Coupling of the Sun's internal oscillations to the solar wind

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ABSTRACT

Spectral analysis was performed on upstream solar wind data obtained from the ACE and WIND satellites in order to investigate the possible existence of periodic variations in the solar wind due to coupling from internal oscillations of the Sun. The solar wind proton density, proton temperature and velocity, and the interplanetary magnetic field (IMF) north-south component were examined. No consistent spectral peaks were found over different years or from different instruments at the same time, indicating that internal solar modes are unlikely to affect these solar wind parameters in a periodic fashion.

INTRODUCTION

Oscillations exist in the Sun in the form of pressure and gravity waves. Gravity waves are trapped in the deep interior of the Sun below the convection zone, while pressure waves can propagate throughout the Sun's interior. Oscillations that propagate around the Sun and arrive in phase at the original point form standing waves called normal modes. Standing pressure waves are called p-modes while standing gravity waves are called g-modes. Normal modes give rise to surface oscillations as the wave energy couples with the boundary of the cavity. This boundary is usually the photosphere where the density drops off rapidly.

Helioseismology is the study of these surface oscillations to measure the internal structure and dynamics of the Sun [1]. One of the earliest studies of solar oscillations established that the power spectrum of the Sun's full disk contained a multitude of Doppler shift peaks between about 2.5 - 4.5 mHz [2]. The Global Oscillation Network Group (GONG) and Birmingham Solar Oscillation Network (BiSON) are examples of recent studies being undertaken to measure these surface oscillations. Fig.1 shows a power spectrum of solar oscillations obtained from disk-averaged observations from the BiSON network. The spectrum spans approximately four months data and clearly shows power at discrete frequencies. Significant power has also been observed at frequencies ranging from 1.4mHz to 5.6mHz, corresponding to periods of 3 to 12 minutes. The oscillations have been named '5 minute oscillations' due to their dominant mean period.

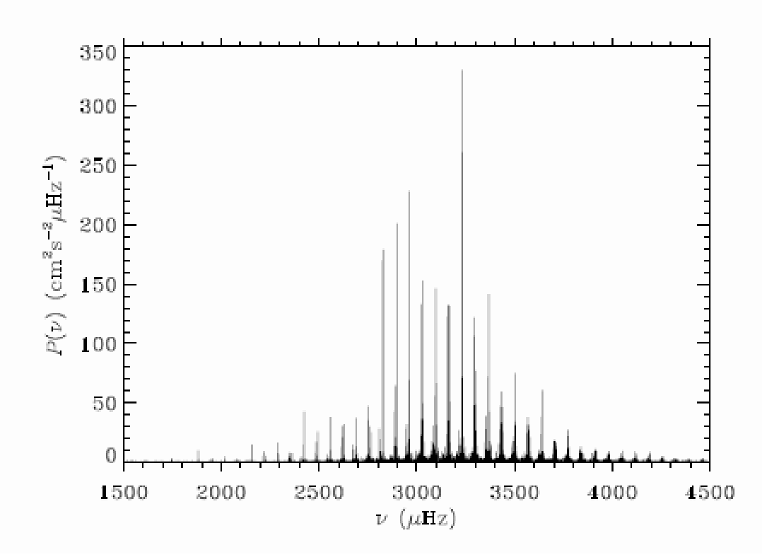

Fig. 1. Power spectrum of internal solar oscillations, obtained from Doppler observations obtained in light integrated over the disk of the Sun (from [3]).

It is possible that these surface oscillations affect the corona in such a way as to produce periodic variations in the solar wind. The solar wind arises from outward expansion of the high temperature corona. The source for coronal heating is the kinetic energy of plasma motions in the photosphere [4]. This affects magnetic field lines mapping to the corona and may be associated with MHD Alfvén waves that dissipate energy in the corona. Such waves with periods of order 5 min have been observed in the solar photosphere [5]. Although the exact mechanism is unclear, it is possible to envisage that the coronal heating rate (and hence the solar wind) may be modulated by wave properties [e.g. 6]. The purpose of the present study was to determine if periodic variations exist in the solar wind and are attributable to internal solar modes. Lessard et al. [7] suggested that the solar wind contains frequencies corresponding to helioseismic p-modes, which couple to the Earth's magnetosphere causing periodic fluctuations in magnetometer data. This implies that periodic variations should be present in the Interplanetary Magnetic Field (IMF).

