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Global Oscillations and Active Regions*

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Abstract

We present further estimates of the amplitude of the modulation of the solar global velocity signal caused by the passage of active regions across the solar disc. Using measurements of the profile of the K I $\lambda769\cdot9$ nm line in the quiet Sun and in plages we find a global velocity variation of ~2 m s^{-1} during the transit of a typical active region of area 3300 millionths of the hemisphere. However, during the period in which a velocity amplitude of 6 m s^{-1} was reported by Claverie *et al.* (1982), the sunspot areas were exceptionally large and we confirm Schröter's (1984) result that the combination of spot and plage contributions is sufficient to account for the observed signal. The velocity modulation is thus attributable to surface inhomogeneities, not to the structure of the solar core.

1. Introduction

In recent years much interest has been shown in the study of global properties of the Sun, particularly those of light from the integrated area of the disc. These studies have two aims; firstly, to establish a link between known properties of the Sun and their suspected counterparts in other stars which cannot be observed with spatial resolution and, secondly, to use the global properties as a diagnostic tool in the study of the solar interior. One such study is being conducted by G. R. Isaak and his group, who have measured the Doppler shift of the K I resonance line from the full disc of the Sun (Brookes *et al.* 1978). When all the sources of shift due to terrestrial and orbital motion are accounted for, a small residual signal of ~5 m s^{-1} remains. During the period July–August 1981 this signal was almost sinusoidal with a period of $13\cdot1$ days. It was attributed to a solar core in rapid rotation (Claverie *et al.* 1982).

However, several authors (Andersen and Maltby 1983; Durrant and Schröter 1983; Edmunds and Gough 1983) were quick to point out that inhomogeneities of the solar surface become significant when velocity measurements are made at the m s^{-1} level. The surface inhomogeneity moving across the disc causes its Doppler-shifted spectral line contribution to move across the mean line profile. Slits measuring the

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intensity at fixed points on either side of the line centre will register a quasi-sinusoidal difference signal. The period of the observed signal is close to half the synodic rotation period and it was suggested that the 13-day periodicity was due to nothing more than the well-known tendency for active regions, the sources of large-scale surface inhomogeneities, to occur at preferred longitudes 180° apart. A detailed study of the size and locations of active regions by J. Schoner and E. H. Schröter (Schröter 1984) does indeed show the requisite periodicity for extended periods—18 months during solar maximum in 1969–70. The reported global velocity measurements were made in 1981 close to the following solar maximum.

What appear to be much less conclusive are the estimates of the magnitude of the effect. Andersen and Maltby (1983), Edmunds and Gough (1983) and Schröter (1984) have all modelled the experiment in different ways. Here we present a new evaluation which takes account of several parameters hitherto ignored and then compare the results with those obtained earlier.

2. Numerical Model

A numerical estimate of the disturbance to the mean solar profile due to an active region on the disc requires knowledge of the line profiles across the disc in both the quiet Sun and active regions. For the quiet Sun, de la Reza and Müller (1975) reported measurements of the K I 769·9 nm line made with the Kitt Peak double-pass spectrograph. These profiles can be interpolated by a simple approximation based on the centre-of-disc profile

$$I = I_c[1 - r\exp\{-(\Delta\lambda/1\cdot 14\Delta\lambda_{\frac{1}{2}})^{2\cdot 8}\}] \quad \text{for } \Delta\lambda < \Delta\lambda_{\frac{1}{2}},$$

$$= I_c[1 - r\exp\{-(\Delta\lambda/1\cdot 22\Delta\lambda_{\frac{1}{2}})^{1\cdot 82}\}] \quad \text{for } \Delta\lambda > \Delta\lambda_{\frac{1}{2}},$$

where $\Delta\lambda$ is the wavelength displacement from line centre, and $\Delta\lambda_{\frac{1}{2}}$ is the half-width at half the line depth given by, in the range of heliocentric angle $0 < \theta < 80°$,

$$\Delta\lambda_{\frac{1}{2}} = 8\cdot 1 + 0\cdot 42 \tan\theta \text{ pm}.$$

The line depth r was found to be sensibly independent of heliocentric angle and equal to 0·84. The continuum limb-darkening function I_c was taken from Pierce *et al.* (1977) at λ770·8 nm.

