THEORY OF SOLAR IRRADIANCE VARIATIONS

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Received November 24, 1999, Accepted November 24, 1999

Abstract. The theory of stellar structure can be used to identify the most plausible mechanisms for the irradiance variations associated with the solar cycle. Changes in surface emissivity, i.e. the reduced cooling in spots and enhanced emission by small scale magnetic fields, are the most effective mechanisms and account for most of the observed variation. New views of stellar surface convection developed from realistic numerical simulations changes the physical description of thermal perturbations of the solar envelope. Helioseismology will soon be able to test the consequences of changes in surface emissivity, and distinguish them from other scenarios for irradiance variability.

1. Introduction

If a sufficiently complete record of solar irradiance measurements were available, it could be used directly for searching possible correlations with the earth's climate. In reality, the short length of the record makes this impossible so that proxies like the sunspot record are used in practice. The use of such proxies, however, involves a model for the causes of the irradiance variations, hence requires some form of theory. In addition, the cause of these variations is of course an interesting problem in its own right in solar physics.

Until the advent of helioseismology, our knowledge of the internal structure of the Sun was based on the theory of stellar structure and evolution. Since this theory is reasonably simple, confidence in the models was high even before helioseismological tests. The main uncertainty had to do with the exact values of the opacity of stellar plasma. Increasingly accurate values for this were computed from first principles (atomic physics) by extensive numerical work. The basic correctness of the theory was then confirmed by helioseismology, to such an extent even that one is now confident that the 'solar neutrino problem' has its cause in neutrino physics, not inaccuracies in the solar models.

Though these solar models are spherical and only slowly evolving in time, the theory behind it can also be applied to time dependent and non-spherical distrurbances. In this form, the theory makes definite predictions about the thermal behavior of the Sun, that is, the evolution in time and position inside the star of perturbations that might be related to the observed irradiance variations. In the following I present my view how this theory can be used to locate the most plausible source of irradiance variations. After this, I discuss how the new helioseismological

Space Science Reviews **00:** 1–14, 1999.
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measurements currently being made can be used to test the predictions of proposed mechanisms of irradiance variation.

Conceptually, one can separate the thermal effects of magnetic fields into three types:

1. 'Sources and sinks'. The generation of a magnetic field involves the conversion of energy of motion into magnetic energy. Since the motions in the solar envelope are thermally driven, this ultimately means conversion of thermal into magnetic energy: building up a magnetic field produces a thermal sink somewhere. The opposite happens when the field decays: magnetic energy is converted into heat. These thermal effects exist only during *changes* in the magnetic energy content of the envelope.

2. 'Shadows', or changes in the heat transport coefficient. Magnetic fields interfere with convection, causing a reduction in the efficiency of heat transport in the envelope. In contrast to (1), these changes last as long as the magnetic field itself is present.

Both these sources and sinks and changes in the transport coefficient cause thermal perturbations, varying with magnetic activity, which propagate through the envelope and cause variations in surface energy flux. Related to the second class of perturbations are:

3. The effects of magnetic fields at the surface of the star. Sunspots, being dark, radiate less than the surrounding photosphere, while the small elements that make up plages and the network have an excess emission. In addition, it is conceivable that the magnetic elements have an indirect effect on surface emissivity by modifying the convective flow in their surroundings slightly (for which there is some observational evidence, see section 3.7).

2. Time scales

The response of the Sun to thermal perturbations is not governed by a single time scale, but by a wide range of time scales. The longest of these is the thermal time scale of the Sun as a whole, called the Kelvin-Helmholtz time scale. It is about 10^7 years, namely the thermal energy content of the Sun, of the order 10^{41} Joule, divided by its luminosity of $4\,10^{26}$ W. Hence, on time scales of human interest, the Sun has a very large thermal inertia. If the central heat source of the Sun were switched off, the internal structure and the luminosity would start to change on this time scale. It is a global time scale for the Sun as a whole; more generally, we can define the thermal time scale $\tau_{\rm t}$ as a function of depth:

