OBSERVATION OF NONACOUSTIC, 5 MINUTE PERIOD, VERTICAL TRAVELING WAVES IN THE PHOTOSPHERE OF THE SUN

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ABSTRACT

Nonacoustic, radially propagating traveling waves have been observed in the solar photosphere. These traveling waves have a period of 278 ± 41 s. The vertical wavelength (~ 500 km) and phase velocity (~ 2 km s\(^{-1}\)) of the waves are among their properties deduced from the data. It is also observed that the waves have outgoing phase part of the time and ingoing phase the remainder of the time. The traveling waves are interpreted to be gravity waves. Their role in the heating of the chromosphere is discussed.

Subject headings: Sun: atmospheric motions — Sun: chromosphere

I. INTRODUCTION

The study in recent years of oscillatory phenomena in the photosphere of the Sun has provided a wealth of information about solar dynamics, but much remains unknown or poorly understood. The oscillations with periods near 5 minutes have been extensively examined and are generally considered to result from the superposition of many low-amplitude, nonradial acoustic modes. In the photosphere and the lower chromosphere, these disturbances are regarded as being evanescent with a small, radial phase shift due to dissipation (see, e.g., Canfield and Mussman 1973; Deubner 1974; Mein and Schmieder 1981).

It is the purpose of this Letter to present observational data on solar oscillations and to demonstrate that these data establish the existence of 5 minute period, nonacoustic, vertically propagating traveling waves.

II. OBSERVATIONAL METHOD AND DATA REDUCTION

The observational data used in the current analysis were obtained by Stebbins et al. (1980). They collected 35 hr of data in four sets of runs, two in 1978 November and two in 1979 February, at the Sacramento Peak Observatory. The data are high-resolution line profiles of the nonmagnetic 5434 Å Fe I line for which Altrock et al. (1975) report a height of formation at line center of 530 km above \(\tau_{5000} = 1\); thus, this line spans a large portion of the photosphere. These data were collected from a 1" X 4" patch at disk center employing the vacuum tower telescope, the echelle spectrograph, and the diode array. The data were gathered in 36.5 minute streams of high-resolution line profiles with a time resolution of 8.55 s for individual lines; that is, 256 individual line profiles were collected during each 36.5 minute period. Owing to the detailed understanding of this line, it was possible to associate positions on the line profile located successively closer to line center with successively higher altitudes in the photosphere. The Doppler shift of the photospheric line at each position in the line profile and at each 8.55 s time point is associated with the velocity of the disturbance at the corresponding optical depth and time point. Stebbins et al. (1980) selected nine depths in the photosphere with this technique and obtained a time stream of velocities for each of these nine depths. Other observations (i.e., those of

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Canfield and Mussman 1973 and Mein and Schmieder 1981), by contrast, distinguish two depths.

The data were bandpassed with full passage between 2.475 and 4.725 mHz, tapering to zero at 1.125 and 6.075 mHz, respectively. A Hilbert transformation was performed on each filtered data set, yielding a velocity amplitude and corresponding phase at each 8.55 s time point for each of the nine different heights in the photosphere. For details of this part of the analysis, see Stebbins et al. (1980). One extreme of the height, $Z_9$, is at the greatest optical depth and is near the base of the photosphere, while the other extreme of the height, $Z_1$, is near the temperature minimum; the intermediate heights lie between, with optical depth decreasing from $Z_9$ to $Z_1$. The Hilbert transform is an important step in the analysis because it yields the radial oscillations in the complex plane where their properties are readily discernible (e.g., the up-and-down motion of a simple harmonic oscillator would become uniform circular motion with this rotation into the complex plane). A useful review of the properties of this transform was given by White and Cha (1973).

