AN IMPROVED SEARCH FOR LARGE-SCALE CONVECTION CELLS IN THE SOLAR ATMOSPHERE

B. J. LaBonte and R. Howard
Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington

AND

P. A. Gilman
High Altitude Observatory, National Center for Atmospheric Research

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ABSTRACT

A reanalysis of Mount Wilson solar velocity observations was made to search for giant cellular patterns. The reanalysis avoids several errors made in a previous search. No cells are detected with sensitivity of 3 to 12 m s\(^{-1}\) depending upon wavenumber. The observed amplitudes do not conflict with recent model predictions.

Subject headings: convection — Sun: atmosphere — Sun: atmospheric motions

I. INTRODUCTION

In previous works (LaBonte and Howard 1980; Howard and LaBonte 1980) we have searched for evidence of large-scale convection cells in the Sun by analyzing horizontal east-west velocities on the solar surface. Cell motions were not observed, with upper limits of 5 to 10 m s\(^{-1}\) per wavenumber.

The validity of these limits was questioned recently by Gilman and Glatzmaier (1980). They showed that some of the analysis procedures used would cause underestimates of the true amplitude of solar giant cell velocities. The specific problems which they found are summarized as follows. (1) In constructing synoptic maps of horizontal east-west velocities an improper weighting function was used, reducing all measured amplitudes by 30% (weighted means were taken by dividing by the sum of the absolute values of the weights, rather than by the sum of their squares). (2) Velocities were averaged over the latitude range ±60°. Actual cell velocity patterns may only extend between ±30°. (3) To reduce the noise level and improve the wavenumber resolution, long series of data were analyzed, greater than three Carrington rotations in duration. If the cell pattern has a lifetime less than this, or if the pattern moves nonuniformly with respect to the chosen rotating coordinate system in this length of time, the measured amplitude will be much less than the true amplitude. (4) Different solar rotation rates were assumed in order to see if a cell pattern appeared at a rate other than Carrington's. If the rotation rate of the cell pattern is not constant or differs for each wavenumber component, this test will give no useful information.

In this paper we present new analyses of the Mount Wilson velocity data which avoid the problems found by Gilman and Glatzmaier and compare the results with relevant theoretical calculations.

II. ANALYSIS

The data set consists of 2800 full disk maps of the line-of-sight solar velocities made between 1967 January 1 and 1980 July 3 with the Mount Wilson 150 foot solar tower telescope and magnetograph. The angular resolution was improved from 17''5 to 12''5 during this interval, yielding 11,000 to 25,000 data points per full disk observation. The Fe \(\lambda\) 5250.2 line was used throughout.

The basic data reduction (Howard, Boyden, and LaBonte 1980) fits the observed data to find the solar rotation rate,

\[
\omega(\phi) = A + B \sin^2 \phi + C \sin^4 \phi, \tag{1}
\]

where \(\phi\) is the solar latitude, and the "ears,”

\[
\epsilon(\phi, \text{CMD}) = (D + E \sin^2 \phi + F \sin^4 \phi) \cos \phi \sin^2 \text{CMD}, \tag{2}
\]

where CMD is the central meridian distance.

These velocity fields are removed from the raw data, along with Earth's motion instrumental drift and limb redshift, to reveal the residual velocities. The residual velocities are averaged into a coarse array with 34 zones of equal intervals in sine latitude and sine CMD.

In removing the daily values of the rotation and ears from the raw data, a large fraction of the giant cell amplitude at low wavenumbers is lost. To avoid this attenuation of the giant cell signal we have reformed the coarse arrays by subtracting average values of the rota-
tion and ears from the raw data, rather than the daily values. The average used was a 27-day mean, centered on the individual day of observation.

From the reformed coarse arrays we construct coarse synoptic maps of the longitudinal (horizontal east-west) velocities on the Sun. The Carrington rotation period (27°2753) is assumed. Each point in the synoptic map is an average of all the daily values (~9 or 10) measured at that point while it was within 70° of the central meridian. Each day's values are weighted by sine of the CMD (including the sign) that the point had on that day. This weighting suppresses radial and meridional velocity patterns (symmetric about the CM) and enhances longitudinal velocities (antisymmetric). Proper weighting was used to eliminate problem one found by Gilman and Glatzmaier. The coarse synoptic maps have 34 zones of equal interval in sine latitude and 90 4° bins in longitude.

When the synoptic maps are plotted, they are found to contain features which are extended in latitude but sharply bounded in longitude. The features are artifacts of the inclusion of the daily fluctuations of solar rotation and ears. The sharp boundaries show that the daily fluctuations are instrumental in nature and not a response to solar velocity patterns. Nearly all the synoptic maps are obviously affected by this instrumental noise. The only extended intervals without obvious contamination are Carrington rotations 1614 to 1622, 1630 to 1632, and 1671 to 1673. During these times the contribution of systematic effects is less than or equal to uncanceled solar velocity noise from oscillations and convection. Our analysis will be restricted to these intervals. Whatever amplitudes we measure for giant cell motions must be regarded as upper limits since the instrumental effect may still be present at reduced amplitude even in the best times.