$$\tau_{\rm t}(z) \equiv U(z)/L(z) \approx \frac{1}{L}\int_{R-z}^{R} 4\pi r^2 u \mathrm{d}r, \qquad (1)$$

where L is the luminosity at depth z, U the thermal energy of the envelope down to a depth z, and u the thermal energy (enthalpy) per unit volume, approximately (for an

ideal gas of constant γ) given by $u = \gamma P/(\gamma - 1)$. This is the time scale on which the structure of the envelope, and the observed luminosity, would start changing when the heat flux in the star were interrupted, by some magical means, at depth z. Some rough values for this quantity are $\tau_{\rm t} \sim 10^5$yr at $z = 2\,10^5$ km (depth of the convection zone), 10 yr at 20 000 km (the size of a supergranule), 10 hrs at 2000 km (size of a granule). This strong dependence on depth is a consequence of the very strong stratification of the solar envelope (the pressure varies by a factor 10^8 between the surface and the base of the convection zone). As a result, the thermal response of the Sun also depends critically on the location of the disturbance. Near-surface disturbances have much larger effects than ones originating near the base of the convection zone.

A second kind of time scale involved in thermal readjustments is the so-called *diffusive* time scale. This is the time scale on which differences in entropy between different parts of the convection zone are ironed out by the convective flows. This is easily computed in a 'mean field' or diffusion model for convection, in which the local convective heat flux is assumed to be a function of only the local conditions (thermodynamic state of the gas and the temperature gradient). The validity of this model is questionable, since it is now known that stellar envelope convection is in fact extremely non-local, with almost all flows generated by cooling at the stellar surface (e.g. Nordlund, 1986; Stein and Nordlund,1989; for reviews see Nordlund and Stein, 1996; Spruit, 1997). The diffusion model has the advantage, however, that it is simple to apply, and is (unfortunately) still almost universally accepted. For these historical and practical reasons, I still use it for the estimates in this section. Estimates in the context of the new nonlocal view of envelope convection have not yet been developed to the same level of detail. I return to this in section 4, where the examples of heat flux blocking by sunspots and 'thermal shadows' are considered in the nonlocal convection picture. I argue there that the new nonlocal view only strengthens the conclusions based on the diffusion model.

For small perturbations, the heat flux in the local model is proportional to the entropy gradient, and time dependent perturbations are governed by a diffusion equation. The 'turbulent' diffusion coefficient in this equation is $\kappa_{\rm t} \approx \frac{1}{3} l_{\rm c} v_{\rm c}$ where $l_{\rm c}$ and $v_{\rm c}$ are the convective length scale and velocity. In mixing length models of the solar convective envelope, this quantity varies only weakly with depth, at a value of the order 10^{13} cm^2/s. In this model thermal inhomogeneities (more precisely: entropy inhomogeneities) of length scale d are smoothed by turbulent diffusion on a time scale

$$\tau_{\rm d} = d^2/\kappa_{\rm t}\,. \tag{2}$$

For $d = 2\,10^5$ km this is about 1 yr, for $d = 2000$ km about 1 hr. Comparing $\tau_{\rm t}$ and $\tau_{\rm d}$, we see that they are of similar magnitude close to the surface (to be precise: in the surface boundary layer where convection is not efficient enough to keep the stratification close to adiabatic). In deeper layers, the thermal time scale is much *longer* than the diffusive time scale, by a factor of up to 10^5.

The two time scales measure different types of thermal adjustment processes. These same processes appear in the thermal behavior of, say, a chunk of metal, aluminum for example, heated from the inside and suspended in space. The thermal time scale is the time scale on which its temperature adjusts to a change in the heat input, such that the heat radiated from the surface into space balances the heat input again. It is determined by the heat capacity [U in eq. (1)] and the power level (L). The time scale on which different parts of the chunk equilibrate to the same temperature is governed by a different process, namely the thermal conduction (the equivalent of the turbulent diffusion in the Sun). The diffusion (conduction) time scale is much shorter than the thermal time scale, because of the large heat conductivity of AL. In the Sun, it is the very large turbulent diffusivity in the bulk of the convection zone that causes the very short diffusive time scale compared with the thermal time scale.

