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OBSERVATIONAL EVIDENCE OF THE HETEROGENEITIES OF THE STELLAR SURFACES

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HETEROGENEITY OF THE SOLAR ATMOSPHERE

D.J. MULLAN
Bartol Research Foundation of the Franklin Institute
Swarthmore, Pennsylvania, USA

1. Introduction

Heterogeneities in the solar atmosphere exist on many different length scales ranging from values as large as the solar radius ($\sim 10^6$ km) down to features which are identifiable only by interferometry ($\sim 10^2$ km). Rather than simply cataloguing the observed parameters of each and every known type of heterogeneity, I would like to concentrate on a few types of heterogeneities, with a view to identifying the information which is currently available concerning the physical mechanisms responsible for creating the inhomogeneities. It is only if we can first identify the physics of each type of heterogeneity that we can hope to take even the first step towards predicting how each particular heterogeneity should scale to other stars. Since the present session is a joint discussion among mainly stellar astronomers, I feel that this approach is probably the most favorable method to present some of the large amount of information now available on solar features. Of course we expect that our solar information will be of most use to stellar astronomers in interpreting observations of stars which have similar spectral types to the sun. Nevertheless, we hope that nature will be kind enough to allow us to scale at least some of our information over a non-negligible area in the H.R. diagram.

2. Classification of Heterogeneities

There are two broad categories of heterogeneities which are unfortunately not mutually exclusive, but which can at least serve as an initial classification scheme. There is one category associated with hydrodynamic effects: these heterogeneities would probably exist even in the absence of a magnetic field. The second category is associated with effects in a magnetized plasma.

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3. Heterogeneities due to Hydrodynamic Effects

3.1. DIFFERENTIAL ROTATION

The largest scale heterogeneity on the white-light sun is differential rotation. The equator rotates 10-20% faster than the polar regions. Several models have been proposed to explain this observation, including detailed numerical solutions of convection in a deep rotating spherical shell (Gilman, 1974). This type of model is sufficiently complicated that it is not yet obvious which physical parameter one may use to predict the degree of differential rotation on other stars. Some observational evidence for differential rotation on the surfaces of red dwarfs exists, but is not yet conclusive (Vogt, 1975).

3.2. CONVECTION

Heat transfer near the surface of cool stars occurs by convection, and the molecular viscosity of the gas is so small in most cases that it is almost inevitable that the convective flow is turbulent. It is generally believed that granulation on the solar surface is the physical manifestation of turbulent convection cells which happen to lie nearest to the top of the solar convection zone. The cells in quiet regions are in general polygonal during their lifetime, with hot gas rising at the center and cool gas sinking at the edges. The optical contrast between hot and cold gas on white light photographs at disk center is about 15%. Thus these granules are relatively small heterogeneities which, when viewed on a large scale, give the impression of an almost homogeneous solar surface. The velocities involved in the cells are several km/sec near $\tau \simeq 1$.

Convective cell sizes cover a range of values from several hundred km up to 2-3 thousand km, but there is a preference for a mean value of 1-1.5 thousand km. The existence of a preferred cell size has until recently been difficult to understand theoretically. Early attemps to derive growth rates for convective instabilities using linear perturbation analysis showed no preferred cell size. Recently, however, Deupree (1976) has published results of numerical work on non-linear convection, in which he finds that the vertical depth H of the small cells within a convective layer does have a preferred value of about one pressure scale height, H_p, although the depth determination is imprecise. Near the solar surface, the cell depth should therefore be 300-400 km. It has been an assumption of the earlier models of stellar convection that the cell depth should indeed be about one pressure scale height: Deupree's results provide some much-needed support for this assumption.

However, visible granule sizes are horizontal scale sizes, and very little information is currently available on what value to choose

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for the ratio of cell diameter to cell depth, D/H. Deupree's value is 0.8, but he admits that this may be an artifact of his numerical scheme. The classical value at marginal stability is $D/H \simeq 3$, but it is not known whether or not this carries over to conditions at large Rayleigh numbers. If (and this is very uncertain) indeed $D/H \simeq 3$ is valid in stars, then Deupree's results allow us to estimate granulation sizes on other stars: the pressure scale height is the relevant parameter. Another relevant parameter might be the vertical extent of the subphotosphere region with high superadiabatic temperature gradient. In either case, granules on dwarf stars will be small features, as in the sun. They will not be detectable photometrically, although their contribution to spectral line profiles may limit the accuracy with which the radial velocity of a star may be measured, unless one chooses a spectral line which is formed sufficiently high in the atmosphere to be above the convection zone (Dravins, 1975). On the other hand, on giants and supergiants, Schwarzschild (1975) has shown that individual granules might indeed be detectable. However, it is worth reiterating that the assumption of $D/H=3$ which enters this result is quite uncertain, and even $H=H_p$ is by no means a result of complete certainty at the present time.