The mean profile was calculated by a method similar to that employed by Andersen and Maltby (1983). The visible hemisphere was dissected into 824 elements of approximately equal area (actual, not projected). The profile appropriate to the centre of each element was then computed, incorporating the Doppler shift due to the line-of-sight component of the solar rotation, assumed to be rigid and equal to $2\cdot 0 \text{ km s}^{-1}$ at the equator. The summed profiles, each weighted according to the projected elemental area, yielded the mean profile.

The effect of an active region plage was modelled by replacing the quiet Sun profile in an element by a plage profile. The Doppler shift and continuum intensity may be taken to be unchanged in active regions, at least to our degree of approximation. The plage profiles were measured by P. N. Brandt with the single-pass spectrograph at the Locarno Observatory. Several plages were observed in the ranges $1\cdot 0 > \mu > 0\cdot 8$

and $0{\cdot}8 > \mu > 0{\cdot}6$, which were then averaged to yield a mean profile at $\mu = 0{\cdot}9$ and $0{\cdot}7$; the neighbouring quiet Sun profiles were also measured. The instrumental profile is not negligible, but it can be estimated by comparing the quiet Sun results with those obtained by de la Reza and Müller (1975). The true plage profiles can be well described by a line with depth and half-width independent of heliocentric angle and equal to $0{\cdot}78$ and $9{\cdot}4$ pm respectively.

The measurements of the global line shift reported by Claverie *et al.* (1982) were made with a potassium resonance spectrograph. This measures the intensity difference ΔI between two 'windows' fixed on either side of the centre of the line. This difference is converted to a line shift, and hence velocity, by the linear relationship

$$v = c\Delta\lambda/\lambda = K\Delta I/2\bar{I}, \tag{1}$$

where $\bar{I}$ is the mean intensity in the two windows.

To model this technique we calculated the difference in the quiet Sun and plage profiles within two windows of width 3 pm (the equivalent width of a line with Doppler broadening of $0{\cdot}65\ \mathrm{km\,s^{-1}}$), separated by $13{\cdot}3$ pm (corresponding to a Zeeman splitting of $5{\cdot}18\ \mathrm{km\,s^{-1}}$). These values, taken from Brookes *et al.* (1978), were assumed to apply to the 1981 apparatus. The quiet Sun profile gave $K = 2600\ \mathrm{m\,s^{-1}}$ which can be compared with the typical figure of $3000\ \mathrm{m\,s^{-1}}$ given by Brookes *et al.* The empirical line slope is thus somewhat less than the model mean line profile. This can be attributed to some instrumental degradation which is unimportant as it is compensated by a reduction in the intensity difference ΔI.

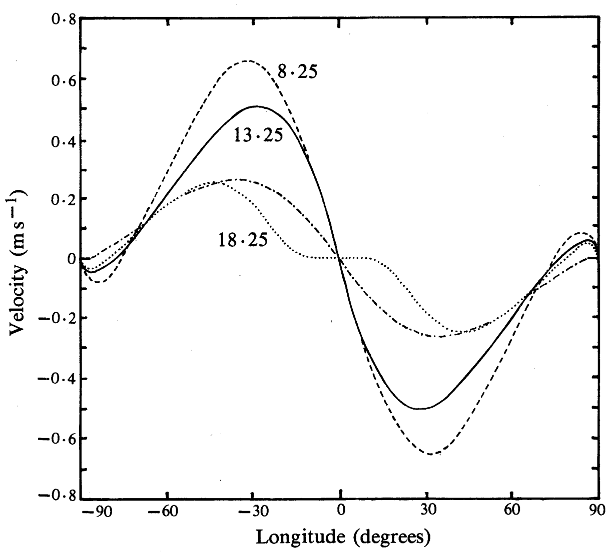

Fig. 1. Global velocity modulation caused by the passage across the solar disc of a plage of area 1224 millionths of a hemisphere and a spot area of 122 millionths (dot–dash curve). The plage curves are labelled by the separation (in pm) of the two windows.