The results of the Hilbert transform for all the data, in microcosm, are represented in Figures 1a and 1b; for height $Z_4$, the mean velocity amplitude and the standard deviation of the velocity amplitudes are plotted as a function of the velocity amplitude at height $Z_9$. From Figure 1a, it can be seen that the mean velocity amplitude at $Z_4$ varies linearly with that at the lowest altitude, $Z_9$, a dependence which holds for each depth with the slope of the line increasing with successive increases in altitude with respect to $Z_9$. This implies that there is sufficient resolution to allow for the study of certain radial properties of photospheric disturbances. The standard deviation of the velocity amplitude at $Z_4$ (as well as at all other depth points) is essentially constant for all values of the velocity amplitude at $Z_9$. For instance, with an increase in the velocity amplitude of a factor of 10, the standard deviation increases correspondingly by only a factor of 1.5. It is this constancy of the standard deviation which plays a central role in the interpretation of the data which follows. The standard deviation, $\sigma_4$, is calculated from the aggregated 36.5 minute data strings and reflects the scatter in the velocity amplitudes occurring at $Z_4$ for a given velocity amplitude at $Z_9$.

The positive and negative mean phase differences between the velocities at $Z_4$ and $Z_n$, $\phi_n - \phi_4$, are obtained using the results of the Hilbert transform and are plotted in Figure 1b as a function of the velocity amplitude at $Z_9$. The fitted curves closely approximate hyperbolae. This behavior is also observed for elevations $Z_1 - Z_9$ against $Z_9$. For small fixed values of the velocity amplitude at $Z_9$, the phase difference, $\phi_n - \phi_4$ ($1 \leq n \leq 8$), increases with increasing altitude in the photosphere. The behavior of the mean phase differences also plays a central role in the following interpretation of the data.

**III. INTERPRETATION OF THE REDUCED DATA**

The behavior of the standard deviation in Figure 1a and the phase difference in Figure 1b could not be produced by the 5 minute acoustic mode acting alone in an otherwise quiet photosphere for several reasons. The 5 minute period, acoustic wave is evanescent in the photosphere, implying that the phase difference would be constant and small and insensitive to the altitude in the photosphere and that the standard deviation, without other power sources, in all cases should be much smaller compared to the observed velocity (assuming observational effects are negligible). Therefore, the effect of some other disturbance survives the bandpass, manifesting power in addition to that of the 5 minute acoustic mode.

A nonsolar origin for this secondary disturbance has been considered and eliminated, primarily because of the difficulty in producing a signal as large as that observed which exhibits an amplitude correlated with the position in the line profile. This secondary disturbance is solar in origin and has two possible sources. One possibility is a disturbance which has a frequency outside that of the bandpass but which nonlinearly couples to the 5 minute acoustic mode, yielding power in the 5 minute period region. The other possibility is a separate, independent disturbance with a period near 5 minutes.
Let us consider the first possibility. The lowest order nonlinearity in this apparently linear system (Fig. 1a) yields a total velocity, \( V_n \), given by

\[
V_n = V_{a,n} + kV_{a,n}V_{b,n} + V_{b,n},
\]

where the symbol \( V_{a,n} \) represents the acoustic mode velocity arising from the superposition of many hundreds of individual modes at depth point \( n \) (1 \( \leq n \leq 9 \)), \( V_{b,n} \) is the velocity of the unknown disturbance, and \( k \) is the coupling constant for the nonlinearity. The standard deviation of the velocity amplitude at \( Z_n \) (1 \( \leq n \leq 9 \)), \( \sigma_n \) defined in the same manner as \( \sigma_9 \) above, and the corresponding phase difference, \( \phi_n - \phi_9 \), can be straightforwardly calculated from equation (1). These theoretical quantities cannot match the requirements of the data that the velocity amplitude curve of Figure 1a is linear, \( \sigma_n \) is independent of \( |V_n| \), and the \( \phi_n - \phi_9 \) curve is hyperbolic. This fact unambiguously eliminates the first possibility.

