results recall the magnetic structure of the Sun, which is also extremely inhomogeneous, with opposite polarities distributed over the solar surface at a rather fine scale.

Comparing this with Donati's ZDI suggests that the solar analogy of a complex field topology may not be too bad for HR 1099. Since ZDI can only resolve relatively homogeneous patches of magnetic field above a certain size this star may well have considerably more field than shown

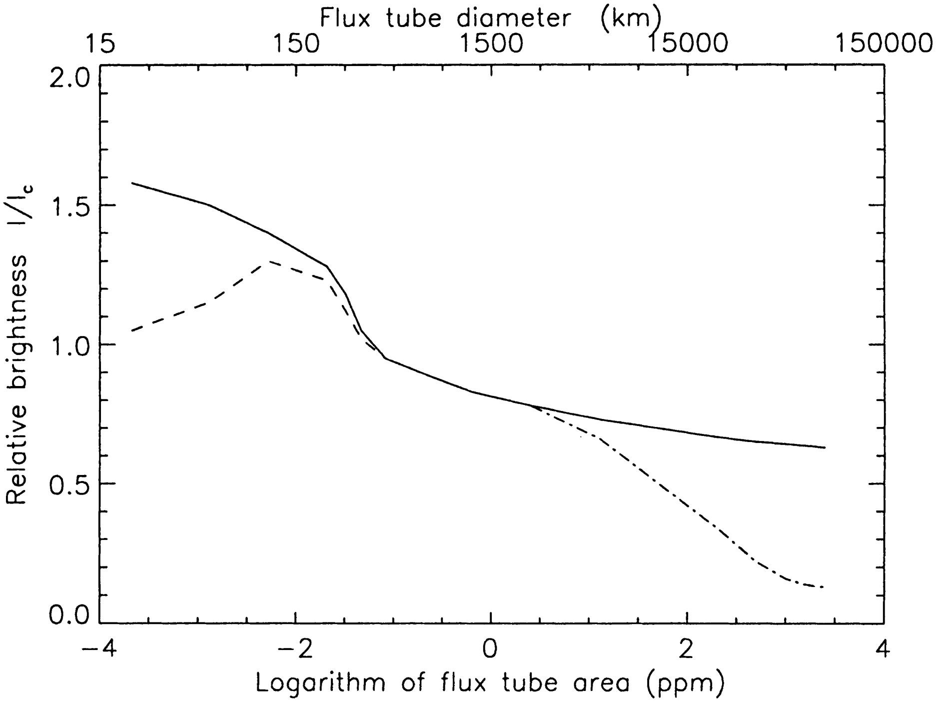

Figure 4. White-light brightness of magnetic features I_m relative to the brightness of the quiet sun I_{qs} vs. the (logarithmic) area of magnetic features in 10^{-6} times the solar hemispheric area (lower axis) and their diameter (upper axis). The solid line represents the brightness averaged over the whole (strong-field) flux tube (including over the umbra and penumbra for sunspots). The dot-dashed line represents the brightness of the umbra only. Finally, the dashed curve shows my estimate of I_m/I_{qs} for the weakest-field small flux tubes. Note that a range of I_m/I_{qs} values is present for a given flux-tube size.

by ZDI. Recall that Zeeman Doppler imaging is only sensitive to the *net* longitudinal magnetic flux.

By just scaling the field strength from the solar case I expect $B \approx 800 - 1200$ G for a K0 IV star like HR 1099. On another RS CVn primary, II Peg, Saar (1996) found a field of 3000 G covering 50% of the star. Both values are considerably larger than the field strength in the ZDI. Due to cancelling polarities (in Stokes V) ZDI may well give low magnetic fluxes. In addition, if magnetic features are not spatially resolved the field strength in ZDI's is lower than the true value.

In summary, the comparison of Doppler and Zeeman Doppler images suggests that the large reconstructed spots are probably not monolithic, with the sub-spots having different polarities, a range of field strengths and field inclinations, as in sunspot penumbrae.

