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# OBSERVATIONS OF LARGE-SCALE MOTIONS OF THE SUN

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## ABSTRACT

Recent observations of large-scale mass motions on the Sun are discussed. The principal large-scale velocity flows are convection, rotation, meridional flow, and torsional and radial oscillations.

## INTRODUCTION

I would like to give a brief review of some recent observational results on the large scale motions of material on and in the Sun. This review is neither complete nor unbiased but is meant to remind people of the kinds of large-scale flows that may or may not be observable in the Sun. The optimistic assumption behind the study of large-scale motions is that large horizontal scales are in some way related to large vertical scales, i.e., great depths into the Sun. Thus, we hope that we are probing the inner working of the Sun. Stix (1981) has shown that large-scale velocity fields can be transmitted to the observable photosphere from great depths. However, if we see a large-scale motion, we cannot tell observationally at what depth it in fact originates. Such a determination requires interpretation in the context of a model. The Mount Wilson data I refer to have been taken by a series of observers under the guidance of Dr. Robert Howard, and with the support of the NSF, NASA, and ONR.

## CONVECTION

In the solar convection zone there is radial outflow of hot gas and radial inflow of cool gas. The conversion of heat flux into gas motions is central to ma solar phenomena.

The observable rm of convection is the granulation. This is the only structure in which the radial velocity-temperature correlation is visible. Granule sized (about 2 arc seconds) are near the spatial resolution limit of velocity observations and therefore difficult to observe individually (Beckers and Morrison, 1970). If we are interested in the statistical properties of convection, however, we may observe a large-scale "velocity" pattern; the limb redshift. The velocity-temperature-intensity correlation in granulation causes the average wavelength of a spectrum line observed near the center of the solar disk to be blueshifted with respect to the wavelength observed near the limb (Beckers and Nelson, 1978). This effect amounts to several hundred meters per second if

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interpreted as a Doppler shift, and is easily observable in low spatial resolution data (Figure 1).

By comparing the properties of the limbshifts observed in spectrum lines formed at various heights in the photosphere, some knowledge of the statistical character of granulation scale convection can be gleaned. From the comments of some of the other speakers it is clear that a more interesting question is whether the statistical character of convection varies with time. If so, then variations in the solar luminosity, radius, and neutrino flux might be expected. There are now 14 years of digital daily velocity maps of the Sun taken at Mount Wilson, and we are in the process of measuring the limbshift effect in that data to set limits on the magnitude of variation of granule convection.

Another velocity field which has been interpreted as an effect of convection is the supergranulation (Simon and Leighton, 1964). In supergranulation there are neither radial velocities (Giovanelli, 1980) nor temperature fluctuations (Worden, 1975), but only a cellular pattern of horizontal velocities. Supergranulation is of particular interest because magnetic fields on the solar surface are roughly organized into a network around the edges of supergranules. Supergranules are large enough (about 40 arc seconds) to be resolved in the Mount Wilson data, and the root-mean-square velocity amplitude in supergranulation is also being examined for time variations.

One other form of velocity pattern caused by convection has been predicted to be observable at the solar surface, namely, giant cells (Gilman, 1979). These cells would originate deep in the convection zone and have correspondingly large horizontal dimensions. We have searched the Mount Wilson velocity data for evidence of the existence of giant cells, but have not positively seen them, to limits of 3 to 10 m $s^{-1}$ RMS amplitude (LaBonte et al., 1981). Model calculations predict amplitudes of this order, so better observations are of immediate importance. Some efforts to measure giant cell motions by using magnetic tracers have been made (Schöter and Wöhl, 1976), but the velocity sensitivity is not yet as good as the Doppler method.

## ROTATION

The rotation of the Sun and the decrease of rotation rate with increasing latitude were known to the earliest telescopic observer from the motions of sunspots. The use of sunspots and other identifiable features as tracers of solar rotation remains a standard procedure. The equatorial rotation rate of recurrent isolated spots is $2.91 \pm 0.01 \mu$ rad $s^{-1}$ (Newton and Nunn, 1951; Ward, 1966; Kearns, 1979; Clark et al., 1979; Neidig, 1980). Spot groups, which are younger on average than isolated spots, rotate 1 to 2% faster than isolated spots (Ward, 1966; Godoli and Mazzucconi, 1978; Kearns, 1979, Neidig, 1980; Wohl and Balthasar, 1980). There is no convincing evidence for systematic variations of spot rotation within a sunspot cycle or from one cycle to another, in the last 100 years;

reanalysis of spot drawings from the early 1600's suggests that variations might have occurred prior to the Maunder minimum (Eddy et al., 1977; Herr, 1978). Sunspots are excellent markers because of their large size and long lifetimes, but unfortunately exhibit peculiar motions which can reach 10 to 15% of the rotation velocity in extreme cases. The difference in rotation rates measured by single long-lived spots and by spot groups is a form of these peculiar motions. An additional problem is that spots are never seen at high latitudes. At Mount Wilson we have just begun a project to measure sunspot positions on the 70 years of direct photographs taken at the 60-foot tower.

