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Observation of Hysteresis between Solar Activity Indicators and *p*-mode Frequency Shifts for Solar Cycle 22

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Abstract. Using intermediate degree *p*-mode frequency data sets for solar cycle 22, we find that the frequency shifts and magnetic activity indicators show a "hysteresis" phenomenon. It is observed that the magnetic indices follow different paths for the ascending and descending phases of the solar cycle while for radiative indices, the separation between the paths are well within the error limits.

Key words. Sun: oscillations, activity.

1. Introduction

Ever since the discovery of global modes in the Sun, it has been expected that solar cycle changes in the Sun's interior would be reflected as a variation in the *p*-mode frequencies. Woodard *et al.* (1991), for the first time, showed that the mode frequencies varied on monthly time scales and were correlated with the average magnetic flux density on the Sun in short time intervals. Bachmann & Brown (1993) pointed out that the frequency shifts were correlated differently with magnetic and radiative indices and was later confirmed by Bhatnagar *et al.* (1999). A recent low *l* analysis (Jimenez-Reyes *et al.* 1998) also indicated that the correlation between mode frequencies and magnetic activity indices is complex; it varies between rising and falling phases of the solar activity cycle. Here, we analyse the intermediate degree modes for the solar cycle 22 and find a "hysteresis" phenomenon between the centroid frequency changes and magnetic activity indicators.

2. Frequency data sets and analysis

The intermediate degree mode frequencies are obtained from different observing stations as these are not available from a single instrument or station for the solar cycle 22. Here we use frequency data sets obtained from HAO/NSO (FTACH) for the period May 1986 to November 1990 (17 sets), Big bear solar observatory (BBSO) data from March 1986 to September 1990 (4 sets), LOWL data from February 1994 to February 1996 (2 sets), GONG data from June 1995 to August 1999 (14 non-overlapping sets). The centroid frequency shifts are calculated by using the frequencies of BBSO station obtained in 1988 as these are also the reference frequencies for

7 B

the FTACH data (Bachmann & Brown 1993). Thus, our analysis is restricted to the spherical harmonic degree range $20 \leq l \leq 60$ and frequency range $2600\,\mu\text{Hz} \leq \nu \leq 3200\,\mu\text{Hz}$. The activity indices considered are: KPMI, (Kitt Peak Magnetic Index) obtained from Kitt peak full disk magnetograms; MPSI, (Magnetic Plage Strength Index) from Mount Wilson magnetograms; R_I, the international sunspot number from the Solar Geophysical Data (SGD); F_{10}, integrated radio flux at 10.7 cm from SGD; FI, total flare index from SGD; He I, equivalent width of He I 10830 Å line, averaged over the whole disk from Kitt Peak.

3. Results and conclusion

In Figs. 1 and 2, the variation in frequency shifts are plotted against the solar activity indices. It is observed for solar cycle 22 that the magnetic field index represented by KPMI follows different paths for the ascending and descending phases of solar cycle; the descending path always follows a higher track than the ascending one. However, in case of radiative indices represented by F_{10} here, the separation between the ascending and descending paths are small and within the error limits. This is further confirmed by carrying out the Spearman's rank correlation between the mean frequency shifts and activity indices. The correlation coefficients (r_s) for the ascending, descending and the full solar cycle 22 are summarised in Table 1. It is evident from the results that the radiative indices have a better rank correlation than the magnetic field indices. In Figs. 1 and 2, we have also shown the trend of variation in frequency shifts with activity indices for cycle 23 (up to August 1999).