How do these different time scales come into play when the convection zone is thermally perturbed by, say, the storage of energy in a growing magnetic field? Such perturbations can be computed in detail, either by numerical methods (Endal et al., 1985; Gilliland, 1988) or more analytically. We can, for example, consider the initial value problem in which a perturbation is allowed to evolve in time by thermal transport in the convection zone. In general this evolution has components on all the time scales of the problem, including the very long thermal time scale. Detailed calculations of this problem have been discussed elsewhere (Spruit, 1982ab, 1991; Arendt, 1992). In the following, the basic conclusions of these analyses are summarized.

3. Expected level of luminosity variations

For quantitative estimates, the strength of the magnetic field and its filling factor in the convection zone have to be specified. Assume that we have a layer of field with strength of the order of 10 000G (equipartition with the convective flows as estimated by a mixing length model), one pressure scale height deep, near the base of the convection zone (where most of the magnetic flux is probably located).

3.1. SOURCES-AND-SINKS

If the energy needed to build up the solar magnetic field during one half of the solar cycle is taken out of the thermal energy near the base of the convection zone, the calculations show that a surface luminosity variation of only $\delta L/L \sim 10^{-7}$ results. This is due to the very large heat capacity of the lower convection zone. The effect is stronger if the source of the magnetic field is assumed to be closer to the surface, but is still much smaller than the observed irradiance effect. Recent models for the emergence of magnetic flux from the base of the convection zone (D'Silva and Choudhuri, 1993; D'Silva and Howard, 1993; Caligari et al., 1998) indicate

that the actual field strength at the base of the convection zone is probably about 10 times higher than the equipartition estimate. The magnetic energy per unit of magnetic flux is then also 10 times higher, but this still does not lead to a significant luminosity effect.

3.2. SHADOWS

If magnetic fields interfere with convection, a thermal perturbation develops as well. This effect depends crucially on the 'covering factor'. If a reduction of convective efficiency is assumed that uniformly covers a horizontal surface at some depth z, magnetic fields comparable to equipartition with convective flows can have stronger effects than the source-and-sink perturbations (Gilliland, 1988), though a measurable effect is predicted only if the field is located close below the surface. At face value, this would make changes in convective efficiency a reasonable candidate for irradiance variations. In practice, the effect is very strongly reduced, however, if the change in convective efficiency does not extend over an entire horizontal surface. This is because the turbulent heat conductivity in the convection zone is so high that the heat flux is easily 'shunted' past blocking objects below the surface (Spruit, 1977). Compare this with efforts to thermally insulate homes. To be effective, it is not enough that *most* of the building's outer surface is very well insulated. A more modest insulation but without any leaks is more effective. For this reason, thermal shadows of subsurface fields are probably not very important.

3.3. SURFACE EFFECTS

By far the most effective way in which a magnetic field influences the irradiance is by its effect on the *net surface emissivity*. The reduced emission from a sunspot area shows up directly in the irradiance records as a dip tracking the passage of the area across the disk. The only complication is that one might expect, depending on one's prejudices, that part of this reduction could be compensated by a brightening elsewhere, for example in the form of a 'bright ring' surrounding the spot. Evidence of such bright rings is absent for most spots that have been studied for this effect, and where observation of a ring is reported, it compensates for only a small fraction of the spot blocking (e.g. Rast et al., 1999). Real brightening around a spot is hard to measure because it is usually masked facular emission. Such faculae are part of all active regions. Though their excess emission is roughly of the same order as the spot deficit, this is a coincidence that does not hold any more on closer inspection. For example, faculae are equally present in active regions with or without sunspots, and their contribution to the irradiance variation does not correlate very well with spot areas (Foukal and Lean, 1986; Lean et al., 1998).

The absence of bright rings is understood in terms of a turbulent diffusion model for the heat flux in the convection zone (Spruit, 1977, 1982b; Foukal et al.,1983; Chiang et al., 1984). The 'blocked heat flux', for the most part, does not reappear elsewhere on the surface, but stays inside the convection zone, being stored/released

on the very long thermal time scale of the convective envelope. This conclusion holds, in the diffusion model, as long as the blocking effect of the spot extends to a depth of at least 1000 km, a mild requirement given that the observed Wilson depression of the umbra of a spot is already of the order of 500 km.

