Signatures of magnetic activity in the p mode frequencies of solar-type stars observed by *Kepler*

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Abstract

Several hundred stars were observed in the short cadence mode of the *Kepler* satellite during the nominal mission phase. This generated a large pool of data which can provide insight into the characteristics of stellar activity cycles of solar-type stars through the methods of asteroseismology. From helioseismology it is known that the frequencies of solar acoustic oscillations (p modes) are positively correlated with the solar magnetic activity cycle. Evidence for a similar behaviour in the p modes of a star, which was observed by the *CoRoT* satellite, was provided by [1]. This showed that it is feasible to trace activity cycles of stars in their p mode frequencies.

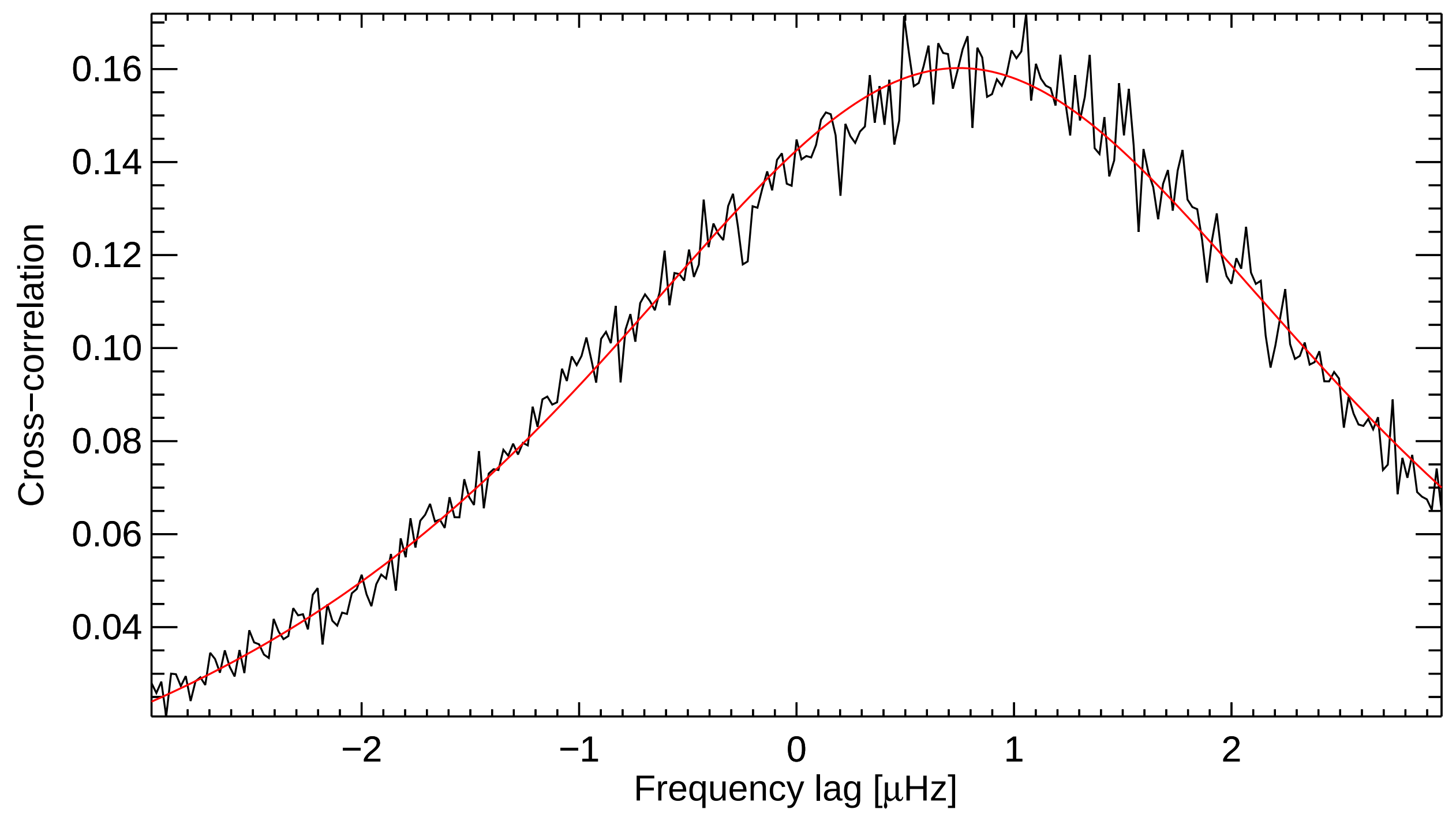
We analyse the *Kepler* time series of a set of solar-type stars with the aim to find signatures of stellar magnetic activity. We divide the time series of each star into shorter sub-series in order to analyse the temporal evolution of the p mode frequencies. The sub-series' periodograms are cross-correlated to retrieve the shift of p mode frequencies over time. The errors on the shifts are computed by a resampling approach of the periodogram. We find significant frequency shifts, indicating stellar magnetic activity, for all stars we investigated. For the most prominent example, KIC 8006161, we find that, not unlike in the solar case, frequency shifts are smallest for the lowest and largest for the highest p mode frequencies.

