Red Noise in Anomalous X-ray Pulsar Timing Residuals

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Timing noise

- Some pulsars deviate from deterministic spin-down models in a quasi-random way.
- White noise in phase has a flat spectrum, while white noise in rotation speed has a spectrum with power spectral index -2, and white noise in torque has a power spectral index -4.
- Flicker noise characterized by a power spectral index of -1, could give rise to odd negative indices.
- Turbulent processes often exhibit power-law scaling with non-integral power spectral indices.
- Observed power spectral indices seem to vary from pulsar to pulsar.

Anomalous X-ray pulsars (AXPs)

- Pulsars observed as strong sources in the X-rays with long periods and hard nonthermal spectra.
- Luminosity too great to be powered by rotation, thought to be powered by the decay of an extremely strong \((10^{30}-10^{31})\) G internal magnetic field (this is the magnetar model [TLK02]).
- Approximately nine are known (see [PG]).
- Highly variable sources: exhibit glitches, bursts, flares, changes in pulse profile, and luminosity-related changes in torque. Given the nature of magnetars, the mechanism behind their timing noise might differ.
- Several measures of the amplitude of timing noise are used, including \(\sigma\) and the related \(\Delta\).

Analysis techniques

- Difficulties:
  - Spectral bleeding prevents the use of Fourier or periodogram techniques.
  - The lowest frequencies contain the most timing noise and are the most interesting but only very poor spectral resolution is available at low frequencies.
  - At high frequencies timing noise is dominated by observational uncertainties.
  - We are measuring a noise process whose expectation values we seek, so any single measurement (e.g. a filter output) provides a very poor estimate of the expectation value ("cosmic variance problem")

- Partial solutions:
  - Orthogonal polynomials allow strong rejection of low frequencies (DBBB2).
  - Theory leads us to expect a power-law model; fitting such a model allows us to combine the data from all filters, reducing uncertainty.
  - Deviations from the chosen model should result in one or more filters giving statistically improbable results.

- Noise with arbitrary spectral index -\(\gamma\) can be simulated as a Poisson impulsive noise process with impulse response of the form \(t^{\gamma+1}/(\gamma+1)!\) ([S+03]).

- Errors can be estimated using a Monte Carlo simulation.

- Deterministic spindown effects can be incorporated in the model and their parameters fitted for

- Remaining difficulties:
  - Requires a great deal of data to constrain model parameters.
  - Strong low-frequency components lead to numerical instabilities in a straightforward implementation.
  - Response to a periodic signal — position errors for example — is complicated, appearing in the outputs of several filters.
  - Computational requirements are fairly high.

Questions we hope to answer

- How does AXP timing noise differ from timing noise in other pulsars? In particular, we see some glitches of all kinds which are more common. We refer to the limits of our ability to detect, could AXP timing noise be the result of "microglitches"?
- Are there any periods through which AXPs go through timing noise and periods of low timing noise?
- Can we estimate properties of deterministic pulsar spindown parameters — position errors, proper motions, braking indices — along with error bars that measure their contamination by timing noise?

Anomalous X-ray Pulsars (AXPs), thought to be magnetars, exhibit poorly understood deviations from a simple spindown. AXP timing noise has strong low-frequency components whose quantification poses significant challenges. We have a procedure for extracting two quantities of interest, the intensity and power spectral index of timing noise. We will discuss the behaviour of several of the AXPs, and for comparison several youth rotation-powered pulsars. We will also discuss the relevance of the parameter \(\Delta\) put forward by Arzoumanian et al. (1994).

Data

- AXPs:
  - Ten-year monitoring program of five AXPs with RXTE.
  - Twenty-one spindle-shaped data gaps
- Radio pulsars:
  - Ten-year monitoring program covering thirty-five radio pulsars.

Other data sets:

- X-ray monitoring of the pulsars in SNR 3C58 and G.11
- PSR J1939+2134

Analysis

- Different AXPs have different timing noise values, but a power-law model is expected.
- Deviations from the chosen model should result in one or more filters giving statistically improbable results.

Filters:

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The quantity \(\Delta\) contains essentially the same information as \(\alpha=0.5\). It therefore measures the timing noise strength in a single observationally consistent frequency band. As a result, correct calculation is simple but will lead to large uncertainties unless many periods of length 105 s can be averaged. A timing noise model can be used to evaluate \(\Delta\) more accurately, although this relies on using other frequency ranges to constrain the model noise unit, which is a factor of \(10^{15}\) smaller than the fiducial noise unit.

Figure 1 A, B, C, D. The effect of strong low-frequency noise on the measured parameter \(\Delta\). The best-fit quadratic has been subtracted.

Figure 2. Sample pulsars from the monitoring campaign conducted with the 85-3 telescope. The best-fit quadratic has been subtracted.

Figure 4 A and B. The power spectral response of two filters. In green is plotted the response of a periodogram bin – analogous to a Fourier bin but applicable to the unevenly sampled data set (the times are those from our observations of the AXPs 1E 1048.1-5937). In blue is the degree 9 orthogonal polynomial constructed as described in [DBBB2]. Figure 4A is the simple unweighted spectral response; both have undesired peaks in the frequency spectrum (note that the periodogram deviates from the simple sinc function expected from evenly-spaced samples) but the orthogonal polynomial is notably worse at high frequencies. Figure 4B is the spectral response weighted by frequency to the power -4. This exponent is expected from white noise torque, and is reasonably typical of some sources. This distribution of energy shifts the peaks somewhat and decreases the high-frequency peaks, but most notable is its effect on the low frequencies: for the periodogram, the response to infinity as we approach zero frequency in other words, the filter response is dominated not by frequencies near the peak but by the very lowest frequencies. This effect is particularly pronounced in the filtering of a periodogram useless. Polynomial detrending can reduce the low-frequency component, suppressing the lowest frequencies just as an orthogonal polynomial does, but a periodogram bin then acquires a bimodal frequency response.

Figure 5 A and B. The frequency response (raw and weighted) of the parameter \(\Delta\) at a fiducial frequency. This has been put forward as a measure of timing noise in pulsars outboard of [MET97]: it is computed by using the filtering polynomials of degree three to stretch data of length 105 s.

Figure 6. Preliminary results of timing noise fits to AXP data.

References


Figure 3 A and B. Telescopes used to collect the data. Figure 3A is the RXTE satellite, and figure 3B is the 85-3 telescope at the Green Bank site. Artist's conception of RXTE courtesy of NASA.

Figure 8. Detailed result of a timing noise fit to observations of the AXPs 1E 1048.1-5937. Purple circles indicate filter responses, horizontal error bars indicate filter bandwidths, blue points indicate expected filter values in the best-fit model, and vertical blue error bars indicate one-sigma uncertainties in filter response. Vertical purple error bars indicate uncertainty in filter values due to observational noise.

$\Delta$ includes all data sets for 1E 1048.1-5937

Figure 9. Monte Carlo simulations used to estimate the uncertainties on fitted parameters for the 1E 1048.1-5937 data set. Simulations are performed by generating data sets using the best-fit model then applying the same fitting procedure.