HIGH FREQUENCY WAVES AND CHROMOSPHERIC MAGNETISM

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ABSTRACT Observations of \( p \) modes in the frequency ranges 1-4.2 mHz and 4-10 mHz have shown conclusively that those modes vary with the solar activity cycle, thus providing a new indicator of the Sun’s activity. The theoretical nature of such changes is unclear. Simple polytropic models with an isothermal, magnetic chromosphere have demonstrated that changes in chromospheric magnetism and temperature produce frequency shifts that are qualitatively similar to those observed for modes in the 1-5 mHz range. Recent observations by Ronan, Cadora and LaBonte (1994) indicate that high frequency modes are significantly different from low frequency modes over the solar cycle. Here we demonstrate that a model with changes in chromospheric magnetism and temperature gives rise to frequency shifts of the kind observed over the complete range of frequency.

INTRODUCTION
The observations of Elsworth et al. (1990) and Libbrecht and Woodard (1990) have firmly established that \( p \) modes vary with the solar cycle, and that this variation is present both for very low degree modes and for intermediate modes (see also Bachmann and Brown (1993) and the review by Pallé (1995)). For intermediate modes, with degree \( l \) in the range \( 5 < l < 62 \), the variation of \( p \)-mode frequency is known to be correlated with solar activity (Woodard et al. 1991). An understanding of this effect is important both for our knowledge of \( p \) modes and for our greater understanding of the solar activity cycle. The \( p \) mode variation with the cycle gives a distinctive measure of activity: if the change in frequency, \( \Delta \nu \), from one time to another, is plotted as a function of frequency \( \nu \), then \( \Delta \nu \) first rises shallowly with frequency at low \( \nu \) but then turns over at about 3.9 mHz to plunge down towards zero shift at about \( \nu \approx 4.3 \) mHz (Libbrecht and Woodard 1990; Woodard and Libbrecht 1991).

What, then, are the causes of the observed frequency shift? Pre-dating the observations, Campbell and Roberts (1989) and Evans and Roberts (1990) argued on theoretical grounds that changes in chromospheric magnetism would lead to measurable changes in frequency over the solar cycle, and also on shorter time scales as chromospheric activity fluctuated. The simple models of chromospheric magnetism investigated led to theoretical frequency shifts \( \Delta \nu \) that were opposite in sign from one another, indicating that the detailed magnetic structure of the chromosphere was important in determining frequency.
shifts. A chromosphere with a uniform magnetic field gave a positive $\Delta \nu$ for an increase in field strength (Evans and Roberts 1990); a positive frequency shift proved to be consistent with those later observed. Subsequent theoretical developments by Evans and Roberts (1992) and Jain and Roberts (1993, 1994) have demonstrated a yet closer agreement with the observations of Libbrecht and Woodard. In the theory, an increase in frequency shift as a function of frequency is associated with an increase in chromospheric field strength. This is consistent with the observed frequency shifts at low frequency, from the year 1986 to the years 1988 and 1989, associated with the rise phase of solar activity from minimum towards maximum. However, at about 4 mHz the frequency shift curve plunges down towards zero values, an effect not apparent in the calculations of Evans and Roberts for an envisaged increase in chromospheric field strength. Recently, Jain and Roberts (1993, 1994) have shown that if simultaneously the chromosphere undergoes an increase in both magnetic field strength and temperature, then a fall in frequency shift occurs at about the observed level. The theoretical shift is qualitatively similar to that observed, though less steep.

Observations by Ronan et al. (1994) of $p$ modes out to 10 mHz have taken the subject significantly further. Ronan et al. compared 1991 Mees Observatory data with South Pole data for 1987, for the frequency range 4.0-6.5 mHz. They have shown that frequency shifts at high $\nu$ (> 5 mHz) are opposite in sign and larger in magnitude than those recorded at low $\nu$ (< 4 mHz). Taken together with the frequency shifts at low $\nu$, we see that the frequency shift as a function of frequency exhibits a peak and trough behaviour, with a small peak occurring at about 4 mHz and a deep trough at about 5.5 mHz. This distinctive feature in the frequency response curve requires detailed theoretical explanation. We show here that the simple uniform chromosphere model is able to produce a double-structure frequency response curve qualitatively similar to that observed.

$p$ MODES AND MAGNETISM

Consider a polytopic medium, modelling the solar convection zone, extending from $z = 0$ to plus infinity; the polytrope is assumed to be field-free. The atmosphere (in $z < 0$) above the polytrope is taken to be isothermal and threaded by a uniform horizontal magnetic field. This region models the magnetic chromosphere. We are interested in the influence of this atmosphere on $p$ modes confined by the polytropic cavity in the medium below. Because the wave amplitude of a $p$ mode penetrates into the magnetic atmosphere, its frequency at fixed horizontal wavenumber is influenced by that atmosphere. Consequently, changes in the atmosphere are reflected in changes in mode frequency: a frequency shift occurs. This may happen on a short timescale of weeks, as active regions come and go, or it may happen over a timescale of years as the solar activity cycle progresses (Campbell and Roberts 1989; Evans and Roberts 1990, 1993; Jain and Roberts 1993, 1994).

 Thermal and magnetic changes in the chromosphere influence the equilibrium structure of the atmosphere in a subtle way, leading to changes in the local sound speed and Alfvén speed. This in turn influences the frequencies of $p$ modes. Frequency shifts $\Delta \nu$ may be determined by a WKB-formulation, a detailed derivation of which is available in Johnston (1994). Calculated frequency shifts are displayed in Figures 1 and 2, for modes of degree $l = 50$ and 150. The
chromospheric field strength is assumed to change from 10 G to 30 G; various changes in chromospheric temperature are considered from a base value of 4170°K. The shifts are seen to be negative at high frequency and of a magnitude comparable to those observed by Ronan et al.

![Graph showing calculated frequency shifts as functions of frequency](image)

**Fig. 1.** Calculated frequency shifts $\Delta \nu$ (in $\mu$Hz) as functions of frequency $\nu$ (in mHz), for $p$ modes of degree $l = 50$. The shifts are a result of an increase in chromospheric field strength from 10 G to 30 G, combined with chromospheric temperature rises from 4170°K to 4170°K (i.e., no change; top curve) to 5000°K, 6000°K, 7000°K, and 8000°K (bottom curve).

The shifts at high $l$ are roughly proportional to $l$ (as expected from the low frequency results of Evans and Roberts (1992), Wright and Thompson (1992), and Jain and Roberts (1993)). The positive shift observed at low $\nu$ is not apparent in Figs. 1 and 2, simply because it is dominated in those figures by the negative shift at high frequency. For example, for a temperature change from 4170°K to 6000°K the $l = 50$ mode has a maximum shift of $\Delta \nu \approx 100$ nHz at $\nu \approx 3$ mHz, falling to zero at $\nu \approx 4$ mHz. For $\nu > 4$ mHz, the shift continues...
to fall until $\nu \approx 6.3$ mHz, when the minimum is reached with $\Delta \nu \approx -2500$ nHz.

Fig. 2. As in Fig. 1, except shifts are calculated for $l = 150$.

This calculated behaviour, a consequence of an increase in magnetic field strength and temperature in the atmosphere, is remarkably similar in form to that observed in the low and high frequency ranges.

REFERENCES

Pallé, P. L. 1995, these proceedings.