Finally, a word of caution: In contrast to normal Doppler Imaging which maps the 2-D distribution of brightness on the basis of time series of the intensity distribution (i.e. a two-dimensional data set), Zeeman Doppler imaging attempts to map the distribution of all three components of the magnetic vector across the stellar surface (i.e. a six-dimensional data set) based on the time series of the Stokes V spectrum (also only a two-dimensional data set). It must as yet be demonstrated if there is enough information in Stokes V time series to uniquely reconstruct highly complex magnetic distributions (cf. Brown et al. 1991).

4. Thermal properties

Similar field strength they may have, but small flux tubes differ significantly from their larger counterparts in their thermal behaviour. Magnetic elements are bright, while sunspots are dark. Giving an exact value to the brightness of flux tubes is difficult, however, since observers often quote widely different brightnesses. Measured brightnesses depend critically on the wavelength and spatial resolution of the observations and on the spatial location of the observed feature (see Solanki 1994 for a detailed discussion). Nevertheless, I have attempted to merge the various observations into an overview plotted in Fig. 4. A similar, but simpler diagram was presented by Stenflo (1977).

There are diverging views among researchers regarding the brightness of magnetic elements. E.g. Title et al. (1992) and Topka et al. (1992) find that at disk centre even small flux tubes are dark, while Koutchmy (1977), at the other extreme, claims that they are twice as bright as the field-free photosphere. Figure 4 keeps to middle ground following, e.g., Spruit & Zwaan (1979), Muller & Keil (1983), Keller (1992), Solanki & Brigljević (1992), Grossmann-Doerth et al. (1994); cf. Solanki (1993). The two curves in the left part of the figure reflect some of the uncertainty in the measured (and theoretically predicted) value — the brightness of individual magnetic elements may even fluctuate significantly with time (Muller 1977; Steiner et al. 1995). In the right part of the figure the brightness of sunspots is also represented by two curves. The lower curve indicates umbral brightness, while the upper curve shows the mean brightness of the whole sunspot, i.e. an area-weighted mean over the brightness of the umbra and the penumbra. The brightness values of pores in Fig. 4 have been adapted from Spruit & Zwaan (1981) and Grossmann-Doerth et al. (1994, for the crossing point from bright to dark), while the brightness of complete sunspots (averaged over umbra and penumbra) follows the results of Chapman et al. (1994), among others. Finally, the plotted umbral brightness is based on data from Collados et al. (1994), Maltby et al. (1986; cf. Albregtsen & Maltby 1978, 1981), Stellmacher & Wiehr (1988), Sobotka (1988) Sobotka et al. (1993).

Why are magnetic elements bright, while pores and sunspots are dark? The continuum brightness of a magnetic feature is determined by two effects; firstly, how well the magnetic field suppresses convective energy transport in the immediate subsurface layers and, secondly how effective radiative transfer is in heating up the flux-tube interior. Relative to the situation in a plane-parallel atmosphere there is a heightened inflow of radiation into the evacuated flux tube through its walls. Recall that due to its decreased gas pressure we see deeper layers within a flux tube (Wilson depression), layers in which the ambient medium is considerably hotter than at its surface. For the heating by inflowing radiation from the walls to be effective the flux tube must be slender. For an extremely slender, horizontally optically thin flux tube, the internal temperature equals the external temperature at equal *geometrical* height. Since the temperature increases very rapidly with depth, such tubes are hotter than the quiet sun at equal *optical* depth. They appear brighter since we see deeper, hotter layers within them.

As the flux-tube diameter increases it becomes increasingly optically thick to the radiation flowing in from the walls. This radiation can no longer heat the flux tube to the ambient temperature, so that it is cooler than the surroundings at equal *geometrical* height. If the flux tube is not too large, it may nevertheless be hotter than the surroundings at equal *optical* depth and thus still appear bright. As the size of the magnetic feature increases further the radiative heating continues to decrease in effectiveness until the flux tube is cooler than its surroundings even at equal optical depth and thus appears dark, like a pore. The largest (solar) flux tubes in addition possess a penumbra and a sunspot results.

The above, highly qualitative statements explain the rough general trend of Fig. 5. They do not, however, explain why we expect the brightness to decrease again with decreasing diameter for the smallest magnetic features, nor do they explain the formation of penumbrae in large flux tubes, a process which is still not well understood.