Whatever can be said about the mean sizes of granules, there appears to be a theoretical lower limit on the expected horizontal size of convection cells, set by the existence of molecular viscosity. This limit is $\lambda_m \sim 200$ km at $\tau \leqslant 1$ in the sun (Spiegel, 1966). This lower limit coincides with the smallest scales observed, and unless this is an effect of limited observational resolution, this result provides a physical basis for estimating minimum granule sizes in other stars.

3.3. SUPERGRANULES

There is a preferred scale size of supergranules of order 30 thousand km on the sun, with a velocity pattern reminiscent of cellular convection. This may be a convective cell pattern associated with a vertical cell depth of order $(1\text{-}5)\times10^4$ km. It is not at present clear why a depth of $(1\text{-}5)\times10^4$ km should be preferred, although suggestions have been made that an opacity maximum, or helium ionization, or the bottom of the convection zone, are involved. A recent suggestion by Gough et al. (1976) is that just as molecular viscosity imposes a lower limit on the scale size of small-scale convection near the upper boundary of the convection zone, so eddy viscosity may impose a lower limit on the larger scales of convection. Gough et al.(1976) use the kinematic eddy viscosity in a solar model to estimate that large scale convection in the sun should be cut off at scales less than 20 or 30 thousand km. This indeed agrees with the lower limit of observed supergranule diameters. Thus this suggestion may provide a method of scaling supergranule minimum sizes to the surfaces of other stars.

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Unfortunately, the assumption that supergranules are a direct convective process is not confirmed at the present time. Any existing temperature differential between rising gas at the center of the cell, and sinking gas at supergranule boundaries, is masked by magnetic heating effects. The general temperature structure over a supergranule cell is not apparently appropriate to convective energy transport (Worden, 1975). It seems permissible to conclude that almost no solar flux is carried by supergranules, and so the regions where supergranules carry the bulk of solar flux must lie far below the photosphere (if such regions do in fact exist at all). This uncertainty in understanding the observed physical properties of supergranules means that there is essentially no reliable way at the present time to scale supergranule sizes at the surface of the sun to supergranule sizes on other stars.

3.4. HEIGHT DEPENDENCE

Still considering hydrodynamic effects, we must realize that the sizes of the heterogeneities quoted above refer to a particular depth in the atmosphere, $\tau = 1$. Granulation cells are not visible higher in the atmosphere than $\tau \simeq 0.1$, which means that although convective overshoot must occur, the fraction of flux carried at $\tau \leqslant 0.1$ is quite small. Overshoot does, however, occur, and the question arises how does the scale size of the granulation pattern vary with height? We might try to get information on this by probing the atmosphere at different wavelengths λ to reach optical depth $\tau_\lambda = 1$, since penetration into the atmosphere varies with λ. At a wavelength of 350μ, we see above the temperature minimum, and at that level, some 500 km above the photosphere, studies of center to limb variations (Lindsey and Hudson, 1976) indicate that heterogeneities are indeed present in the solar atmosphere, with both vertical and horizontal scale sizes of order 1500 km. Thus the vertical scale size is several times larger than that of the photospheric granules. The vertical scale of roughness in the solar atmosphere must increase strongly with altitude: the chromosphere has a much rougher surface than the photosphere.

In the ultraviolet, we can also probe the high layers of the atmosphere, near the temperature minimum using continuum observations at about 1650 Å. An NRL rocket group has found (Brueckner and Bartoe, 1976) that the brightness temperature at this level of the atmosphere varies between 4200^{0}K and 4800^{0}K at different parts of the surface. There are differences in intensity by a factor of almost 2 between the brightest and the darkest features (excluding sunspots). The heterogeneities have sizes of 1"-2" which are comparable to the sizes deduced from infrared observations. However, these features are not associated with convective overshoot, for, contrary to the situation in the photospheric granulation, the brightest gas is moving downward towards the sun, rather than upwards. The downward flow is funnelled in such a way that heterogeneities which are only 1"-2" in diameter

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at the temperature minimum, spread out to 2"-5" in the transition zone. This is due to magnetic field effects, and now we may turn our attention to heterogeneities caused by the presence of a magnetic field.