A sunspot may be considered as a single unit of magnetic field. Unfortunately, photospheric magnetic fields outside spots are comprised of units, filigree, much too small and short-lived to measure individually. Larger groupings of filigree are long-lived, however, and rotation may be measured by using magnetic field patterns as tracers (Wilcox and Howard, 1970), We have recently looked at rotation in this way with Mount Wilson data and find the equatorial rate to be 2.91±0.01μ rad $S^{-1}$ for each of the last 14 years. The magnetic field data may be used to measure rotation to the poles (Howard, 1978). A number of other magnetic tracers (white light faculae; chromospheric plages, and filaments; coronal emission patterns) have been used in the past, but the resulting accuracy has been low, since these features are ill-defined averages over many individually identifiable magnetic features.

There are only two tracers on the Sun which are not magnetic: granules and supergranules. Granules are too shortlived to be used, but Duvall (1980) has measured the equatorial rotation rate from the supergranulation velocity pattern to be 2.97μ rad $s^{-1}$, about the rate of young sunspot groups. This measurement should be repeated.

The other way to measure solar rotation is to observe the Doppler shifts of spectrum lines. In this type of data the rotation signal is by far the largest amplitude velocity pattern (Figure 1). The angular rotation rate can be measured at all latitudes, especially close to the poles. The observation of a strict monotonic decrease of rotation rate with latitude (Beckers, 1978a) sets limits on the structure of the convection zone (Gilman, 1979).

Because magnetic fields cover only a small fraction of the Sun, the Doppler measures essentially refer to nonmagnetic material. Doppler rotation measurements do not present a unified result. Stanford data (Scherrer and Wilcox, 1980a) give an equatorial rate of 2.90μ rad $s^{-1}$, the same as isolated recurrent sunspots. They also show no significant variation above the measurement noise on any timescale. Mount Wilson (LaBonte and Howard, 1981a) and Kitt Peak data (Livingston and Duvall, 1979; Duvall, 1981) give a rate 1 to 2% lower, and show variations on all timescales. Most of the day to day variations are caused by the instrument, but the origin of long term variations is not yet settled. The elimination of systematic errors is crucial to obtain an absolute rotation rate. There are differential measurements (Foukal, 1979) which suggest there is a difference in rotation rate between magnetic and nonmagentic gas in the photosphere; more tests of this type should be done.

## MERIDIONAL FLOW

The differential character of the surface rotation implies that angular momentum is redistributed within the Sun, either radially, meridionally, or both. Theories differ on the amplitude and direction which is expected. The Doppler observations all agree that the flow is poleward, with amplitudes of $\simeq$ 20 m $s^{-1}$ (Duvall, 1979) $\simeq$ 40 m $s^{-1}$ (Beckers, 1978b) or $\simeq$ 15 m $s^{-1}$ from Mount Wilson data. Beckers and Taylor (1980) have cautioned that meridional flow may be enhanced or masked by a latitude variation of the limb redshift (and thus, granulation), and their observations suggest that all the quoted values should be increased by $\simeq$ 30m $s^{-1}$ poleward. Tracer measures of meridional flow are possible, using longlived magnetic patterns, and give a poleward flow $\simeq$ 10 m $s^{-1}$ (Howard and LaBonte, 1981).

## OSCILLATIONS

The role of short period oscillations in the Sun has been considered by other speakers, so I will restrict attention to long period oscillations. The sunspot cycle itself has long been thought of as a magnetic oscillation, but only recently has a velocity field been observed which shows some of the mass motions involved. This is the torsional velocity oscillation (Howard and LaBonte, 1980; Scherrer and Wilcox, 1980b; LaBonte and Howard, 1981b). The zones of magnetic (sunspot) appearance are found to be the shear zones of a torsional wave emanating from the poles toward the equator, with an 11 year period and 22 year travel time. Thus 2 waves are visible on the Sun at all times. There is also a lower wavenumber torsional oscillation with a period of 11 years, which has the appearance of a periodic steepening and flattening of the differential rotation curve (Livingston and Duvall, 1979; LaBonte and Howard, 1981b). These wave modes have amplitudes 3 to 10 m $s^{-1}$. It is possible that other torsional modes exist but are of lower amplitude. No meridional component of these waves is detected with limits $\simeq$ 30 m $s^{-1}$.