The expected decrease in brightness at very small flux-tube sizes has to do with the expected decrease in efficiency of the convective collapse mechanism for small amounts of magnetic flux (Venkatakrishnan 1986). Thus the field strengths are expected to be smaller than of larger flux tubes, so that the small flux tubes $\tau = 1$ layer lies correspondingly closer to the respective quiet sun layer, i.e. their Wilson depressions are small. Consequently, weak-field flux tubes are not expected to be much hotter or brighter than the quiet solar surface (and if they are situated in dark intergranular lanes may even be darker than the average quiet sun).

The continuing decrease in total sunspot brightness with increasing sunspot size has two main causes. Firstly, on average the ratio of umbral to penumbral area appears to change with sunspot size, although the scatter is as large as the trend. Secondly, at least for sunspots up to a diameter of 25 000–30 000 km the umbral brightness decreases with increasing size, as can be seen from the lower curve in Fig. 4.

It is clear from a comparison of the two curves that the importance of the penumbra for the total brightness of sunspots (and presumably starspots) cannot be overestimated. Although the temperature contrast between sunspot umbrae and the quiet sun reaches 2500 K for the largest and coolest umbrae, it corresponds to only 700-800 K for even the largest sunspots as a whole.[2]

Finally, I wish to briefly return to the trend plotted in Fig. 2. It suggests that as active regions become larger, i.e. stars become more active, the weight shifts from small bright flux tubes to large dark ones. For the total brightness this implies that whereas the sun is brighter at its activity maximum (Willson & Hudson 1988, 1991; Hickey et al. 1988; Hoyt et al. 1992), more active stars show the opposite trend (Radick et al. 1990).

5. Conclusions

The magnetic field on the sun and on most other late-type stars is concentrated into flux tubes ranging from small and bright magnetic elements to large and dark sun- or starspots. Although the maximum field strength in a flux tube depends significantly on its size, the field strength averaged over the whole flux tube is nearly the same for almost all solar magnetic features. This may by analogy also be true for other stars. The absolute values of the field strength inside flux tubes, however, are expected to be quite different from star to star since they depend on $T_{\rm eff}$ and $\log g$. For main-sequence stars and subgiants horizontal gas pressure gradients are expected to provide the dominant confining force, while in giants and supergiants the kinetic energy of the turbulent gas may play an important if not dominating role. The ZDI images of Donati (1996) imply that the magnetic field on the rapidly rotating K0 IV primary of HR 1099 has a complex geometry and that the large polar spot of this star is not monolithic.

In contrast to the field strength the brightness, i.e. temperature, of magnetic flux tubes depends strongly on their size, with small flux tubes being bright and large flux tubes dark. Again, however, the difference between the brightest parts of small flux tubes and the darkest parts of large flux tubes is much greater than the difference between the various flux tubes

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[2] I have neglected possible variations of the umbral brightness with the solar cycle proposed by Albregtsen & Maltby (1978).

when the brightness averaged over the whole flux tube is considered. The fraction of the surface area of a solar active region covered by sunspots increases with the size of the active region. Extrapolating to active regions larger than those found on the sun, as are theoretically predicted on more rapidly rotating stars, we expect starspots to dominate the light curve variations, as is observed. This suggests that extrapolations from the sun may often be acceptable approximations for the stellar case. It is always of advantage, however, to employ physical insight as a guide when carrying out such extrapolations.

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References

Adam M.G., 1990, *Solar Phys.* **125**, 37
Albregtsen F., Maltby P., 1978, *Nature* **274**, 41
Albregtsen F., Maltby P., 1981, *Solar Phys.* **71**, 269
Bogdan T.J., Gilman P.A., Lerche I., Howard R., 1988, *Astrophys. J.* **327**, 451
Brants J.J., 1985, *Solar Phys.* **98**, 197
Brants J.J., Zwaan C., 1982, *Solar Phys.* **80**, 251
Brown S.F., Donati J.-F., Rees D.E., Semel M., 1991, *Astron. Astrophys.* **250**, 463
Bünte M., Steiner O., Pizzo V., 1993, *Astron. Astrophys.* **268**, 299
Bünte M., Saar S.H., 1993, *Astron. Astrophys.* **271**, 167
Chapman G.A, Cookson A.M., Dobias J.J., 1994, *Astrophys. J.* **432**, 403
Collados M., Martínez Pillet V., Ruiz Cobo B., del Toro Iniesta J.C., Vázquez M., 1994, *Astron. Astrophys.* **291**, 622
Donati J.-C., 1996, these proceedings