4. Heterogeneities due to Magnetic Effects

4.1. GENERAL

The occurrence of turbulent cyclonic convection in a differentially rotating star almost inevitably leads to the generation of magnetic fields. In theories of the solar dynamo, the solar field is usually calculated as a dipole or a quadrupole field (Stix, 1976), and there certainly is a general magnetic field of the sun which causes heterogeneities on a large scale (order of 1 solar radius) in the corona. This large scale general field has a period of 22 years, but scaling this period to other stars is currently a very uncertain art on account of the complexity of dynamo models.

Besides the general field, there are more intense fields, confined locally in features which are small compared with the solar radius. There are large areas of somewhat enhanced field, called active regions, with areas up to a few percent of a hemisphere, and with mean fields of order 100 gauss. Within these large areas, there are large numbers of small compact flux tubes, no more than 100-300 km across, where the field may exceed 2000 gauss. These tight bundles of strong field (which also exist outside active regions, but with smaller number densities) may be the sites of strongly convergent gas motions, and much theoretical work is currently being devoted to understanding how such compact flux tubes are created by the small-scale convective circulation. Viewing the sun as a star, there may be a chance of discovering features analogous to the active regions on other stars, but there is no chance of being able to discover the analog of the small compact flux tubes. In the present discussion therefore, which is directed mainly to stellar astronomy, I will confine my attention to the larger scale magnetic heterogeneities.

The horizontal scale sizes of active regions are probably determined by the diameter of a magnetic flux rope, but other effects may also be important. Supergranules may play a role. Perhaps the depth of the convection zone H_c is important. If the latter is true then stars with convection zones having depths of an appreciable fraction of the stellar radius would be prime candidates for looking for active regions. But we again stress that it is not clear why solar active regions have a certain size. Also we must ask what causes the mean field to be about 100 gauss? The answer is not clear, Parker (1975) suggests that it is an effect of magnetic buoyancy: if the field gets larger than about 100 gauss, then buoyancy carries the

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flux tube up through the convection zone so fast that there is not enough time to allow local amplification of the weaker general dipole field of the star. Moreover, Parker suggests that the place where the dynamo field is being generated is in the very lowest levels of the convection zone. Therefore, if Parker's suggestions are correct, in order to scale to other stars, we will need to know the structure of the deepest layers of the convection zones.

4.2. WHITE LIGHT FACULAE

The field strength now becomes one extra parameter which must be known before we can scale reliably from solar results to stellar conditions.

The interactions between magnetic flux and the gas and the radiation field are complex. Effects of a field depend on the altitude in the atmosphere at which one observes. At the photosphere the effect of a field is such that at small fluxes, the localized magnetic areas are brighter than normal (white light faculae), while at large fluxes, the localized magnetic areas are darker than normal (sunspots). White light faculae are local heatings in the upper photosphere, visible at optical wavelengths with greatest contrast (60% brighter than normal) near the limb and <10% contrast at disk center. They cover up to 0.5% of the solar surface at solar maximum, but it is not clear what types of magnetic structures they are associated with. Perhaps they are associated with lateral heat influx into small magnetic flux tubes (Spruit, 1976). Perhaps they are associated with closed field loops confined close to the surface, where hydromagnetic waves are trapped and dissipate. The non-thermal flux required to power the white light faculae may be very high, perhaps some 30% of the entire thermal flux passing outward through the surface (Wilson, 1971). Despite this large flux, the faculae are not spectacular heterogeneities because the energy is dumped too low down in the atmosphere. If there are white light faculae on other stars, then in order to predict brightness contrasts we may need to know the diameters of flux tubes, or the heights of closed magnetic loops on the surface of the stars (perhaps related to a granule scale size), and also the efficiency of conversion of thermal to mechanical flux. None of these quantities is known with any certainty at the present time.

