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IS TURBULENT CONVECTION THE ONLY EXCITING MECHANISM OF ACOUSTIC MODES IN SOLAR-LIKE OSCILLATORS ?

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Abstract. The solar convective envelope generates, by dynamo effect, a surface magnetic field whose strength evolves on an 11-year cycle, with a change in polarity at the end of each cycle. A similar magnetic variability exists in other solar-type stars, influencing their dynamics. Furthermore, solar-like oscillators exhibit acoustic modes whose properties, such as their frequency, amplitude and energy vary over time in relation to the activity cycles. The turbulent motions in the convective envelope of these stars were so far considered as the only mechanism for exciting the modes. In this work, we investigate the variation of mode excitation during Cycles 23, 24, and the beginning of Cycle 25 for the Sun. To do so, we analyze data obtained since 1996 by the VIRGO SunPhotometers on the SoHO satellite, using a method that provides a better time resolution than classical methods such as spectrum fitting. By combining the small-time-scale variations in energy for several low-degree modes, we found a statistical discrepancy in the observed excitation rate compared to the one expected under the hypothesis that modes are only stochastically excited by convection. Our results indeed show that several modes can be excited at the same time. During this presentation, we explored the possible sources of high energy in the modes, i.e. instrumental problems or other exciting mechanisms, which may be linked to the magnetic cycle of the star, such as flares or Coronal Mass Ejections, and compare the results with data from the GOLF spectrometer, also on board SoHO.

Keywords: asteroseismology, helioseismology, stellar activity, solar-type, oscillations, data analysis

1 Introduction

A solar-like star consists of an internal radiative zone enveloped by an outer convective region, whose upper boundary is the photosphere, topped by the chromosphere. The internal structure of such stars can be probed through asteroseismology, by studying pressure (p) modes, which are clearly detected in main-sequence stars. These modes are known to be stochastically excited by turbulent convective motions (e.g. Goldreich & Keeley 1977). Early analyses using data from the InterPlanetary Helioseismology by IRradiance measurements (IPHIR, Fröhlich et al. 1988) aboard the PHOBOS satellite, as well as the first 310 days of observations from the Global Oscillations at Low Frequencies (GOLF, Gabriel et al. 1995; García et al. 2005) instrument on the SOlar and Heliospheric Observatory (SoHO, Domingo et al. 1995), revealed evidence of correlated excitation among low-degree modes (Baudin et al. 1996; Foglizzo 1998). This unexpected result, under the assumption of purely stochastic excitation, led Foglizzo (1998, hereafter F+98) to suggest an additional excitation mechanism-possibly linked to coronal mass ejections (CMEs), given their large spatial extent and kinetic energy. Solar-like stars display surface magnetic features that vary across different spatial and temporal scales, with their appearance closely linked to magnetic activity cycles. These magnetic variations also affect oscillation mode properties: as magnetic activity increases, mode frequencies rise while amplitudes and energies decrease (García et al. 2013; Salabert et al. 2015; Régulo et al. 2016; Santos et al. 2019). Such effects impact the asteroseismic determination of fundamental stellar parameters (Bétrisey et al. 2025), highlighting the importance of characterizing magnetic activity, particularly in the context of upcoming missions such as PLAnetary Transits and Oscillations of stars

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(PLATO, Rauer et al. 2025), scheduled for launch in December 2026. PLATO aims to detect and characterise terrestrial exoplanets orbiting solar-like stars. Achieving the required accuracy demands a precise determination of host star properties, which in turn requires a thorough understanding of how magnetic activity affects oscillation modes. The Sun, being the best-observed solar-like star, provides a unique opportunity to investigate these effects. In this study, we revisit the assumption of purely stochastic excitation and explore the possible connection between mode energy, magnetic activity, and solar eruptive events, using over 28 years of Sun-as-a-star observations from SoHO, covering solar cycles 23, 24, and the first half of cycle 25. This work has been published in Panetier et al. (2025); readers are referred to that paper for a complete description and detailed analysis.

2 Retrieving the energy time-series of the modes

We analyzed data from two instruments aboard SoHO, launched in December 1995: GOLF, which provides Doppler velocity measurements, and the Sun PhotoMeters of the Variability of Solar Irradiance and Gravity Oscillations (VIRGO/SPM, Fröhlich et al. 1995), which record intensity variations. For this study, we reconstructed time series for all acoustic modes with radial orders $n = 14$ to 25 and angular degrees $l = 0$ to 2, following the approach originally described in Foglizzo et al. (1998). Each mode was isolated using a spectral window of width 8 μHz centred on its frequency ν, as determined from the peakbagging analysis of Lazrek et al. (1997). This selection procedure is illustrated in the left panel of Figure 1. The energy of a mode was estimated as $E_{n,l} = 2|f_v(t)|^2$, where $f_\nu(t)$ is the inverse Fourier transform of the filtered signal around the mode frequency. This method yields a time resolution of approximately 1.45 days. In the following analysis, we use energy time series that are normalised by their mean.

