Millisecond Pulsar Timing 2: Radio Frequency Dependent Timing Delays
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Interstellar Dispersion
Lower-frequency radio waves travel through the ISM more slowly than high frequency waves, causing them to reach Earth slightly later. This effect is called dispersion, and results in a time delay:

\[ \Delta t = D \times \frac{DM}{f^2} \]

Where \( f \) is the radio frequency, \( D \) is a constant and \( DM \) is a measured quantity called the dispersion measure. The \( DM \) is defined as:

\[ DM = \int \frac{n_e \, dl}{\mu_e} \]

Where \( n_e \) is the electron density of the ISM.

Problems With Previous Methods
In Hao Lu’s (16) senior thesis, he found that for some pulsars, the \( DM \) varies differently at different frequencies. This suggests that there is some other frequency dependent phenomenon affecting the TOA.

Our Methods
We started by introducing a new, frequency-dependent parameter to our model and seeing if it improved the precision of the model. We called this new parameter “XMX.” At first, we theorized that XMX could cause a time delay that is proportional to the frequency raised to some exponent. We tested many different exponents for each pulsar, and compared the fit in each case, but believe that it could be a time delay that is proportional to the frequency raised to some exponent. We tested many different exponents for each pulsar, and compared the fit for each. Below is a complete version of the equation for \( \chi^2 \):

\[ \chi^2 = \frac{1}{2} \left( \frac{\lambda - \mu}{\sigma} \right)^2 \]

Where \( \lambda \) is the observed TOA, \( \mu \) is the predicted TOA, \( \sigma \) is the error in the TOA, and \( XMX \) is the variable that we are testing.

XMX Varying Timescales
We also tried varying the timescale over which XMX was calculated and saw if we could observe broader trends over longer periods of time. These three plots are all fits for the pulsar J1643+1224 where the XMX is calculated every 50, 100, or 200 days instead of every 6 top-left: 50 days. Bottom-left: 100 days. Bottom-right: 200 days.

Principal Component Analysis and Future Work

Results
Through this method, we generated a variety of different plots, leading us to believe that there may be different causes in frequency variations for different pulsars. Below are three of our plots demonstrating some of the patterns of behavior we observed, along with analyses. Several of the pulsars we observed exhibited minima around the exponent -4. We believe that this may be characteristic of scattering, as scattering is known to delay radio waves in proportion to their frequency to the -4th power. Scattering is an effect caused by the refraction of the pulses in the interstellar medium. It causes time delays that impact our model, but is not observed in all of our pulsars. This makes sense, as the ISM is not homogeneous throughout space. From these plots, we can tell which pulsars appear to have scattering based on where there minima lie.

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Dispersion Measures