Methodology

To investigate the temporal variation of p mode frequencies, the time series were divided into shorter sub-series. To compromise between frequency resolution and number of independent sub-series, we chose a typical length of 150 days for the sub-series. From one sub-series to the next, the starting point was shifted by 50 days, resulting in a three time overlap for sub-series with a length of 150 days.

The first sub-series of each star was used as the reference for defining zero frequency shift. We computed the shift relative to the reference sub-series by calculation of the cross-correlation of those parts of the periodograms which contain the p modes.

In the figure below, the part between $\pm 3\,\mu\mathrm{Hz}$ of the cross-correlation between the p mode region of the first and the nineteenth sub-series of KIC 8006161 is shown in black. The Lorentzian fit to the data is shown as a continuous red curve. The maximum of the cross-correlation is clearly shifted towards positive values.



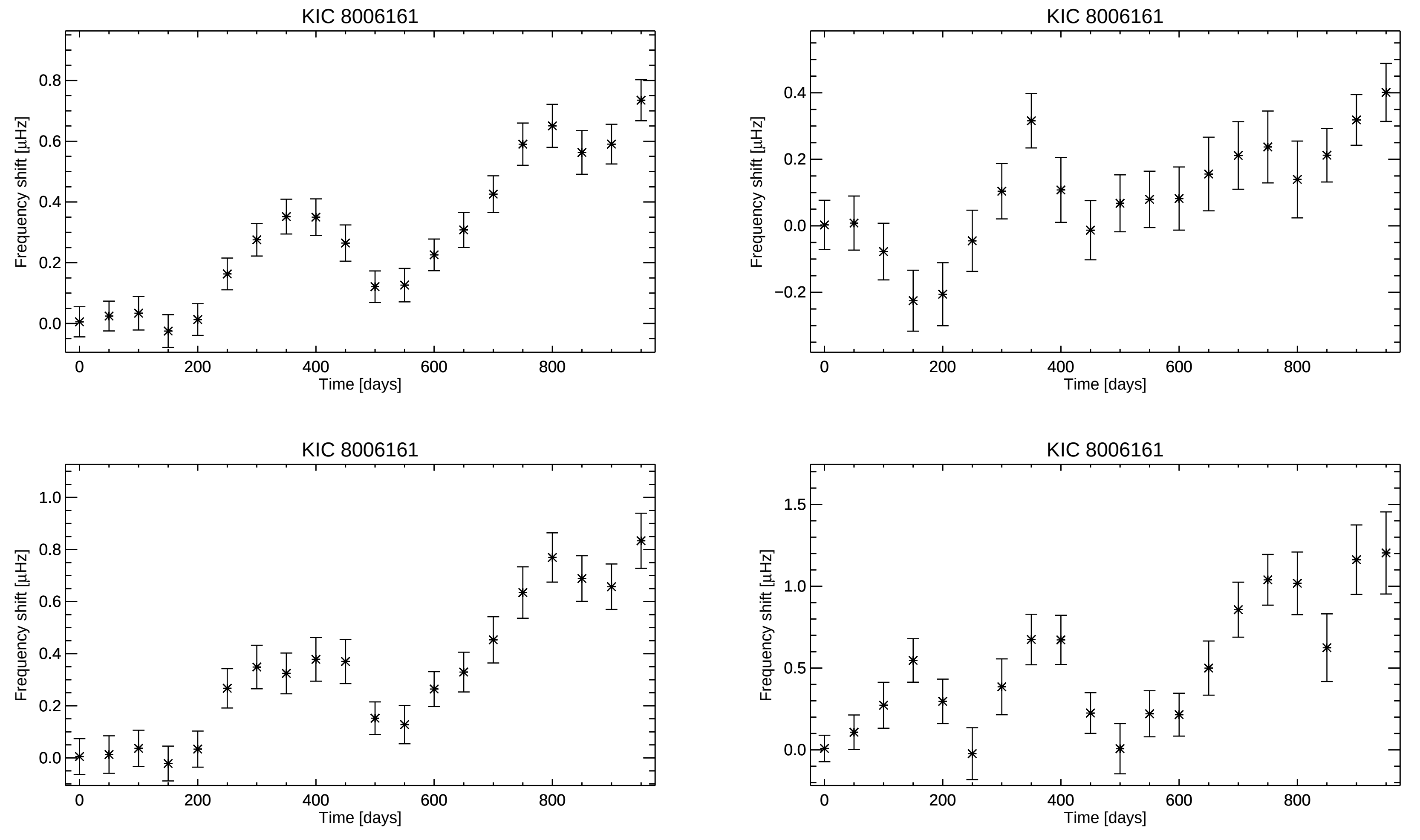
The periodogram is a χ^2_2 distributed estimator of the power spectral density

