The Detection of Quasi-Periodic Pulsations in Solar Flares From a Single Active Region

Chloë E. Pugh
University of Warwick, UK

Supervisors:
Valery M. Nakariakov, Anne-Marie Broomhall
Quasi-periodic pulsations (QPPs)

- Time-variations of the intensity of light emitted by a flare
- First observed in solar flares by Parks & Winckler (1969)
- Example of QPPs in a solar flare: The Seven Sisters Flare, observed by Kane et al. (1983)
- Seem to be a fairly common feature of flares
Quasi-periodic pulsations

Two groups of possible mechanisms:

- Magnetohydrodynamic (MHD) oscillations...
  ..of the flaring structure
  ..of a nearby structure

- Load/unload or ‘magnetic dripping’ mechanisms of energy release (periodically induced reconnection)
Solar flare QPP study

- 181 GOES class flares from a single (very) active region
- 137 C class, 38 M class, 6 X class
- How many have QPPs?
- Do QPP properties evolve with time?
- Do QPP properties depend on the type of flare?
Solar flare QPP study

- GOES, RHESSI, Fermi, Vernov (Myagkova et al. 2016), Nobeyama Radioheliograph (NoRH)

![Graphs showing GOES, RHESSI, and Fermi counts over time]
How to detect the QPPs?

- Definition of QPP signal:
  - At least 3 cycles of oscillation (or 3 pulses with ~equal time spacing)
  - Can be in rise and/or decay phase of flare
  - Can have modulated amplitude
  - Stationary or non-stationary (focus on stationary here)

- How to quantify a detection? —> Fourier analysis —> periodogram or wavelet —> confidence levels

- Flare time series data has intrinsic red noise —> to detrend or not to detrend?
Confidence levels: white noise case

- For $\chi^2$ distribution with 2 degrees of freedom, probability is:
  \[
  \Pr\{\chi^2 > \gamma\} = \frac{1}{2} \int_{\gamma}^{\infty} e^{-x/2} \, dx = e^{-\frac{\gamma}{2}}
  \]

- (See Horne and Baliunas 1986 for more detail)

- Right: periodogram of white noise, which follows a $\chi^2$, 2 d.o.f distribution
Confidence levels: red noise

- Red noise means a power-law power spectrum — power depends on frequency
Confidence levels: red noise

- We can fit a power law model to the spectrum:
  \[ \log(\hat{P}(f)) = \log(A) - \alpha \log(f) \]

- Data have associated uncertainties \( \rightarrow \) periodogram powers will have uncertainties \( \rightarrow \) fitted power law model will have uncertainties

- Can estimate uncertainties on power law model by performing monte carlo simulations with original time series data uncertainties

- Additional source of uncertainty from model will affect probability distribution
Confidence levels: red noise

- A confidence level can be found by solving this equation (see Vaughan 2005 or Pugh et al. 2017 (in prep) for more detail):

\[
\Pr\{x_j > \gamma_j\} = \int_{\gamma_j}^{\infty} \int_0^{\infty} \frac{1}{\sqrt{8\pi S_j}} \exp\left\{\frac{-(\ln w)^2}{2S_j^2} - \frac{wz}{2}\right\} dw dz
\]

which reduces to:

\[
\Pr\{x_j > \gamma_j\} = \int_0^{\infty} \frac{1}{\sqrt{2\pi S_j}} w \exp\left\{\frac{-(\ln w)^2}{2S_j^2} - \frac{\gamma_j w}{2}\right\} dw
\]
Confidence levels: red noise

Set false alarm probability to 1% for 99% confidence level

\[ \Pr\{x_j > \gamma_j\} = \frac{0.01}{N} = \int_0^\infty \frac{1}{\sqrt{2\pi S_j w}} \exp\left\{ \frac{-(\ln w)^2}{2S_j^2} - \frac{\gamma_j w}{2} \right\} dw \]

Number of values in the power spectrum (set to 100 here)
Examples

- Solar flares observed by Nobeyama Radioheliograph
- Left: Correlation time series of part of a flare
- Right: Periodogram with a peak above 99% confidence level, at a period of ~10 seconds
Examples

- Solar flares observed by Nobeyama Radioheliograph
- Left: Correlation time series of part of a different flare
- Right: Periodogram with no significant peak
QPPs in flares from a single AR

- Out of 181 flares: 16 with QPPs above 99% level, 23 above 95% level

- Periods ranging from 7.5 to 79.5 seconds

- Right: histogram of QPP periods

- Can also use method described by Inglis et al. 2015/2016 to test for presence of QPPs
Summary

- Solar flares have intrinsic red noise/trends — need to account for this in the statistics
- We have adapted the method described by Vaughan 2005 to test for the presence of QPPs in flares
- Applied the method to a sample of solar flares from a single active region
- Now we have a sample of flares with candidate QPPs, we can use these to investigate whether the QPP properties relate to the active region or flare properties