Millisecond Pulsar Timing: Frequency Dependent Parameters

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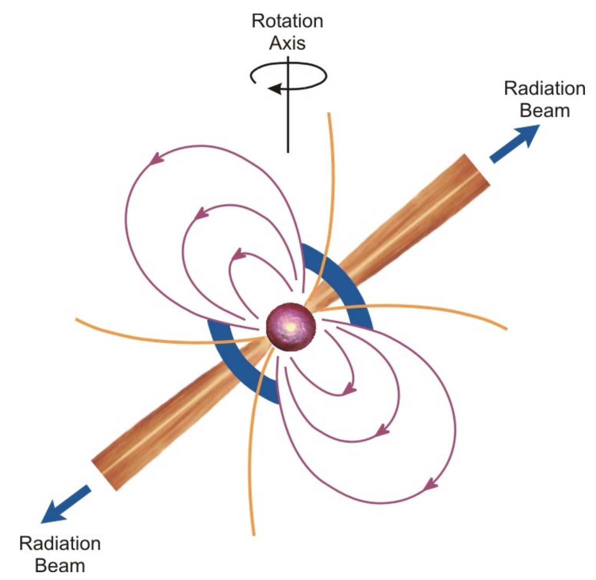
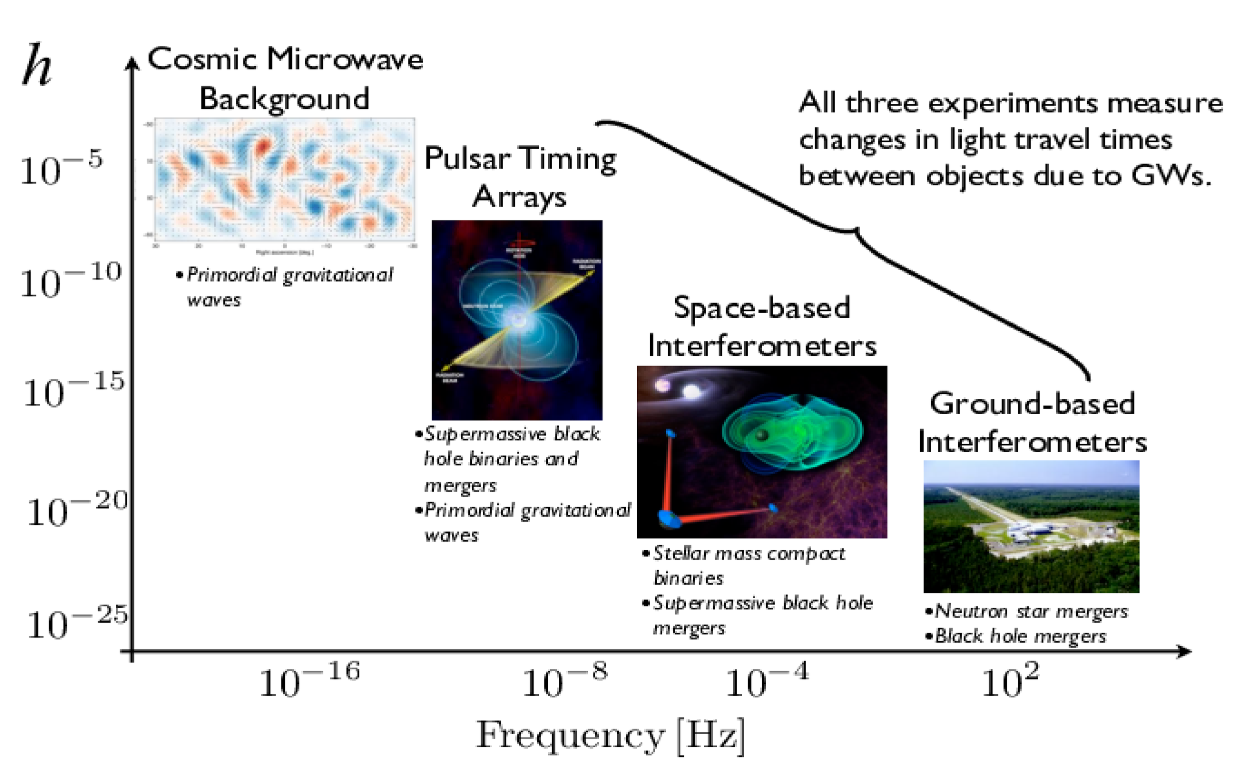
Pulsar Timing and Gravitational Waves

When a star collapses, one possible type of stellar remnant is called a neutron star. Neutron stars are incredibly dense, having more than 1.1 times the mass of the sun with diameters on the order of 10 km. Due to the conservation of angular momentum, they also rotate rapidly. Pulsars are highly magnetized neutron stars that emit beams of electromagnetic radiation; this radiation can be detected from Earth in the form of "pulses."