$$\hat{P}(\nu) \approx \frac{1}{2}\hat{S}(\nu)\,\chi^2_2\,, \qquad (1)$$

where $\hat{P}$ is the periodogram and $\hat{S}$ is the power spectral density. We use this statistical property of the periodogram to simulate 200 realisations each sub-series' periodogram. An estimate of $\hat{S}$ is obtained by smoothing the original periodogram with a 50 bin boxcar window. Employment of Eq. 1 then yields a new realisation of the periodogram.

Each realisation of the periodogram of a given sub-series is cross-correlated with a realisation of the periodogram of the reference sub-series. The standard deviation of the centroid values of the Lorentzian profile of the 200 fits is used as the error for the shift of the p modes, while their mean is used as the value of the shift.

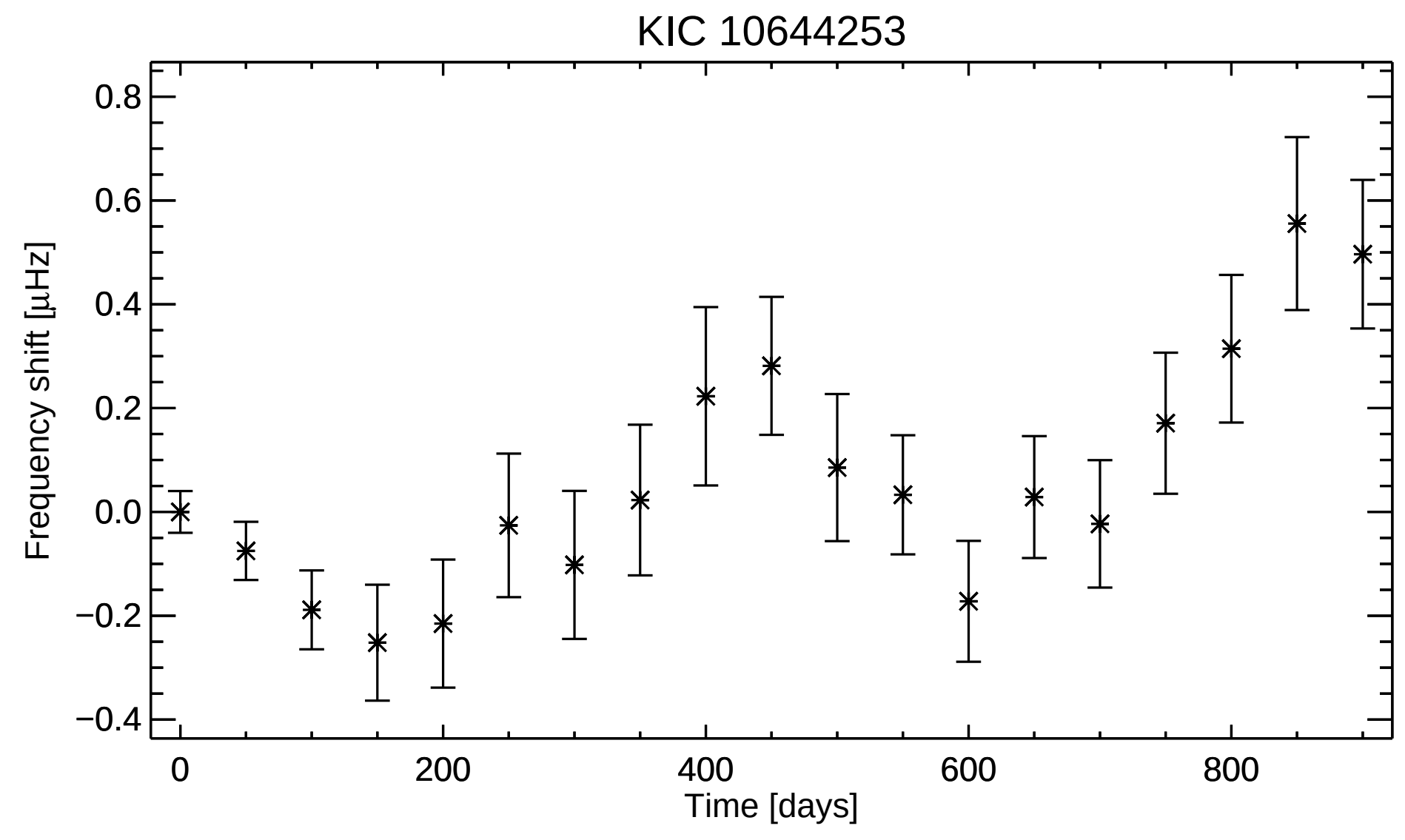
KIC 8006161



These plots show the variation of the p mode frequencies in four frequency ranges: the full frequency range 2800–4400 μHz, a low frequencies range 2800–3300 μHz, an intermediate range with frequencies 3300–3800 μHz, and high frequency range between 3800–4400 μHz (clock-wise, starting at the top left panel). As in the solar case [e.g. 2–4], the amplitude of the frequency shifts increases with increasing mode frequency. The modes in the low frequency range vary by only $\sim 0.6\,\mu$Hz, while the modes in the intermediate range shift $\sim 0.8\,\mu$Hz. The modes in the high frequency range even shift by as much as $\sim 1.2\,\mu$Hz.

For the Sun, there is a positive correlation between the p mode frequency shifts and the level of magnetic activity. Since this star is very similar to the Sun regarding its fundamental parameters ($M = 1.00 \pm 0.01\,\mathrm{M}_\odot$, $R = 0.93 \pm 0.00\,\mathrm{R}_\odot$, $T_\mathrm{age} = 4.28 \pm 0.12\,\mathrm{Gyr}$ [model values from 5]), our findings for the shifts of its p mode frequencies suggest that the magnetic activity on KIC 8006161 is somewhat stronger than on the Sun, following the results presented by [6].