3.4. SPOT BLOCKING: STOVE TOP ANALOGY

The absence of bright rings in the diffusion model can be understood by a kitchen analogy. Imagine a stove top with an electric heater plate. Assume this plate to be made of a massive block of a metal with a high thermal conductivity, such as aluminum. Such a block, like the solar convection zone, has two time scales, the thermal time scale, given by the heat content divided by the heating rate, and the thermal conduction time scale given by the diffusion time across the block. If the thermal conductivity is large, the diffusion time scale can be much shorter than the thermal time scale. In the solar convection zone this is the same except that the ratio of time scales ($\sim 10^5$) is much more extreme. Suppose the heater plate has been on and has reached a steady temperature, so that heat input balances the conduction/convection losses at the top. Suppose also that the ratio of time scales is sufficiently large. Then put a piece of thermally insulating material on top, covering part of the surface of the plate (as a model for the effect of a spot). Where does the blocked heat flux go? The answer is of course that it does not go anywhere, the blocked heat stays in the block, heating it up slowly, instead of being radiated at some other part of the surface. On account of the large thermal conductivity, the temperature in the block stays uniform, and almost no 'bright ring' appears around the spot. When the insulating spot is removed after a while, the heat flux returns to its old value instantaneously. The temperature has increased only slightly during the blocking phase, and this slight enhancement decays again on a thermal time scale.

3.5. EXCESS EMISSION BY SMALL SCALE MAGNETIC FIELDS

Apart from the highly visible sunspots, the Sun has a small scale magnetic field consisting of a very large number of tiny magnetic elements. They are called faculae if their density is high, and 'network' at lower density, and collectively contain much more magnetic flux than sunspots. They are visible especially near the solar limb, showing that they radiate more isotropically than the limb-darkened normal solar atmosphere. This excess emission has two components, one originating in somewhat higher atmospheric layers, in the form of line- and UV-continuum emission. This component probably is due to dissipation of mechanical (wave) energy carried by the magnetic field. In addition, there is a component seen in white light, originating in the surface layers of the magnetic structures. This second component is understood theoretically as a radiative transfer effect (Spruit, 1976, 1977): the radiating surface in a magnetic element is a little 'dimple' in the surface, whose side walls radiate an extra flux compared with a flat surface. The large number of small magnetic elements effectively corrugates the surface, and makes it radiate both more

effectively and more isotropically, just as a rough surface has a higher emissivity than a polished surface. This effect increases the radiative flux from any part of the surface where small scale magnetic fields are present. It is a net effect (predicted before observation, Spruit, 1977) that is not balanced by a deficit somewhere else on the surface. Since the magnetic elements are so small, they are hardly resolved in the observations. Recent high-resolution observations (Topka et al. 1997), however, verify the picture predicted by flux tube models (Spruit, 1976, figure 11; Steiner et al., 1997) for the appearance of small magnetic elements.

Since the effect of small scale fields is an increased *emissivity*, it increases the *cooling rate* at the surface.

3.6. SURFACE EFFECTS: DISCUSSION

In the above I have outlined

- How the observed excess emission can be explained in terms of the local effects of small scale magnetic fields.
- That this local excess is not expected to be compensated by deficits elsewhere at the surface: the solar surface has a higher effective emissivity in regions of small scale magnetic fields and a lower one in sunspots.

Together with the observed correlation between the irradiance signal and the magnetic indicators (e.g. Foukal and Lean, 1986; Solanki and Unruh, 1998; Lean et al., 1998), this shows that local surface emissivity changes due to magnetic fields (a reduction in spots, enhancement in small scale fields) account for at least a significant fraction of the observed irradiance variation. It is much harder to prove that there could not be some contribution from other effects as well, for example the photospheric temperature enhancements proposed by Kuhn et al., (1988); Kuhn and Stein (1996). It makes clear, however, that in order to find such other effects one first has to remove the magnetic surface effects. Measurements such as those of Dicke et al. (1987), Kuhn et al. (1988), in which the contamination by magnetic surface effects is ignored, can not be used to claim the existence of photospheric temperature changes. Whether there is anything left to be explained after the surface effects are taken out is not clear at the moment. Lean et al. (1998) and Solanki and Unruh (1998) argue that no photospheric temperature increase is needed to explain the available irradiance data.