4.3. SUNSPOTS

Sunspots are the most obvious heterogeneities on the white light photospheric surface. They can occupy areas up to 0.1% of the solar hemisphere, and can have effective temperatures of 4000^0K and lower, with flux deficits of 80% of the normal flux. Fields at the spot surface are usually almost vertical and have strengths in excess of 1200-1400 gauss and very few (<5%) have fields greater than 3000 gauss,

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according to current investigations. Little evidence is currently available about depth-dependence of the field strengths. It is remarkable that field strengths in spots are on the whole confined to within such a narrow range (factor of 2). Why such field strengths are preferred is not certainly known, although the kinetic energy density in models of the deep solar convection zone is roughly equivalent to the magnetic energy density of a 2000 gauss field (Danielson and Savage, 1968). Thus if equipartition were a valid argument, then this might provide a method of estimating spot field strengths in other stars, if one had believable models of their deep convection zones. However, according to numerical dynamo work by Nagarajan (1971), there seems little or no reason to believe that equipartition will in fact be a valid concept in a turbulent dynamo. It may be that the turbulent dynamo has time to generate fields of order only a few hundred gauss, as seen in active regions, and then we must rely on subsequent instability to amplify the general active region field into locally strong fields with local energy density much larger than local equipartition would permit. If such a two-stage process is in fact at work, then it becomes doubly difficult to know how to scale magnetic field strengths to spots on other stars.

The darkness of sunspots (i.e. their effective temperatures) are determined physically by whatever mechanism carries away the missing flux. The flux which compensates for the missing flux of sunspots is an elusive quantity. One line of thought (cf. e.g. Meyer et al. 1974) is that by means of modified convection just around the spot, the missing flux is redistributed below the photosphere over an area much larger than the spot, so as to form and undetectable excess brightening over an area much larger than the spot. Alternatively, the missing flux may be in the form of Alfvén waves (Mullan, 1974) which are comparatively difficult to dissipate and can therefore propagate along field lines to distant regions of the sun. The propagation may occur either upwards along the open vertical field lines in the umbra into the corona, or downwards into the deep interior of the sun. Beckers (1976) claims to have discovered an appreciable flux of Alfvén waves in the surface layers of a sunspot: as much as 20-50% of the missing flux may be carried by the waves, according to Beckers. A decision between the two sunspot missing-flux mechanisms must be made before one knows how to scale the missing flux to starspots.

Sizes of sunspots are determined by physical processes which are as yet only partially known. In certain cases, sunspots have a tendency to have areas equal to supergranule areas (Dmitrieva et al. 1968), but since we do not know for sure what causes supergranules to have their characteristic sizes, we are uncertain about spot sizes. Lifetimes of spots are determined probably as a result of erosion by the surrounding turbulent gas motions. An eddy diffusivity can be

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defined to describe the sunspot erosion, and reproduce the observed decay of spots at certain phases of their evolution, during which the area declines linearly with time (Meyer et al., 1974). With models of convection zones for other stars, eddy diffusivity might be estimated and lifetimes predicted, but again, this requires knowledge of supergranule sizes.

4.4. HEIGHT DEPENDENCE OF HETEROGENEITIES

It is a general rule that the degree of heterogeneity becomes more pronounced with increasing height. The reason is that as we increase height we must make a conceptual transition from what is usually called an ionized gas to what must be called a plasma (cf. Alfvén and Arrhenius, 1973). As long as we concentrate on material near the photosphere, the gas pressure exceeds the magnetic pressure, and the degree of ionization is not too large. In these conditions, cosmic electrodynamics can be studied fairly well with the "first approach", i.e. with assumptions of homogeneous models, with infinite conductivity, zero parallel electric fields, frozen-in field lines, and neglecting instabilities. But at greater altitudes, specifically at $h \gtrsim 1500$ km, where the chromosphere-corona interface becomes extremely rough, the gas pressure need no longer be large compared to the magnetic pressure, and the ionization need not be small. In these conditions, the "first approach" to cosmic electrodynamics must be abandoned for it may lead to conclusions and conjectures totally divorced from reality. Alfvén and Arrhenius argue that a second approach to cosmic electrodynamics becomes necessary, in which the plasma must be allowed to have a complicated heterogeneous structure, with electrical conductivity depending on the current, sometimes with zero conductivity, with electric fields parallel to the magnetic field lines, and with current lines and the electric circuit just as important to consider as the magnetic field lines. These currents automatically produce filamentary structure and flow in this sheets. Many plasma configurations are unrealistic because they are subject to one of at least 32 known plasma instabilities. And the frozen-in field line picture is often completely misleading. Thus at great altitudes we expect to find a totally heterogeneous solar atmosphere in which the heterogeneities, rather than being simply minor perturbations superposed on a fairly homogeneous background, now become the dominant constituents of the atmosphere. Thus, whereas in the photosphere, faculae are small perturbations on a generally homogeneous sun, with increasing altitude, the faculae show up as plages of ever increasing contrast. Moreover, the functional dependence of contrast on magnetic field strengths becomes fundamentally different as the altitude increases: active regions remain bright and spots remain dark up through the chromosphere, but then at altitudes in the transition region, this behavior reverses, and spots become the brightest features in active regions (Foukal et al., 1974). This is

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due to a widening of the transition zone, but how to scale this widening to other stars is not known.