Foukal P., 1993, *Solar Phys.* **148**, 219
Foukal P., Solanki S.K., Zirker J., 1996, in *Astrophysical Quantities, 4th Ed.*, C.W. Allen, A.N. Cox (Eds.), Athlone Press, in press
Gray D.F., 1975, *Astrophys. J.* **202**, 148
Gray D.F., 1988, *Lectures on Spectral-Line Analysis: F, G, and K Stars*, The Publisher, Arva, Ontario
Gray D.F., 1992, *The Observation and Analysis of Stellar Photospheres*, Cambridge University Press, Cambridge
Grossmann-Doerth U., Knölker, M., Schüssler M., Solanki S.K., 1994, *Astron. Astrophys.* **285** 648
Hasan S.S., 1984, *Astrophys. J.* **285**, 851
Hasan S.S., 1985, *Astron. Astrophys.* **143**, 39
Hickey J.R., Alton B.M., Kyle H.L., Hoyt D., 1988, *Space Sci. Rev.* **48**, 321
Hoyt D.V., Kyle H.L., Hickey J.R., Maschhoff R.H., 1992, *J. Geophys. Res.* **97**, 51
Keller C.U., 1992, *Nature* **359**, 307
Keller C.U., Deubner F.-L., Egger U., Fleck B., Povel H.P., 1994, *Astron. Astrophys.* **286**, 626
Kopp G., Rabin D., 1992, *Solar Phys.* **141**, 253

Koutchmy S., 1977, *Astron. Astrophys.* **61**, 397

Kurucz R.L., 1991, in *Precision Photometry: Astrophysics of the Galaxy*, A.G. Davis Philip, A.R. Upgren, K.A. Janes (Eds.), L. Davis Press, Schenectady

Lites B.W., Skumanich A., 1990, *Astrophys. J.* **348**, 747

Lites B.W., Elmore D.F., Seagraves P., Skumanich A., 1993, *Astrophys. J.* **418**, 928

Maltby P., Avrett E.H., Carlsson M., Kjeldseth-Moe O., Kurucz R.L., Loeser R., 1986, *Astrophys. J.* **306**, 284

McPherson M.R., Lin H., Kuhn J.R., 1992, *Solar Phys.* **139**, 255

Meyer E., Schmidt H.U., Weiss N.O., 1977, *Monthly Notices Royal Astron. Soc.* **179**, 741

Moreno Insertis F., 1992, in *Theory of Sunspots*, J.H. Thomas, N. Weiss Cambridge University Press, p. 385 (Eds.),

Muller R., 1983, *Solar Phys.* **85**, 113

Muller R., Keil S.L., 1983, *Solar Phys.* **87**, 243

Parker E.N., 1975, *Solar Phys.* **40**, 291

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

Rabin D., 1992a, *Astrophys. J.* **390**, L103

Rabin D., 1992b, *Astrophys. J.* **391**, 832

Radick R.R., Lockwood G.W., Baliunas S.L., 1990, *Science* **247**, 39

Roberts B., Webb A.R., 1978, *Solar Phys.* **56**, 5

Rüedi I., Solanki S.K., Livingston W., Stenflo, J.O., 1992, *Astron. Astrophys.* **263**, 323

Rüedi I., Solanki S.K., Mathys G., Saar S.H., 1996, *Astron. Astrophys.* to be submitted

Saar S.H., 1990, in *Solar Photosphere: Structure, Convection and Magnetic Fields*, J.O. Stenflo (Ed.), Kluwer, Dordrecht, *IAU Symp.* **138**, 427