The situation is similar for measurements of (variations of) the solar radius and a possible oblateness of the Sun. At the current sensitivity (a small fraction of an arc second) the high brightness contrast of small scale magnetic fields near the solar limb seriously interferes. In these measurements one typically determines (Kuhn et al., 1998) an average brightness profile across the limb, and variations of the limb position are then measured as offsets (in time or as a function of position around the Sun) of this given profile. Bright areas near the limb cause spurious outward offsets. Since the measured effects are very small, and the brightness of magnetic areas near limb is large (faculae immediately stand out on a solar image) detailed information

on any magnetic brightness changes near the limb is necessary to correct for this. As the history of Dicke's oblateness measurements shows, limb positions that ignore the effect of these inhomogeneities are not believable.

A possible way of distinguishing true photospheric temperature changes from small scale surface emissivity effects is through the wavelength dependence of the irradiance signal. The excess emission from magnetic fields is concentrated in the magnetic elements, which have a small surface filling factor. For a given (bolometric) excess, it has to have a higher color temperature than excess emission from something with a large filling factor. This has been tested by Solanki and Unruh (1998, see also Unruh et al., 1999), who conclude that the observed wavelength dependence of the irradiance excess signal favors the small scale magnetic interpretation rather than a diffuse surface temperature increase.

3.7. CHANGES IN GRANULATION IN ACTIVE REGIONS

The changes of surface emissivity by magnetic fields discussed above are due to the different radiative properties of small magnetic elements ('flux tubes'). More indirect effects may play a role as well. The shape of granules appears to be different in magnetic regions (Macris and Roesch, 1983; Muller and Roudier, 1984; Muller, 1986; Title et al., 1992). They are smaller, more irregular, and the measured flow speeds are lower. These effects are present *in addition* to the magnetic elements themselves, which also change the appearance of granulation by filling in the intergranular lanes, especially when seen at low spatial resolution. The changes may be the result of the geometric constraints the magnetic tubes put on the convective flow outside them.

Since the flow appears to be different, it would seem possible that the heat flux it carries is also different. This might contribute to the observed solar cycle variations of irradiance (Muller, 1986; Kuhn and Libbrecht, 1988). Limits on this contribution can be put by observations of the *colors* of the solar cycle variation signal. As discussed above, Solanki and Unruh (1998) find that the wavelength dependence of the irradiance signal argues against a dominant contribution from small changes of surface temperature over a larger areas, but do not quote quantitative limits. In order to contribute in the right sense to the solar cycle variation, the constraints imposed on the flow by the magnetic flux elements would have to lead to an *increase* in the heat flux carried by granulation. Direct (spatially resolved) measurements of a heat flux change in granulation in magnetic regions are probably difficult, since the effect would be small and hard to separate from the enhanced emission from the magnetic elements. Numerical simulations (Nordlund, private communication) indicate, however, that an effect of the right sign may be present.

Changes in surface heat flux by modified granulation, if they exist, will affect the convective envelope in the same way as the excess emission from the small scale magnetic field. They can also be represented by an effective change of the emissivity of the solar surface. In particular, one does not expect these changes to

be 'compensated' by opposite changes elsewhere on the surface (except, as before, on the 10^5 yr thermal time scale of the envelope).