METHOD

Solar wind data were obtained for 1994 – 2003 from both the WIND [8] and ACE satellites [9], accessed via the NASA omniweb data portal site [10]. The parameters selected for analysis were the north-south (z) component of the IMF (in GSM coordinates), and the solar wind proton density, temperature and velocity.

The data were obtained from whichever of the satellites was near the L1 Lagrange point, approximately 220 Earth radii upstream. However, ACE replaced WIND at the L1 point at the beginning of 1998, after which WIND was moved to another orbit around the Earth before being moved again for a different purpose. Data for 1998 therefore came from both satellites at two different locations.

Helioseismic oscillations have periods in the range of 3 – 12 minutes. In order to obey the Nyquist sampling criterion and avoid aliasing, data with a resolution of less than 90 seconds should be used to measure these modes. The majority of the data obtained satisfied this criterion. The exception was 18 months of solar wind velocity data obtained from WIND, for which the resolution was 92 seconds. Oscillations with significant powers at higher frequencies may be aliased as noise or artifacts. There is no evidence of this in the results.

Spacecraft data were organised into time series files approximately one month long, then unwanted features such as spikes and error flags were removed. Power spectra were then computed by an FFT using typically 120 minute long data windows weighted by a Hanning window, and stepping successive spectra by 50%. The individual spectra were then summed together and averaged over a month of data at a time. This averaging process minimises the effects of random features and makes persistent features more evident**.** The 50% overlap compensates for the weighting of the Hanning window function, hence improving statistical reliability. Window lengths of 6 hours and 2.5 days, and step lengths of 10% were also used with no difference in the results.

The resultant averaged spectra had a roughly 1/f dependence and were therefore frequency weighted to compensate for this dependence.

Finally, 99% confidence intervals were calculated for each spectrum. These indicate the statistical significance of peaks in the data. Overall, approximately 14 years of solar wind data were analysed in this way.

RESULTS

The majority of the spectra showed little deviation from the power spectrum of 1/f noise. Fig.2 shows a typical 1 month long time series for the IMF magnitude, and the resultant averaged power spectrum. The spectrum has a log-log scale and shows an approximate power law slope of $f^{-0.9}$. The error bars in the figures indicate 99% confidence intervals. The time series shows typical fluctuations that occur in all solar wind parameters. These large fluctuations produce irregularities in the spectra, but their effect is reduced by averaging discrete spectra over the full month. This example is typical of solar wind IMF z-component spectra.

Many of the proton density spectra obtained from the ACE spacecraft show a peak near 4-5mHz. Fig.3 presents an example ACE proton density spectrum, in which such a peak is clearly evident. Similar peaks were not present in data from other instruments or from WIND. This is discussed later.

Fig.4 shows a typical unweighted (left hand panel) power spectrum for proton temperature and the weighted spectrum for the same time series (right). Although some peaks are present none are above the 99% confidence interval, and they are therefore statistically insignificant. This is typical of proton temperature observations.

Fig. 5 shows a typical power spectrum for solar wind velocity. These spectra also did not show any significant peaks.

The spectra in figures 3, 4 and 5 exhibit smaller power law slopes than the spectrum in figure 2.