Saar S.H., 1994, in *Cool Stars, Stellar Systems and the Sun, VIII*, J.-P. Caillault (Ed.), Astron. Soc. Pacific Conf. Ser., Vol. 64, p. 319

Saar S.H., 1996, these proceedings

Saar S.H., Linsky J.L., 1985, *Astrophys. J.* **299**, L47

Schüssler M., 1984, *Astron. Astrophys.* **140**, 453

Schüssler M., Caligari P., Ferriz Mas A., Solanki S.K., Stix M., 1996, *Astron. Astrophys.* submitted

Sobotka M., 1988, *Bull. Astron. Inst. Czechosl.* **39**, 236

Sobotka M., Bonet J.A., Vázquez M., 1993, *Astrophys. J.* **415**, 832

Solanki S.K., 1993, *Space Sci. Rev.* **61**, 1

Solanki S.K., 1992, in *Cool Stars, Stellar Systems and the Sun, VII*, M.S. Giampapa, J.A. Bookbinder (Eds.), Astron. Soc. Pacific Conf. Ser., Vol. 26, p. 211

Solanki S.K., 1994, in *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, J. Pap, C. Fröhlich, H.S. Hudson, S.K. Solanki (Eds.), Cambridge University Press, Cambridge, *IAU Coll.* **143**, 226

Solanki S.K., 1995, in *Infrared Tools for Solar Astrophysics: What's Next?*, J.R. Kuhn, M.J. Penn (Eds.), World Scientific, Singapore, p. 341

Solanki S.K., Brigljević V., 1992, *Astron. Astrophys.* **262**, L29

Solanki S.K., Schmidt H.U., 1993, *Astron. Astrophys.* **267**, 287

Solanki S.K., Rüedi I., Livingston W., 1992, *Astron. Astrophys.* **263**, 339

Solanki S.K., Zuffrey D., Lin H., Rüedi I.,1996, in preparation

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

Spruit H.C., Zwaan C., 1981, *Solar Phys.* **70**, 207

Spruit H.C., Zweibel E.G., 1979, *Solar Phys.* **62**, 15

Steiner O., 1995, in *Solar and Galactic Magnetic Fields*, D. Schmitt (Ed.), Nachr. der Akad. der Wiss. in Göttingen, Göttingen, in press

Steiner O., Grossmann-Doerth U., Knölker M., Schüssler M., 1995, *Rev. Mod. Astron.* **8**, p. 81

Stellmacher G., Wiehr E., 1988, *Astron. Astrophys.* **191**, 149

Stenflo J.O., 1977, in *The Energy Balance and Hydrodynamics of the Solar Chromosphere and Corona*, R.-M. Bonnet, Ph. Delache (Eds.), G. de Bussac, Clermont-Ferrand, *IAU*

Coll. **36**, p. 143
Stenflo J.O., 1994, *Solar Magnetic Fields: Polarized Radiation Diagnostics*, Kluwer, Dordrecht
Thomas J.H., Weiss N., (Eds.) 1992, *Sunspots: Theory and Observations*, NATO ASI Series, Kluwer, Dordrecht
Title A.M., Topka K.P., Tarbell T.D., Schmidt W., Balke C., Scharmer G., 1992, *Astrophys. J.* **393**, 782
Topka K.P., Tarbell T.D., Title A.M.: 1992, *Astrophys. J.* **396**, 351
Valenti J.A., Marcy G.W., Basri G., 1995, *Astrophys. J.* **439**, 939
Venkatakrishnan P., 1986, *Nature* **322**, 156
Wang J., Wang H., Tang F., Lee J.W., Zirin H., 1995, *Solar Phys.* **160**, 277

Willson R.C., Hudson H.S., 1988, *Nature* **332**, 810
Willson R.C., Hudson H.S., Chapman G.A., 1991, *Nature* **351**, 42
Zayer I., Solanki S.K., Stenflo J.O., 1989, *Astron. Astrophys.* **211**, 463

Marcello Rodonó searches for the next speaker.

Doug Hall explains the size of a typical starspot ...and argues with Klaus Strassmeier on whether we should actually believe this. Mimi Hall (*left*) plays the referee.