III. WAVENUMBER SPECTRUM

Giant convection cells are assumed to be features of alternate longitudinal velocity sign which are extended in latitude. We have averaged the synoptic maps over latitudes ±28°1 (equatormost 16 zones) to form a time series of longitudinal velocity. Power spectra of the times series were computed for the intervals of good data, and the spectra averaged together. Figures 1a and b show the averaged spectra taken from groups of 128 and 256 time series points (one and one-third and two and two-thirds Carrington rotations).

The resulting amplitudes are very low. There is no measurable excess power at integer wavenumbers as compared to fractional wavenumbers. Expressed as rms velocity per wavenumber, our limits on giant cell motions vary from 12 m s⁻¹ at wavenumber 1 to 3 m s⁻¹ for wavenumbers 20 through 45. This limit is for cell pattern lifetimes of one third to three Carrington rotations. Over such short times there should be little attenuation by differential motions of the individual wavenumber patterns. These limits are comparable to those stated in Howard and LaBonte (1980) of 5 to 10 m s⁻¹ per wavenumber, based on long series of synoptic maps from which the daily rotation and ears had been removed.

Other tests for the presence of giant cell motions are possible. For example, the synoptic maps of Howard and LaBonte (1980) could be analyzed over short intervals. Also, Gilman and Glatzmaier (1980) show that giant cell motions introduce cross-correlations between the rotation and ears parameters A and D (eqs. [1], [2]).

Fig. 1.—(a) Average power spectrum of solar longitudinal velocity. Power is given as m² s⁻² per bandwidth, which is 0.35 wavenumbers. Five original spectra from the intervals of Carrington rotations 1614–1622, 1630–1632, and 1671–1673 were averaged. Each spectrum comes from a set of 256 points, each covering 4° of Carrington longitude. Longitudinal velocity was averaged over latitudes −28.1° to 28.1° at each longitude. (b) Same as (a), except that 10 spectra with bandwidth 0.70 wavenumbers were averaged. (c) Predicted power spectrum of longitudinal velocity. Plotted values are from averages over latitudes +30° to −30° of the velocity in the surface grid layer of the model (Gilman 1979).
IV. COMPARISON WITH THEORY

It is reasonable to ask how the limit we have placed on giant cell motions compares with theoretical predictions. Such predictions require calculations of nonlinear convection in a rotating spherical shell. Only one such model currently exists in a form which can be used for this purpose, namely that of Gilman (see Gilman 1979, and earlier references cited therein). The physics of that model, primarily its lack of compressibility, makes it much simpler than the real Sun. However, it is useful to pose the following question: what velocity amplitude spectrum is predicted in solutions for which the calculated differential rotation is similar in amplitude and profile to that of the Sun? Gilman and Glatzmaier (1980) used one answer to that question in demonstrating how the reduction techniques used by Howard and LaBonte (1980) could artificially attenuate the observed spectrum. The particular theoretical spectrum Gilman and Glatzmaier used had much more power in low longitudinal wavenumbers than we have found from the observations. However, new solutions at lower eddy viscosity, found by Gilman for another purpose, yield an east-west velocity amplitude spectrum for the top layer of the model which is much closer in amplitude to the observed spectrum, as seen in Figure 1c. The calculated differential rotation is still quite close to the observed amplitude and profile. The theoretical spectrum is somewhat flatter than the observed one, but there is reasonable compatibility between theory and observations, even though the theory is oversimplified for the Sun. Clearly, this compatibility must be tested with more realistic theoretical convection models which include compressibility.

Some compressible convection models applied to stars, e.g., Latour, Toomre, and Zahn (1981) suggest that convective flow occurring over several density scale heights may be turned into horizontal velocities which are larger below the top surface than at it, even with stress free velocity boundary conditions. If this is true for giant cells on the Sun, it would provide an additional reason why such cells have been so hard to find. On the other hand, it is not clear just how model dependent this particular theoretical result is—further study is needed before more conclusions are drawn. If this effect appears in the compressible extension of the global convection model which produced the spectrum seen in Figure 1c, then the new spectrum may have even lower amplitude. It is also quite possible that the solar giant cell velocity spectrum has considerably lower power than seen in Figures 1a and b. To find out, systematic instrumental effects must be eliminated down to the m s$^{-1}$ level. In addition, cancellation of solar velocity noise from short-lived features such as granulation and 5 minute oscillations must be improved by obtaining observations much more often than once per day. We expect that the ultimate limit in sensitivity will be set by the velocity contributions of long-lived solar features such as supergranules and active regions.

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REFERENCES


P. A. GILMAN: High Altitude Observatory, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307

ROBERT HOWARD and BARRY J. LABONTE: Mount Wilson and Las Campanas Observatories, 813 Santa Barbara Street, Pasadena, CA 91101