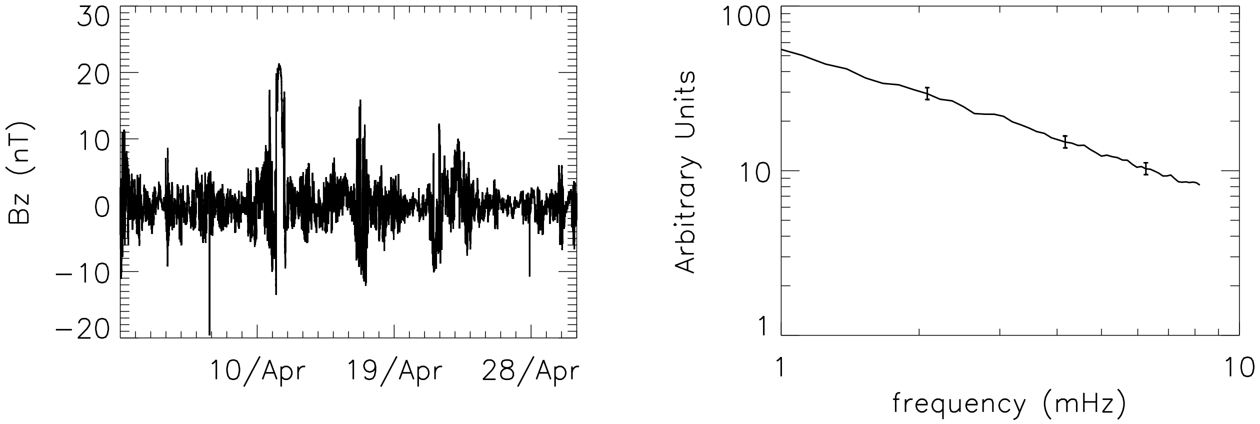

Fig. 2. Time series (left) and power spectrum of the IMF north-south component magnitude as measured by WIND over April 1997. Time resolution is 1 minute, spectral resolution is 0.14mHz. Error bars denote 99% confidence intervals.

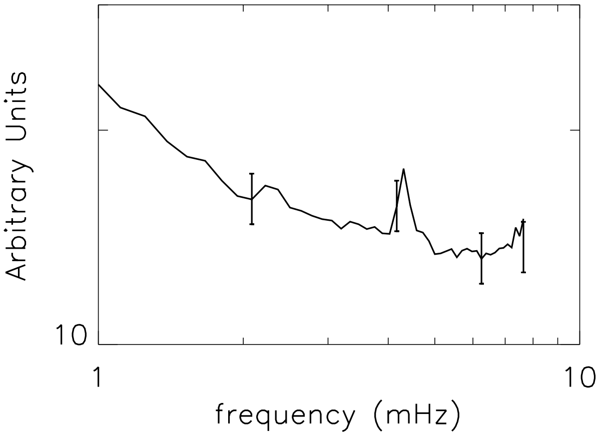

Fig. 3. Power spectrum of proton density from ACE for March 2003. Spectral resolution is 0.14mHz.