Consider the case in which the secondary disturbance is an independent entity having a period which is near 5 minutes. In that eventuality, equation (1) becomes

\[
V_n = V_{a,n} + V_{b,n}.
\]

From equation (2), making a Maclaurin expansion with \( V_{b,n}/V_{a,n} \) as the expansion parameter, and keeping terms to second order,

\[
\sigma_n^2 = \left( \frac{|V_n|^2}{|V_{a,n}|^2} \right)^2 \frac{1}{2} \left( \frac{|V_{b,n}|^2}{|V_{a,n}|^2} + \frac{1}{2} \left( \frac{|V_{b,n}|^2}{|V_{a,n}|^2} \right) \right)
\]

and

\[
\Delta\phi_n,9 = \phi_n - \phi_9 = \frac{|V_{b,n}|}{|V_n|} \sin \theta_n - \frac{|V_{b,n}|}{|V_9|} \sin \theta_9
\]

are obtained, where \( \theta_n \) is the angle between \( V_{a,n} \) and \( V_{b,n} \). If \( |V_{b,n}| \) is independent of \( |V_{a,n}| \), then \( \sigma_n \) is independent of \( |V_n| \), and the \( \phi_n - \phi_9 \) curves are hyperbolic. This precisely matches the properties of the data. These requirements are not met if \( |V_{b,n}| \) depends on \( |V_{a,n}| \).

It is therefore concluded that \( V_{a,n} \) and \( V_{b,n} \) represent two distinctly different, superposed, independent phenomena, each of which has a period near 5 minutes.

IV. PROPERTIES OF THE SECOND 5 MINUTE PERIOD DISTURBANCE

A further examination of the data allows a fairly detailed description of this second phenomenon. This stage of the analysis exploits the fact that, as a result of the Hilbert transform, the data are represented in the complex plane. In Figure 2a the clockwise rotation of a pure, 5 minute period, acoustic wave is represented by showing its orientation in the complex plane at three successive time points. Each velocity vector in Figure 2a represents the theoretical evanescent acoustic mode at all nine altitudes in the photosphere with the altitude dependence of the acoustic mode eigenfunction removed, i.e., the \( |V_n| \) under study was divided by the mean slope of the \( |V_n| \) versus \( |V_9| \) curve. Figure 2b idealizes the superposition of an outward radial traveling wave on the radially evanescent wave of Figure 2a. The wave is traveling because its phase changes, in a counterclockwise sense, with altitude. The traveling wave has an outgoing phase because the rotations in time and space (radial direction) have opposite senses. Figure 2c shows typical real data at three time points in the complex plane. This figure clearly represents the superposition of an acoustic mode and a traveling wave. If the secondary disturbance exhibits a systematic rotation with altitude, either clockwise or counterclockwise, for at least 3.5 minutes, it can be considered to be a traveling wave. The secondary disturbance meets this requirement half of the time. A typical traveling wave with ingoing phase, taken from real data, is shown in Figure 2d. These traveling waves show a coherency in time longer than 20 minutes in some cases.

To further quantify the conclusion that the secondary disturbance is a traveling wave, its radial Fourier transform is calculated at every eighth time point for all the data without regard to its traveling wave character. To perform this calculation at a particular time point, the altitude dependence of the observed 5 minute period mode is removed, as previously discussed. The mean of the \( V_n, \Sigma_n(V_n/9) \), is then removed to approximate the removal of the acoustic mode, and finally the Fourier transform is performed. The individual transform multiplied by its complex conjugate yields the power spectrum of the traveling wave as a function of vertical wavenumber. The individual power spectra for Figures 2c and 2d are shown in Figures 3a and 3b, respectively. The large peak in each of these two power spectra yields a dominant vertical wavenumber which has a magnitude of about \( 3\pi/2H \), where \( H = Z_9 - Z_0 \). The power spectrum aggregated from those for every eighth data point for all the data is represented by the solid curve of Figure 3c. The individual contributors to this solid curve have power spectra closely resembling those shown in Figure 3a or 3b. The two main peaks in Figure 3c are at \( \pm 3\pi/2H \) and are of approximately equal height. The fact that there are two main peaks reflects the removal of small \( k \) (long wavelength) traveling waves along with the acoustic mode. The small peaks for high \( k \) and the resolution are not inconsistent with their being a result of the Fourier transform of the contribution function. The total area under the curve in Figure 3c for \( k > 0 \) is very close to that for \( k < 0 \), where \( k \) is the vertical wavenumber. The two main peaks imply that some of the vertical traveling waves have outgoing phase (\( k > 0 \)) and some have ingoing phase (\( k < 0 \)). It should be
Fig. 2.—(a) An idealized representation of a single, 5 minute period, acoustic wave in clockwise rotation is shown at three successive times which are two time points apart (17.1 s). (b) The acoustic mode of (a) is shown with an idealized outgoing traveling wave of smaller amplitude superposed. (c) Typical real data are shown with an outgoing phase velocity. (d) Typical real data are shown with an ingoing phase velocity.