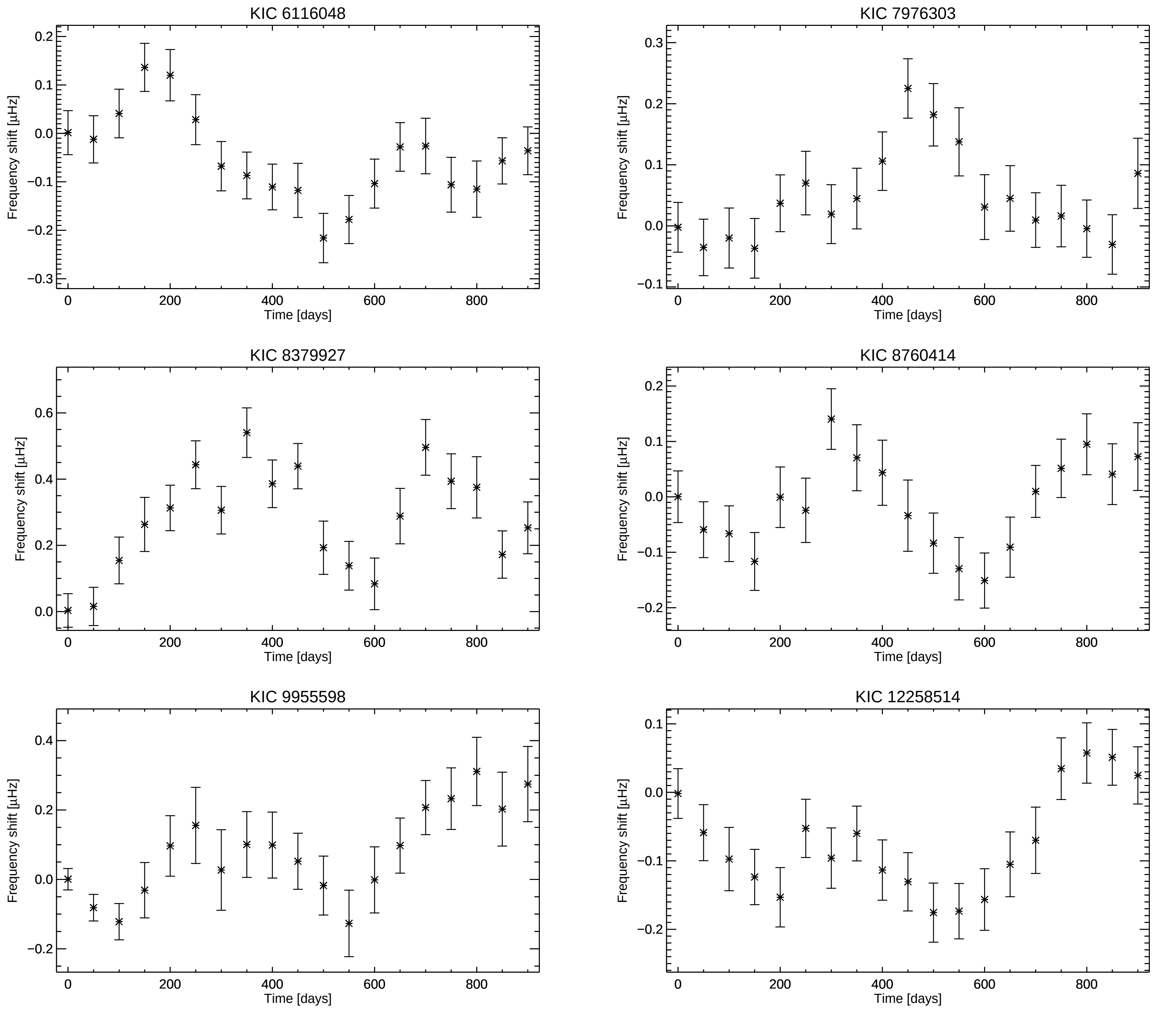
KIC 10644253



The frequency shifts we found for this star follow a cycle-like pattern. [7] spotted the strongest peak in their cycle proxy of KIC 10644253 during Quarter 10, which corresponds to a time during day 400-450 for our data set. Indeed, the frequency shifts are at a local maximum during this period. The minima before and after this maximum are also reflected in the cycle proxy of [7]. However, we find another strong positive shift in frequencies towards the end of the time series, which indicates strong stellar activity. [7] do not see a strong indication of activity during this period.

Due to its rather low inclination of $43.44 \pm 14.48^\circ$ [from 7], it is conceivable that the regions of high activity are confined to the out-of-sight part of the star during the last 250 days of the time series. The global, low degree modes we use for our analyses are susceptible to magnetic activity throughout the star. Therefore, the frequency shifts might reveal signatures of magnetic activity which are hidden to photometry based techniques like those used by [7].

Frequency shifts of 6 stars



Summary

We presented variation of p mode frequencies of 8 stars which are interpreted as a signature of stellar magnetic activity. A cycle-like behaviour could be spotted in the frequency shifts of a couple of stars (e.g. KIC 8379927). The star KIC 10644253 exhibited shifts in p mode frequencies which might be caused by two stellar cycles during the available data set. When compared to the activity indices of [7], we conclude that we found indications of stellar activity on the out-of-sight part of this star.

For the solar-like star KIC 8006161 we were able to investigate the frequency dependence of the mode frequency shifts. We found that the shifts are larger for p modes of higher frequencies, just like in the solar case.

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