3. Results

Because of the relation (1) the effects of plages distributed arbitrarily across the disc may be superposed, and hence we need consider only a single case in order to obtain a scale for the model. Fig. 1 shows the velocity modulation caused by the transit across the disc of a plage of area 1224 millionths of a hemisphere at a latitude of 17·5°. The simple formula employed by Durrant and Schröter (1983)

$$v \propto \cos\theta \sin\phi\,(A \cos\theta \cos\phi), \tag{2}$$

where θ and ϕ are the latitude and longitude measured from the central meridian, predicts a maximum signal at $\phi = \frac{1}{4}\pi$ for a given θ. Fig. 1 reveals substantial departures from a simple sinusoid which are caused by the presence of limb darkening and by the fact that the intensity changes in the windows are not independent of the Doppler shift of the line. At the point where the signal is a maximum, $\phi \sim \frac{1}{6}\pi$, one window has the core of the line shifted towards it and registers the increase of intensity in the plage profile. The line wings are moved into the other window, where the broader plage profile causes a reduction in intensity. The intensity difference combines these contributions and yields an amplitude of $0{\cdot}50\ \mathrm{m\,s^{-1}}$.

This signal can be increased by increasing the intensity difference between the cores of the plage and quiet Sun profiles. Reducing the plage line depth by 0·04 increases the amplitude to $0{\cdot}60\ \mathrm{m\,s^{-1}}$. Similarly, increasing the width of the plage profile increases the signal. A broadening of the form adopted for the quiet Sun profile increases the amplitude to $0{\cdot}56\ \mathrm{m\,s^{-1}}$.

The amplitudes are thus relatively insensitive to uncertainties in the plage line profiles. They are much more sensitive to the location of the windows in the line wings. Fig. 1 also displays the transit curves for window separations of 8·25 and 18·25 pm, and shows that the closer the windows, the larger the signal. An amplitude of $0{\cdot}65\ \mathrm{m\,s^{-1}}$ can be produced with a separation of 8·25 pm. Changes in the width of the windows result in little change of the predicted velocity signal.

In sunspot umbrae the continuum intensity at λ790 nm is less than one-fifth that of the photosphere, so a close upper estimate of the effect of sunspots is afforded by assuming that radiation is completely absent from spots. The global velocity modulation caused by the transit of a black spot of area 122 millionths of the hemisphere at 17·5° latitude is also depicted in Fig. 1 (dot–dash curve). It contributes a maximum amplitude of $0{\cdot}25\ \mathrm{m\,s^{-1}}$ and has the same sign as the plage signal, as noted by Edmunds and Gough (1983). This value is insensitive to the location of the slits.

4. Discussion

According to Bruzek (1981) a medium-sized active region contains a plage of area 3300 millionths and some 20 spots with a total area of 200 millionths. On this basis, we would predict a global velocity modulation of $1{\cdot}35\ \mathrm{m\,s^{-1}}$ for the plage and $0{\cdot}4\ \mathrm{m\,s^{-1}}$ for the spots, or a total modulation of $1{\cdot}75\ \mathrm{m\,s^{-1}}$. Such a region tends to persist for two to three solar rotations, so the modulation should be coherent over a period of two to three months. A large active region with an area of 13 000 millionths and total spot area of 800 millionths could produce a periodic global velocity modulation of $7\ \mathrm{m\,s^{-1}}$, which would last for about 4 months.