As other speakers have indicated, it is not known whether the solar radius varies. Low amplitude radial oscillations are not ruled out by existing data. At Mount Wilson we are testing this question in two ways. From our daily full disk magnetic observations we obtain objective radius values, with a precision of $\simeq$ 0.25 arc seconds. We are now analyzing the past 8 years of data to search for radius changes. Second, the project to measure the 70 year series of direct photogaphs will include measures of the radius. Tests indicate that a precision <1 arc second per plate should be possible, and systematic errors uniform and controllable for the entire dataset. The plate measuring project will take about 2 years.

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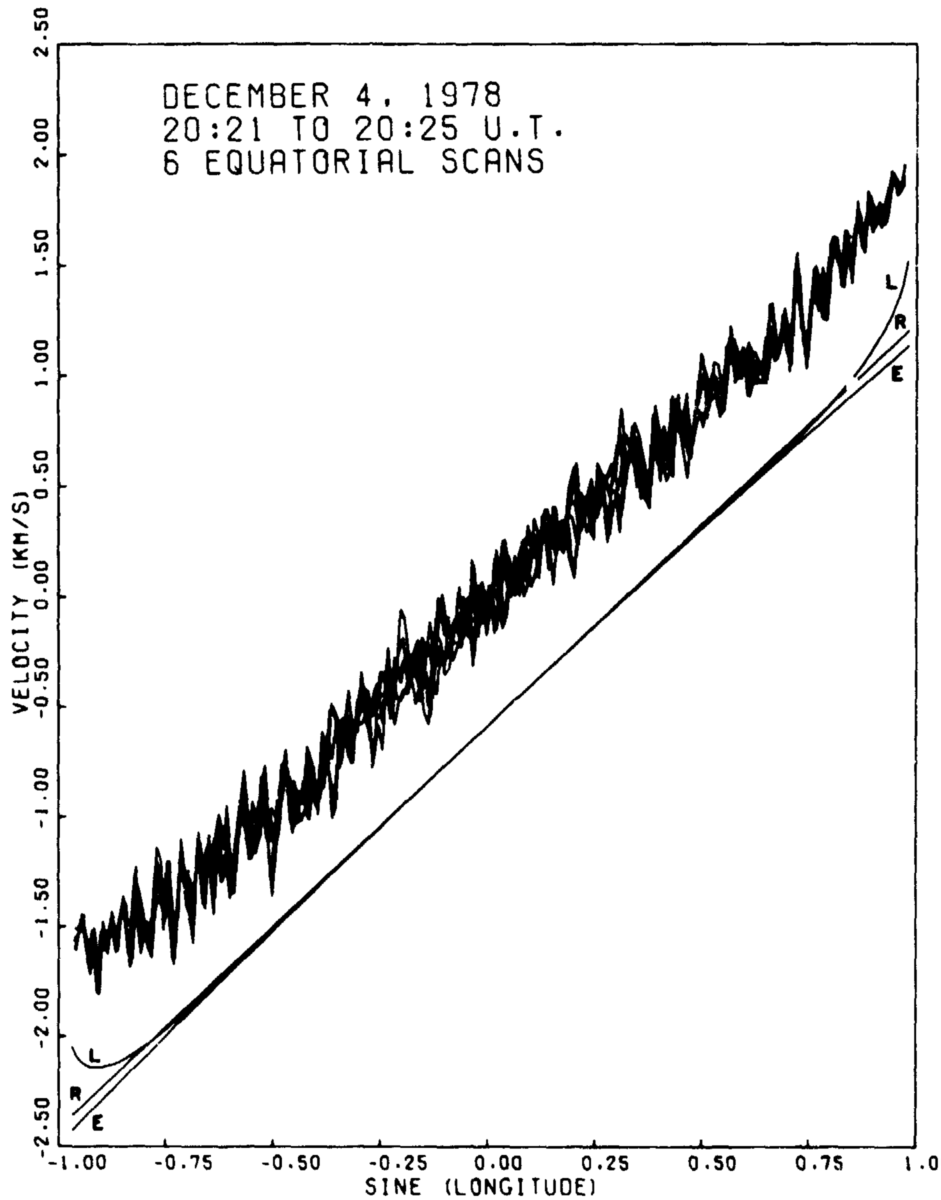


1) Raw Doppler velocity data. Measured line of sight velocities from 6 scans along the solar equator are plotted. The total time interval was 4 minutes. The smooth curves (displaced downward by 0.5 km $s^{-1}$) labelled R, E, and L are respectively the solar rotation; rotation plus "ears" (Howard et al., 1980); and rotation plus ears plus limbshift, as measured from the data. The velocity zero is arbitrary; positive velocities are motions away from the observer. Spatial resolution is 12.5 arc seconds, or 0.013 in sine longitude. Five minute oscillations dominate the velocity variations for $|$sine longitude$| < 0.5$, and supergranulation for $|$sine longitude$| > 0.5$.