4. Improving on the turbulent diffusion picture

In the results quoted a diffusion model for convection was used. It assumes that convection can be modeled by a turbulent viscosity for momentum and a turbulent diffusivity for the transport of heat. While this was a simple and somewhat justifiable model of convection in the absence of detailed knowledge of the convective flows in a stellar envelope, we now know that it does not represent stellar convective envelopes well. Numerical simulations (Nordlund, 1982, 1985ab, 1986, 1990; Nordlund and Dravins, 1990; Nordlund and Stein, 1990, 1991, 1996; Stein and Nordlund, 1989, 1991, 1998; Steffen et al., 1989; Steffen, 1993; Ludwig et al., 1999) show an extremely *nonlocal* picture. The convective flows are driven almost exclusively by cooling at the surface, with narrow fast moving downdrafts between slow almost isentropic upflows (for a discussion see also Spruit, 1997). In the present context, the most important property is that the convective flow at all depths is driven by cooling at the surface rather than by a local overturning process. The material in the cool downdrafts survives to large depths below the surface with little mixing into the upflows.

Given this extremely nonlocal picture, it is appropriate to ask how the thermal behavior of perturbations in the convection zone can be estimated without appealing to a turbulent diffusion model. I do this below for two of the effects discussed, the spot blocking and the 'thermal shadow' problems. In both cases, the conclusion is that thermal perturbations of the normal solar surface are even smaller than in the diffusion picture. This has to with the fact that the flows in the new non-local picture are caused by cooling at the surface, and that much of the changes are one-way only (downward). The diffusion picture on the other hand communicates perturbations equally well in all directions.

4.1. SPOT BLOCKING

Below the spot (modeled as a region of reduced heat transport efficiency extending to some depth below the surface) the upflows have exactly the same temperature as upflows in the unspotted surroundings at the same level, namely that given by the entropy at the base of the upflows. In this sense, there is no 'pile up of heat below the spot'. Because of the reduced heat loss at the surface, however, the downflows below the spot will be less vigorous. The unspotted surface notices nothing of the spot's presence (except for an extremely narrow ring where lateral radiative exchange takes place, and except for the presence of a moat flow, see below). It continues to cool upwellings into downdrafts as before, since the entropy in the upflows has not changed. Thus, we expect again that bright rings will be absent around spots,

but the reason is even simpler than in the diffusion model. The spot is a region at the surface where less heat is radiated away, and this is now independent of the depth of the spot below the surface (in contrast to the diffusion model, where the spot has to extend to a minimum depth of 1000 km for the explanation to work).

Still, one may wonder what happens to the amount of heat generated in the solar interior that now fails to be emitted at the surface. This part of the problem is the same as in the diffusion model: the imbalance causes a secular increase of the entropy in the entire convection zone until a new thermal equilibrium is reached. Because of the very long thermal time scale of the convection zone (10^5 yr), the effect is negligible on observable time scales. In a steady state, when the average number of spots does not change, the convection zone does not heat up, because its mean temperature is higher than it would be without spots (Spruit and Weiss, 1986). Episodes of larger than average spot coverage cause heating, those of less than average spot coverage cause cooling on this time scale.

4.2. THERMAL SHADOWS

The thermal shadow expected from a blocking object below the surface (Spruit, 1977; Goode and Kuhn, 1990), which is a small effect already in the turbulent diffusion model, is likely to be even smaller in the new picture of stellar envelope convection. Since all upward flowing gas has nearly the same entropy, a blocking object below the surface has no effect on what happens above it, as long as there is enough room above it for upflows to comfortably reach the solar surface. It may interfere somewhat with downflowing gas, but this has no consequence for the surface temperature above the blocking object, since only a small fraction of the downward moving gas is carried back up to the surface. As before, this is a consequence of the non-local nature of the convective flow.

5. Helioseismological tests

In the above I have concentrated on surface effects, and argued that temperature enhancements with origins deep inside the convection zone are less likely to contribute. Such deep origins have been advocated by Kuhn et al. (1988), and Kuhn and Stein (1996) who propose that a temperature enhancement with origin at the base of the convection zone causes a temperature enhancement of 0.5K in the active latitudes. Potentially exhausting theoretical debates for or against these models can probably be circumvented since the models make different predictions for the associated perturbations below the surface that can be tested by observation. The excess radiation from small scale magnetic fields comes about through an increased surface emissivity, associated with the increased 'surface roughness'. This increases the average cooling rate at the surface and creates somewhat stronger and/or cooler downdrafts. It therefore causes slightly *lower* horizontally averaged temperatures

below the surface. The two models thus predict opposite thermal effects below the surface.