Pictures of the corona in optical lines (showing prominences) and in X-rays show examples of the extremely heterogeneous nature of the solar atmosphere at these altitudes. In general, the heterogeneities in the corona follow the active regions although not all active region loops are filled with emitting material. There are also bright X-ray points associated with emerging flux regions all over the sun. In trying to scale these heterogeneities to other stars, we can make almost no progress at all. The physical mechanism responsible for hot coronal regions above active regions may involve dissipation of trapped Alfvén waves, as Wentzel (1974) has suggested. If this is so, then in order to scale to other stars, we need to know at least the scale sizes of the trapping magnetic field arches, the field strengths, the densities, and the period of the Alfvén waves. None of these data are currently available.

The most interesting large scale type of heterogeneity in the solar corona is a coronal hole, where densities and temperatures are reduced below the quiet coronal values as a result of enhanced solar wind flux along locally open magnetic field lines. These holes may extend more than 90^0 in latitude, and some tens of degrees in longitude, and their most remarkable feature is that they rotate essentially rigidly: the amount of differential rotation of a hole boundary is an order of magnitude less than the differential rotation of the photosphere and the chromosphere (Timothy et al., 1975). This observational fact may contain information about the internal rotation of the sun, but such information has not so far been unravelled in a completely unambiguous fashion. Other stars will also presumably have open field lines at certain parts of their surface, and so, coronal holes should also be a feature of stellar coronae, but what their physical characteristics will be is not yet clear.

4.5. FLARES

Finally, I would like to turn briefly to the transient heterogeneities called flares, for these are the examples *par excellence* of heterogeneities caused by plasma instabilities in the upper atmosphere of the sun. Flares were of course historically one of the first types of solar features to be observed in other stars. A solar flare involves conversion of magnetic field energy to thermal energy in the upper chromosphere by a process which may involve the mediation of rapid electric current dissipation, or large fluxes of Alfvén waves. The flare process involves complex plasma-field interactions. The process is such that it is reasonable to expect that flare plasma should have a beta (= gas pressure/magnetic pressure) of order unity (Moore and Datlowe, 1975). This is an important phys-

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ical constraint, for if we have some way to determine gas densities and temperatures in the flare plasma (e.g. from X-ray data), then we can estimate the order of magnitude of the field strength in the chromosphere near the flare. Time scales for flare decay are determined in the sun mainly by conductive energy losses. It seems to be true that the conductive time scale is also the relevant physical parameter which we must scale in order to predict decay times of flares on other main sequence stars (Mullan, 1976).

The relation between flares and the missing flux in sunspots is not yet clear, but it certainly is energetically favorable to tap the reservoir of missing spot energy (wherever it is) and energize large solar flares (De Jager, 1968). Applying this idea to stars, we note that spotted stars and flare stars should be related: in fact the two groups are essentially identical. There is even a quantitative reproduction of rates of occurrence of flares as a function of amplitude by this model (Mullan, 1975).

5. Conclusion

I have tried to summarize certain aspects of heterogeneities in the solar atmosphere, stressing our ignorance in identifying at the present time the physical parameters which control the sizes and lifetimes of many of the heterogeneities. Thus we have no yet gotten enough information to provide a starting point in attempting to scale these heterogeneities to other stars. There is such a wealth of observational data currently available on heterogeneities in the solar atmosphere that at first sight it appears to provide a goldmine of valuable information from the point of view of interpreting observations of other stars. Unfortunately, in many cases the relevant physical parameters which determine the characteristics of solar features are not well known, and so the scaling from solar to stellar atmospheres is not on firm ground at the present time. Hopefully, in the next few years improved knowledge of the internal structure of the solar convection zone, and improvements in our knowledge of how small-scale magnetic flux tubes are formed, may help to put this scaling on a firmer basis.

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