Fig. 3.—(a) The power spectrum (in arbitrary units) as a function of vertical wavenumber at one time point is presented for the traveling wave portion of Fig. 2c. (b) The corresponding power spectrum (in arbitrary units) is shown for Fig. 2d. (c) The curve represents the aggregate power spectrum from the data at every eighth time point, with the mean removed, as a function of the vertical wavenumber. (d) The power spectrum (in arbitrary units) is shown for the evanescent wave of Fig. 2a.
noted that the evanescent acoustic mode is largely re-
moved, since its power spectrum is a sinc² function
peaked at $k = 0$ (see Fig. 3d). Thus, it is clear that the
secondary disturbance is due to traveling waves which
have outgoing phase about half the time and ingoing
phase about half the time.

The period of these traveling waves is determined by
measuring, at each altitude, the angular frequency of
those which are most stable. The average stability is
longer than 10 minutes. The period obtained in this
manner is $278 \pm 41$ s (or $\omega = 0.023 \pm 0.003$ rad s$^{-1}$).
There is no apparent difference in period between the
traveling waves with outgoing and ingoing phase.

Both of these types of waves have approximately the
same dominant vertical wavenumber (strongly peaked at
$3\pi/2H$) and the same angular frequency. Their vertical
phase velocity is $\pm \omega/k$ which corresponds to a magni-
tude of about 2 km s$^{-1}$ if $H$ is taken to be 400 km (Altrock et al. 1975).

V. DISCUSSION

The existence of a second, separate disturbance in the
solar photosphere has been established. The disturbance
is composed of traveling waves having a period near 5
minutes. These disturbances have a vertical wavelength
of about 500 km and a period of $278 \pm 41$ s. The
vertical phase velocity of these disturbances is about 2
km s$^{-1}$.

These 5 minute period, traveling waves are most
consistent with gravity waves, which are allowed in this
region of the atmosphere. The 5 minute period, acoustic
mode is evanescent here. The small phase shift assigned
to the acoustic mode implies a vertical wavelength and
phase velocity about two orders of magnitude larger
than that of the disturbance identified here. In addition,

the observed phase and amplitude variations of the
secondary disturbance with height cannot be reproduced
by the superposition of ingoing and outgoing evanescent
solutions to yield zeros in the eigenfunction which move
up and down rapidly (see Zhugzhda 1972). A predomi-
nantly magnetic disturbance in the quiet photosphere
would be due to a primarily vertical field leading to a
primarily horizontal disturbance (Thomas, Clark, and
Clark 1971). The current observational technique is
insensitive to horizontal disturbances.

In conclusion, gravity waves are tentatively identified
as a major component of the traveling waves. In fact,
the data are consistent with gravity waves being gener-
ated below $Z_0$ and being partly reflected back from
above $Z_1$.

The estimated outgoing energy flux of the “gravity”
waves, ignoring spatial filtering effects, is about two
orders of magnitude smaller than that required to heat
the chromosphere. However, corrections for spatial
filtering effects could lead to estimates of the flux which
would be of the required order of magnitude. Estimating
the energy flux of these waves is further complicated by
the “reflected” waves and by the fact that a small
minority of the waves with outgoing phase appear to be
some sort of horizontally local pulse.

To acquire more details regarding the properties of
these traveling waves, further observations will be made
to obtain their horizontal spatial properties.

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