The prospects for a test of these predictions are good, since helioseismological data are now quite sensitive, with the data obtained by SOHO/MDI and the GONG network (Kosovichev, 1996; Kosovichev and Schou 1997; Duvall et al. ,1998; Duvall and Kosovichev, 1999). Changes in the p-mode frequencies related to the solar cycle were reported by e.g. by Libbrecht and Woodard (1990), Dziembowski et al. (1998). The dependence of the signal on wavenumbers (l, m) shows that most of the effect is due to a change in wave propagation in a layer very close to the solar surface, at the latitudes of magnetic activity. The sense of the effect, an increase of the frequencies, is the *opposite* (Goldreich et al., 1991) of what would be expected if the temperature in these latitudes were higher. Though a higher temperature increases the propagation speed (increasing the frequencies), it also expands the solar envelope at these latitudes, by vertical hydrostatic balance. This lengthens the path traveled and decreases the mode frequencies. The net effect turns out to be dominated by the the second effect, the path length increase, because it is linear in T, while the propagation speed increases only as $T^{1/2}$. In addition to the thermal effect, the presence of the magnetic field has an effect, since it increases the 'stiffness' of the gas (in terms of propagation, the relevant speed is the fast mode speed, which is larger than the sound speed). Since the relative contribution of this effect scales with the ratio of magnetic to gas pressure, it is important only in a thin layer near the surface. The observed changes in mode frequency can thus be due either to a somewhat lower temperature, or to the effect of the magnetic field in the atmosphere. The observation that most of the effect is localized at the surface argues for a major contribution from the magnetic stiffness effect (Goldreich et al., 1991; Woodard et al., 1991). In any case, the observed sign of the effect is incompatible with enhanced temperatures being the main change in envelope structure in the active latitudes.

A second way of measuring variations in propagation conditions below the solar surface is through time-distance seismology (Duvall et al., 1996; Kosovichev, 1996; Braun et al., 1997), in which one does not measure the mode frequencies but their travel time between points on the surface (much like seismology is used to measure irregularities in the earth's interior). These measurements show shorter travel times in the active regions (Duvall et al., 1998; Duvall and Kosovichev, 1998; Giles et al., 1997; Bogdan et al., 1998; Goode and Dziembowski, 1999), and downflows below the surface. The shorter travel times are compatible with a contribution of the magnetic field to the propagation speed, and with *lower* subsurface temperatures (Brüggen and Spruit, 2000). The results from time-distance seismology have shown some internal inconsistencies, however, and reliable methods for interpretating the data are apparently still in the development stage.

The lower temperatures expected by enhanced surface cooling in the small scale magnetic field has further observational consequences. In the absence of rotation, the increased negative buoyancy would just cause a downdraft below active regions.

Associated with it a horizontal flow converging on the active region is expected. Effects like these are beginning to be explored by time-distance seismology.

5.1. TORSIONAL OSCILLATIONS

The effect of rotation on these flows can probably not be ignored, since the relevant Rossby number (rotation period divided by circulation time scale) can be of order unity. In addition to the circulation, one then expects the Coriolis force to produce a 'thermal wind' (e.g. Pedlosky, 1982) in the active latitudes. A lower average subsurface temperature in these latitudes causes a reduced pressure on equipotential surfaces, which is balanced by horizontal flows in the cyclonic sense. The average effect over longitude would be a contribution to the differential rotation, such that the lower edge of the active latitudes rotate faster, and the upper edge slower than average. The maxima of the disturbance would be at the latitudes where the latitudinal gradient of the magnetic activity has its maxima. Such a pattern of rotation variations associated with the active latitudes is indeed observed in the form of the so-called 'torsional oscillations' (e.g. Ulrich, 1998). A temperature enhancement in the active latitudes such as proposed by Kuhn et al. would cause a thermal wind of the same order of magnitude but of the opposite sign. It must be stressed, however, that other plausible explanations for the oscillation exist, such as the effects of magnetic forces in the deep convection zone (Schüssler, 1981).

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