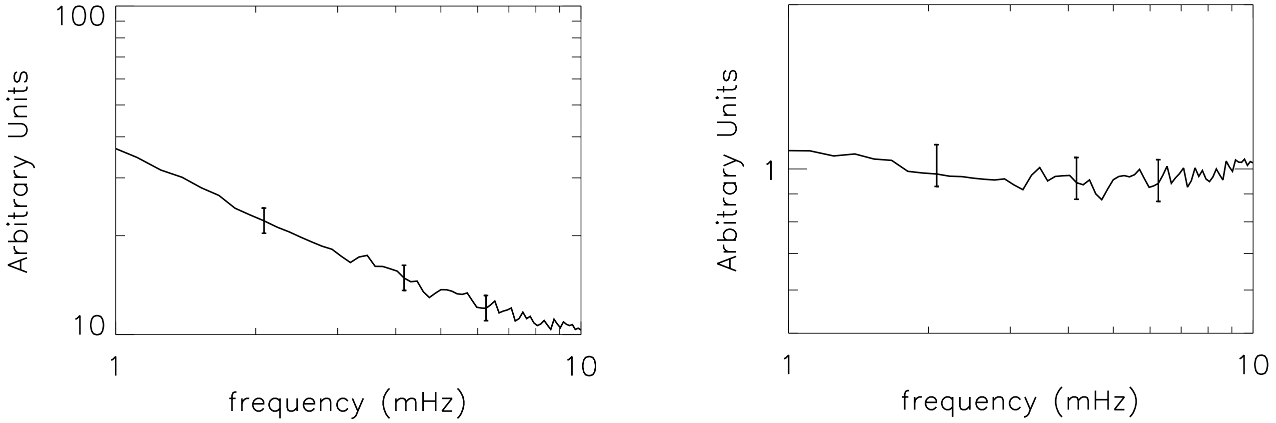

Fig. 4. Power spectrum (left) and weighted spectrum of proton temperature from WIND for January 1995. Spectral resolution is 0.14mHz.

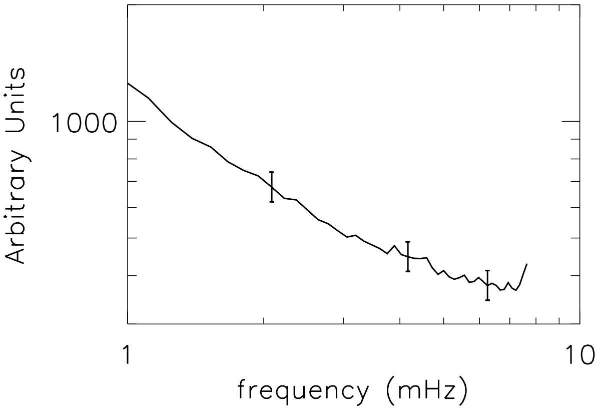

Fig. 5. Power spectrum of solar wind velocity from ACE for June 1999. Spectral resolution is 0.14mHz.

DISCUSSION

The results suggest that internal solar modes do not couple to the Sun's atmosphere efficiently enough to produce periodic variations in the solar wind, or that the variations cannot be detected using the method employed here. Since no peaks in the IMF intensity were observed, it is difficult to understand how helioseismic modes can couple to the Earth's magnetosphere.

Data were used from years 1994 to 2003 with the majority of the data coming from before 2000. The reason for this is that solar activity reached a peak in 2000/2001, and enhanced solar activity is assumed to add noise and extra complexities to the spectra that are unrelated to internal normal modes.

Many of the ACE proton density spectra exhibit a peak near 4 mHz. The peaks did not necessarily appear in consecutive months or in data from other instruments on ACE. Since normal modes are stable oscillations with lifetimes in the range from days to years, peaks corresponding to modes with a long lifetime should be present for long intervals. WIND proton density data for the same time periods showed no peaks in the spectra. This suggests that the peaks in the ACE data may be due to the SWEPAM instrument itself.

The window length used to compute a power spectrum defines the minimum spectral resolution [11]. For this reason, larger window lengths were tested. Apart from the 120 minute window, a 6 hour window and a 2.5 day long window were also used. In all of these cases, no significant spectral peaks were found. Using a larger window size for a given data length reduces the number of sample spectra that can be averaged and increases the chances of random features being present in the spectra.

The solar wind parameters analysed in this study are believed to be those most likely to show periodic variations if a coupling exists between the normal modes and the solar wind. It is possible that some other parameter may be better suited to this.

CONCLUSION

An extensive study of solar wind data was undertaken to determine if periodic variations exist in the solar wind at the same frequency as internal solar modes. Spectral analysis was performed on solar wind proton density, temperature and velocity, and the z component of the IMF using data from the ACE and WIND satellites over 1994 - 2003. Approximately 14 years of solar wind data were analysed in total.

No consistent peaks were observed in any of the solar wind parameters investigated. This suggests that the internal solar modes do not couple significantly with the solar wind.

Spectral peaks near 4 mHz were observed in ACE proton density data. These peaks did not occur each month and were not found in other instruments on ACE or in WIND proton density data during the same period. This suggests that the peaks may be an artefact of the SWEPAM instrument itself.

This study suggests that the Sun's internal oscillations do not couple to the solar wind efficiently enough to be measured. However, further studies are required to more fully substantiate this.

ACKNOWLEDGEMENTS

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