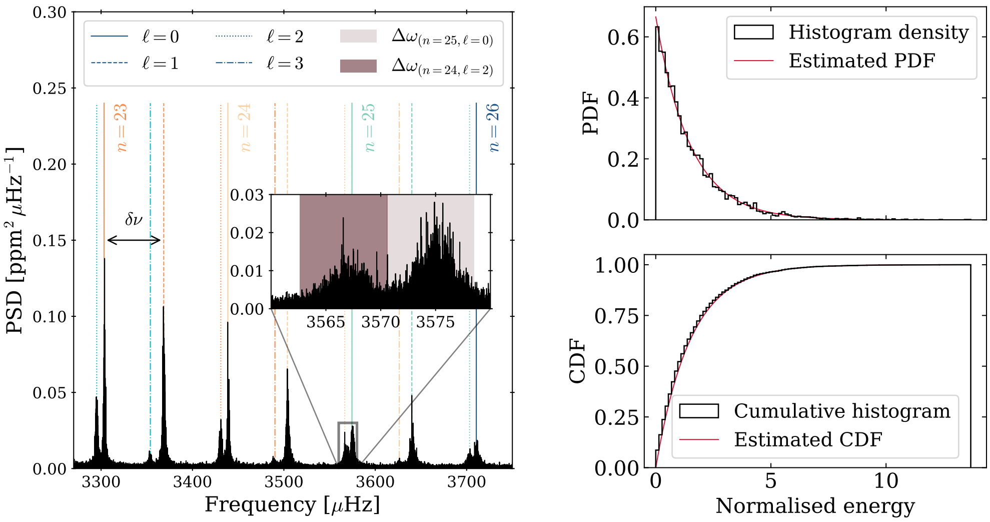

Fig. 1. Left: PSD of the VIRGO/SPMs light curve (23.01.1996-23.11.2023) showing frequencies between 3270 and 3750 μHz, highlighting the large frequency separation ($\delta\nu$) between modes $\ell = 0$ and $\ell = 1$ for $n = 23$. Modes are marked by vertical lines with colors for $n = 22$ (light blue), $n = 23$ (orange), $n = 24$ (yellow), $n = 25$ (cyan), and $n = 26$ (dark blue); line styles indicate degree: $\ell = 0$ (solid), $\ell = 1$ (dashed), $\ell = 2$ (dotted), $\ell = 3$ (dot-dashed). Inset shows the 8 μHz window used to reconstruct mode energies around ($n = 25$, $\ell = 0$) and ($n = 24$, $\ell = 2$). **Right:** Probability (top) and cumulative (bottom) distributions for mode $n = 22$, $\ell = 0$. Black histograms are observed data; red curves show fitted theoretical exponential distributions.

3 Kolmogorov-Smirnov (KS) Statistical tests

For fully stochastically excited modes, each mode energy $E_{n,\ell}$ should follow an exponential distribution (Chaplin et al. 1997; Foglizzo 1998). This was tested using the Kolmogorov-Smirnov (KS) statistic (Massey 1951), comparing observed and fitted exponential cumulative distributions. An example for mode $n = 22$, $\ell = 0$ is shown in Figure 1. Using a 5% significance level, all time series yielded p-values supporting the null hypothesis that the data follow the expected exponential distribution, consistent with stochastic excitation.

4 The combined energy time-series of the modes

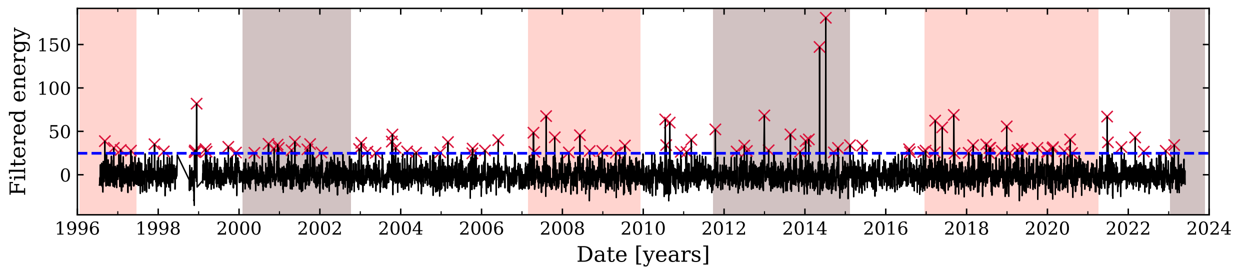

Fig. 2. Combined time series of the 36 analysed modes. This time series was normalised by its one-year moving mean. The blue dashed line shows the 98th percentile and the red crosses mark the studied higher energy points. Periods of low and high magnetic activity, inferred from the solar radio flux index $F_{10.7}$ (Tapping 2013) used as a proxy for solar activity, are highlighted in pink and brown, respectively.

