WAVES IN THE SOLAR PHOTOSPHERE

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Abstract. Time-sequences of line profile data have been subjected to a unique analysis which produces an amplitude and phase of the velocity and intensity at several line depths for each time sample and spatial point on the Sun. The data have been filtered to pass only the frequencies and spatial wavenumbers of the 5-min band. Yet, a secondary oscillation emerges, the phase of which propagates downward. Empirical eigenfunctions for velocity and intensity are given, and the kinetic energy flux is computed.

1. Introduction

The behavior of waves in the solar photosphere has been studied since the discovery of waves (Leighton, 1960). The initial thrust was aimed at augmenting the facts known about waves to understand their origin and their contribution to the heating of chromosphere and corona. Eventually, the waves with periods around 5 min were understood to be resonant acoustic modes (Ulrich, 1970; Leibacher and Stein, 1971; Deubner, 1975) with little importance in the heating of the outer layers (Lites and Chipman, 1979). Since that time, the acoustic modes have usually been studied for clues into the unseen layers of the Sun.

The understanding of the global modes still rests to some extent on their behavior in the photosphere. All methods of observation detect their manifestations in this layer; its response is important for calibration and intercomparison of different observations. The photosphere constitutes the outer boundary of the Sun's resonant cavity. As such, it affects the resonant frequencies, and Christensen-Dalsgaard (1984) has suggested some of the discrepancy between observed and theoretical frequencies may be attributable to an incorrect upper boundary condition in pulsation models.

The velocity and temperature fluctuations associated with altitude-dependent material motions are difficult to infer from absorption lines. Spectral diagnostics are confused by several factors: a spectral line may appear to shift, broaden, change its strength and change its asymmetry in response to an altitude-dependent velocity field. Different velocity phenomena enjoy different admixtures of these responses according to frequency, spatial scale, spectral line, etc. Separation of these phenomena (e.g.,

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convection, evanescent waves, traveling waves) eases the interpretation of spectral lines. The observer must define measures of the line which can be related to velocities and temperatures and can be analyzed for their temporal and spatial behavior. If these difficulties can be largely overcome by taking advantage of the resonant character of the global modes (i.e., periodic in time nonpropagating in space), then something might be learned about the photosphere. And the difficulties with spectral diagnostics might thereby be reduced.

This work consists of the simple measurement of line profiles and a novel analysis to deduce the behavior of the 5 min oscillations in the photosphere. That behavior is characterized by the amplitude and phase of velocity and intensity eigenfunctions at several points in a single line profile. The average velocity, intensity variations and derived energy flux agree well with earlier studies of wave behavior. However, this different analysis reveals several new and surprising features of wave behavior in the photosphere.

2. Related Work

Observational studies of photospheric waves have been ongoing for nearly three decades. Extensive related work has been done as part of the broader efforts of measuring the Sun's velocity fields and intensity variations, studying the energy balance of the outer layers, refining spectral diagnostics and theoretically predicting wave behavior. While reviews of all these areas are far beyond the scale of this paper, this section will attempt to direct the reader to current, milestone or review articles in these subjects. This paper itself is an outgrowth, and to some extent a re-examination, of previous work (Stebbins *et al.*, 1980, Hill *et al.*, 1982) stimulated by investigations of global oscillations.

The original study of photospheric wave behavior was reported in a series of papers from Sacramento Peak Observatory (Evans and Michard, 1962a, b, c; Jensen and Orrall, 1963; and Evans *et al.*, 1963) investigating the spatial and temporal properties of waves, and the phase relation between intensity and velocity. The ensuing flood of reports on velocity studies is reviewed in Beckers and Canfield (1975), Beckers (1981), and Deubner (1981). The essence of these two decades is that the 5 min oscillation is nearly, but not completely, evanescent (Canfield and Musman, 1973; Lites and Chipman, 1979), the intensity phase lags the velocity by about 90° (e.g., Evans *et al.*, 1963; Deubner, 1974). The average amplitudes of intensity perturbations and velocity were established by many investigators. Mein and Schmieder (1981) and Staiger *et al.* (1984) report recent efforts to determine phase and amplitude of velocity.

Measurements of intensity oscillations in lines or continuum are somewhat more difficult, and reports are less numerous. Many velocity observations referenced above produce some intensity results, but observations specifically tailored for the study of temperature fluctuations concentrate mainly on intensity. Pravdjuk *et al.* (1974), Altrock and Musman (1976), Keil (1977), and Keil and Canfield (1978) all infer increasing temperature fluctuations with depth. Andersen (1984) has reported intensity data treated for phase comparison with computed eigenfunctions (Frandsen, 1984).