On this basis, the calibration of the plage-weighted Doppler signal (see Fig. 1 in Durrant and Schröter 1983) should be ten units equals $3\cdot5\ \mathrm{m\,s^{-1}}$ (the average plage imbalance being some 4500 millionths during the period of July–August 1981). This agrees well with the estimate of Edmunds and Gough (1983) who quoted a signal of $2\cdot7\ \mathrm{m\,s^{-1}}$ from plages and $1\cdot0\ \mathrm{m\,s^{-1}}$ from spots for this interval on the basis of (invalid) local thermodynamic equilibrium line formation calculations of the K I line profile. These values are significantly smaller than the measured signal of $6\cdot6\ \mathrm{m\,s^{-1}}$.

However, Andersen and Maltby (1983) obtained an amplitude of $5\ \mathrm{m\,s^{-1}}$ from spots alone in a detailed study of the interval June–August 1981. The cause of the discrepancy was pointed out by Schröter (1984) who noted that the latter end of this period was dominated by several very large sunspots with areas of several 1000 millionths. In the presence of such spots the plage signal is of lesser importance. Thus, with the neglect of plages, Andersen and Maltby found good agreement towards the end of the interval, but amplitudes which were too small at the beginning.

Schröter (1984) has also provided a reconstruction of the total signal, plage plus spots, for July 1981 using a similar numerical simulation to that above. He adopted the centre-of-disc profile of the quiet Sun and the off-centre plage profiles, ignoring their variation with heliocentric angle, a procedure which exaggerates the differences between them. Moreover, Schröter assumed that the calculated signal should be scaled by $\frac{1}{2}I$, where I is the visual estimate of the Ca plage brightness on an arbitrary scale from 1 to 4. However, the synthetic signal is usually dominated by a large bright plage on one side of the central meridian so the profiles of the large bright plages, as measured by Brandt, should represent the significant contributions to the velocity signal without further scaling.

5. Conclusions

If the model presented here is adopted, the velocity signal due to the observed plages and spots during the period 18–25 July 1981 increases from $-1\cdot33$ to $+11\cdot6\ \mathrm{m\,s^{-1}}$ and then falls to $-2\cdot1\ \mathrm{m\,s^{-1}}$, the spot contributions being $-0\cdot5$, $-10\cdot6$ and $-0\cdot8\ \mathrm{m\,s^{-1}}$ respectively. The range of velocity values does indeed reproduce the measurements in this interval, although the zero point is shifted some $0\cdot3\ \mathrm{m\,s^{-1}}$, as noted by Schröter (1984). We thus confirm the conclusion of Schröter that the combination of plage and spots in active regions provides a global velocity modulation that has not only the correct period and phase but also the correct amplitude.

The detection of periodic signals of only a few metres per second in the integrated light of the Sun is a remarkable feat. It shows how important properties of the Sun can indeed be deduced from measurements without angular resolution. However, it also provides a warning that the interpretation can be ambiguous and that a careful assessment of the effects caused by known resolved features of the Sun can contribute to the diagnostic repertoire of stellar observers.

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References

Andersen, B. N., and Maltby, P. (1983). *Nature* **302**, 808.
Brookes, J. R., Isaak, G. R., and van der Raay, H. B. (1978). *Mon. Not. R. Astron. Soc.* **185**, 1.
Bruzek, A. (1981). *In* 'Landolt–Börnstein VI/2a Astronomy and Astrophysics' (Eds K. Schaifers and H. H. Voigt), p. 112 (Springer: Berlin).
Claverie, A., Isaak, G. R., McLeod, C. P., van der Raay, H. B., Palle, P. L., and Roca Cortes, T. (1982). *Nature* **299**, 704.
de la Reza, R., and Müller, E. A. (1975). *Sol. Phys.* **43**, 15.
Durrant, C. J., and Schröter, E. H. (1983). *Nature* **301**, 589.
Edmunds, M. G., and Gough, D. O. (1983). *Nature* **302**, 810.
Pierce, A. K., Slaughter, C. D., and Weinberger, D. (1977). *Sol. Phys.* **52**, 179.
Schröter, E. H. (1984). *Astron. Astrophys.* **139**, 538.

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