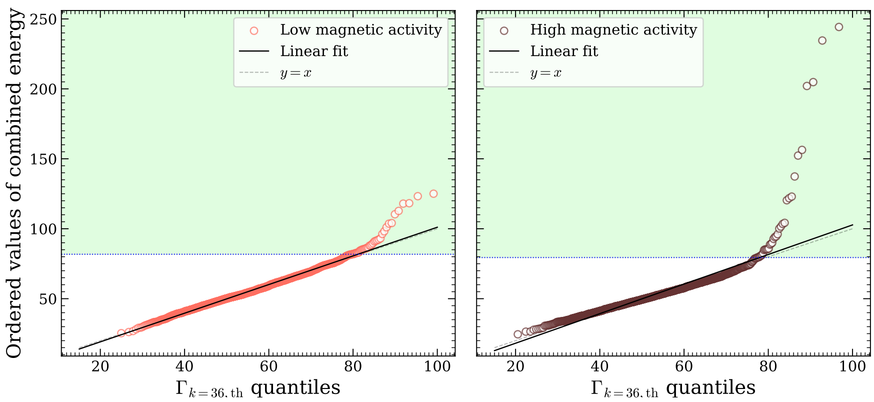

Fig. 3. Q-Q plot comparing the combined energy time series with $\Gamma_{k=36,\mathrm{th}}$ distributions. Panels correspond to two selected sub-samples: low magnetic activity (pink, left) and high magnetic activity (brown, right). The general trend of the Q-Q plot was fitted with a least square regression to the data and is shown as a black line on all panels. The grey dashed line shows the line $y = x$, and the blue dotted line shows the value of the 98th-percentile for each period. The green regions in both panels indicate areas where the observed and theoretical distributions diverge significantly, highlighting their incompatibility.

To investigate potential correlations in mode excitation, we combined the 36 reconstructed mode energy time series into a single composite dataset. To account for long-term energy variations caused by solar magnetic activity, the combined time series was normalized by its 1-year moving mean. This produced a normalized time series, denoted $\mathcal{S}_{\mathrm{phot}}$, which enhances short-term fluctuations and reveals prominent energy peaks, as shown in Figure 2. Under the assumption of fully stochastic excitation, $\mathcal{S}_{\mathrm{phot}}$ is expected to follow a Γ-distribution with shape parameter $k = 36$, corresponding to the sum of 36 independent, exponentially distributed mode energies. To test for deviations from this theoretical distribution and assess the influence of magnetic activity, we isolated two sub-samples from $\mathcal{S}$phot corresponding to low and high magnetic activity periods. We compared each sub-sample to the expected $\Gamma_{k=36,\mathrm{th}}$-distribution using quantile-quantile (Q-Q) plots, shown in Figure 3. In both cases, the data deviate from the $y = x$ line at high energies, indicating a systematic excess of high-energy events. These discrepancies are highlighted in green in the plots and appear similar regardless of magnetic activity level. To quantify this excess, we adopted a high-energy threshold corresponding to the 98th percentile of the theoretical distribution. This threshold, indicated by blue dotted lines in Figures 2 and 3, allowed us to identify 108 extreme events out of 6612 data points in $\mathcal{S}_{\mathrm{phot}}$. The expected probability of such events occurring purely by chance ($P < 10^{-3}$) is significantly lower than the observed 1.6% rate, confirming their statistical significance and suggesting a departure from purely stochastic excitation.

5 Possible explanations to the excess of energy

The observed excess of mode energy could partly result from photon noise or transient non-modal signals (e.g. particle hits or cosmic rays), which would also manifest at unrelated frequency ranges. To test this, we reconstructed 36 time series using the same temporal windowing as for the modes but shifted by 4500 μHz, outside the p-mode region, to create a combined noise time series. Comparing its 98th-percentile peaks with the 108 high-energy events in $\mathcal{S}_{\rm phot}$, we found 26 coincident events likely attributable to noise, leaving 82 unexplained peaks. To assess their solar origin, we compared these 82 peaks with those from a similarly processed GOLF time series, identifying 14 coincident events, suggesting intrinsic solar excitation. We then examined temporal coincidences with solar eruptive events using a 1.45-day window: 22 peaks matched with CMEs, 8 with solar flares, but only 2 overlapped with the GOLF-correlated peaks. To explore the depth of excitation, we split the modes into three frequency bands (2090-2620, 2620-3160, and 3160-3710 μHz) and reconstructed combined energy time series for each. Of the 82 unexplained peaks, 20, 23, and 28 were found in the low, medium, and high-frequency bands respectively, suggesting a slight preference for excitation in the upper convective layers. However, no clear correlation with the solar cycle was observed.

6 Conclusions

The main objective of this study was to investigate the impact of surface activity features on mode excitation. Our analysis revealed a discrepancy with the standard theory of stochastic excitation, showing that modes are occasionally excited simultaneously at significantly higher rates than theoretically expected. This excitation, that could not be only attributed to a sudden increase in the photon noise, seems not magnetic-cycle related. It is sometimes correlated with CMES and/or flares but this is not automatic and it comes slightly more often from the most external layer of the convective zone.

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