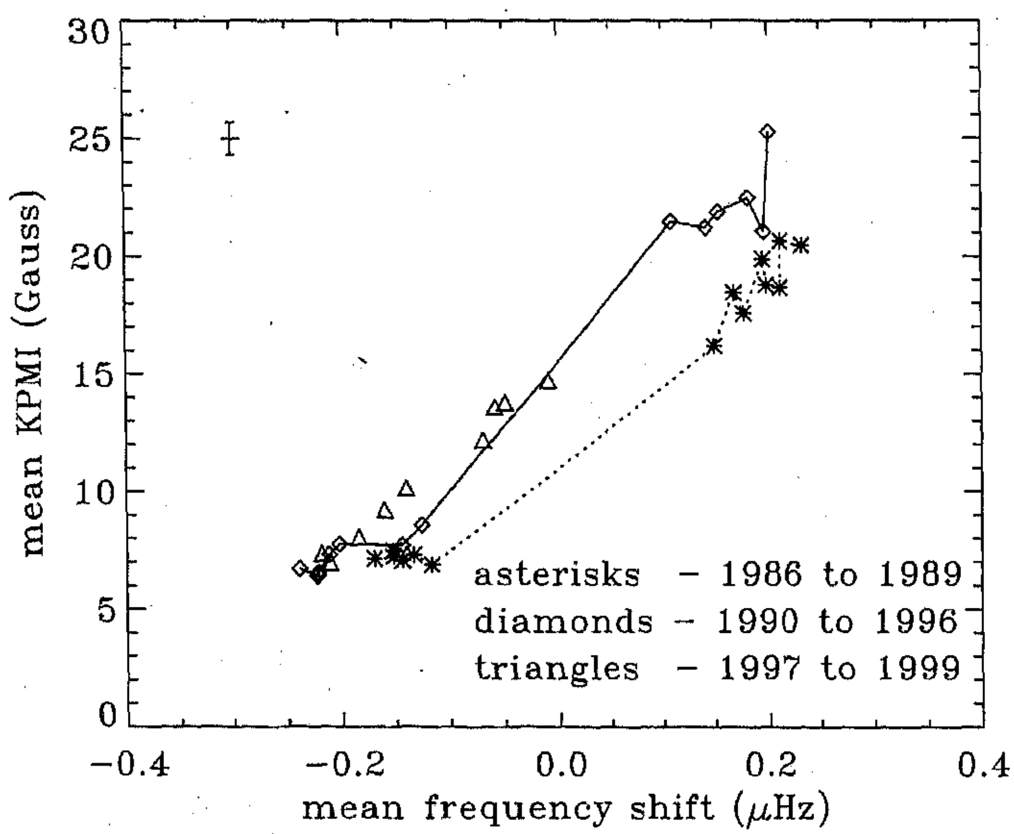

Figure 1. Variation of Kitt Peak Magnetic Index (KPMI) with frequency shift. It is observed for solar cycle 22 that the descending phase follows a higher track than the ascending one showing "hysteresis" phenomenon. The error-bars at the top left corner indicate 1σ values.

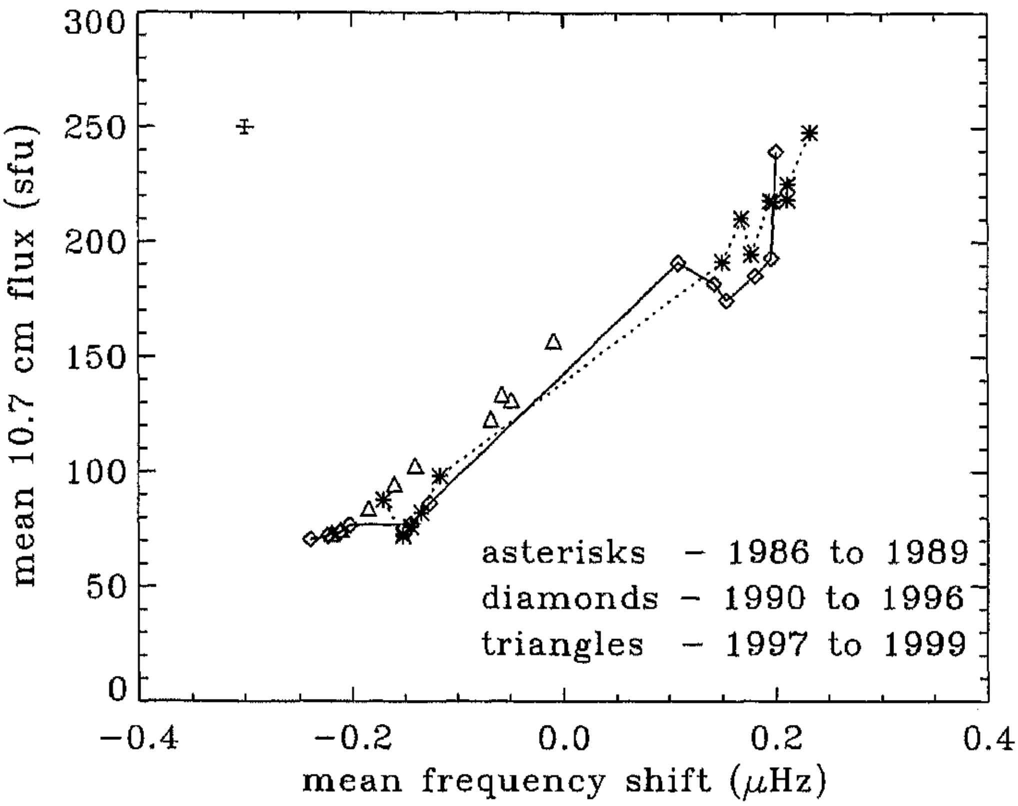

Figure 2. Variation of 10.7 cm radio flux (F_{10}) with frequency shift. It is observed for solar cycle 22 that the descending and ascending paths cross each other and the separation between the paths is well within the error limits. The error-bars indicate 1σ values.

Table 1. Spearman's rank correlation statistics for solar cycle 22.

Activity index	r_s (ascending phase)	r_s (descending phase)	r_s (full solar cycle)
KPMI	0.87	0.91	0.79
MPSI	0.83	0.96	0.88
R_I	0.92	0.93	0.94
F_{10}	0.94	0.96	0.95
FI	0.94	0.85	0.93
HeI	0.89	0.91	0.90

Table 2. Values of the parameter $\oint \Delta\nu$ for different activity indices for cycle 22.

Activity index	$\oint \Delta\nu$ (nHz)
KPMI	110 ± 8.56
MPSI	60 ± 8.39
R_I	20 ± 8.36
F_{10}	-10 ± 8.93
FI	-10 ± 8.83
HeI	-20 ± 8.43

We have further evaluated the parameter $\oint$ r ν (Jimenez-Reyes *et al.* 1998) which represents the mean frequency difference between the descending and ascending phases of solar activity cycle as shown in Table 2. We find that the integral is nearly zero for radiative indices indicating that there is no "hysteresis" phenomenon for these indices. We believe that this phenomenon may explain the reason for the better correlation of radiative indices with the frequency shift than the magnetic indices.

To summarise, we find that the intermediate degree frequencies of solar cycle 22 show a "hysteresis" phenomenon with the magnetic indices whereas no such effect exists for the radiative indices.

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