A diagram of a pulsar.

The spectrum of gravitational wave astronomy



Our reason for studying pulsars is to try to detect gravitational waves, which are ripples in the "fabric" of spacetime as predicted by Einstein in his theory of general relativity. They are generated by gravitational interactions, such as the merger of black holes, and propagate outward as waves from their sources at the speed of light. Gravitational waves distort spacetime such that the distance along a fixed path may change.

The gravitational waves studied by NANOGrav ((North American Nanohertz Observatory for Gravitational Waves) are emitted by supermassive black hole binaries and mergers. These black holes can be hundreds of thousands to billions of solar masses.

The ISM

One of several complications in pulsar timing is the existence of the interstellar medium (ISM), the matter that lies in the space between star systems (and between us and the pulsar).
The ISM is comprised partly of ionized hydrogen. As the pulse signal travels through the ISM, it becomes distorted by it, and therefore must be adjusted for. However, the ISM is difficult to model in comparison to other factors affecting pulse arrival time because it is not homogeneous, there is limited information available about its effects, and it has never been mapped.
My research this summer has been mainly concerned with understanding the effects the ISM has on pulse arrival times and determining appropriate ways to compensate for it.

DMX – The Standard Timing Model

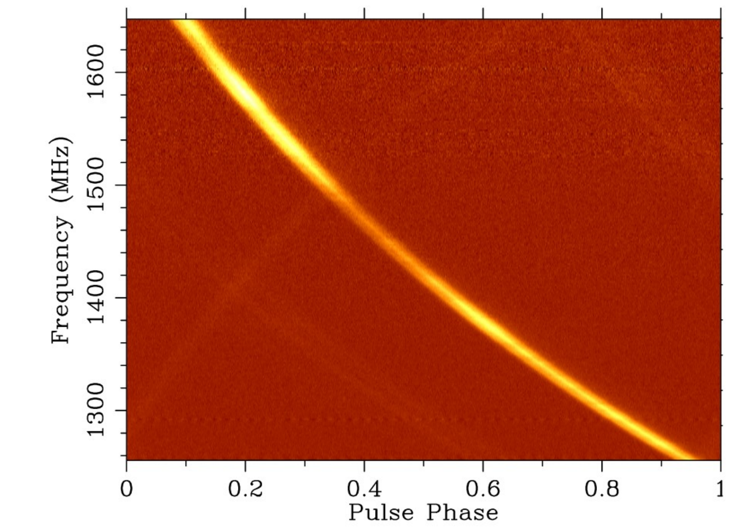
Lower-frequency radio waves travel through the ISM more slowly than high frequency waves, causing them to reach Earth slightly later. This effect is called dispersion, and results in a time delay:

$$\Delta t = \mathcal{D} \times \frac{\text{DM}}{f^2}$$

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:

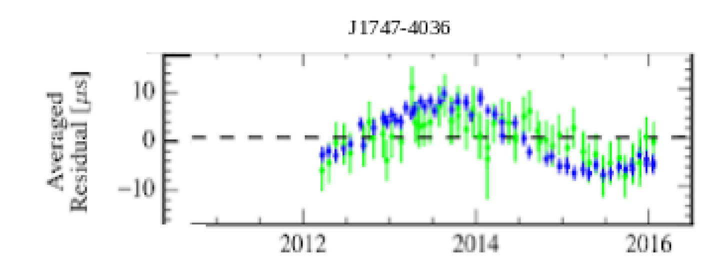
$$\text{DM} = \int_{\text{Earth}}^{\text{Pulsar}} n_e \, dl$$

Where n_e is the electron density of the ISM.
By observing delays in the pulse TOAs, we can calculate the dispersion measure and subtract the effects from our data. The concentration and composition of the ISM varies, so as the pulsar moves through it, the DM changes. We measure the DM as it changes over time (DMX).



Above: This figure shows the change in pulse arrival time across different frequencies due to dispersion.

Below: This figure, from Hao Lu's ('16) thesis, shows dispersion measure over time for the pulsar J1747-4036. Blue and green points correspond to different frequency bands. Notice the difference between the colors.

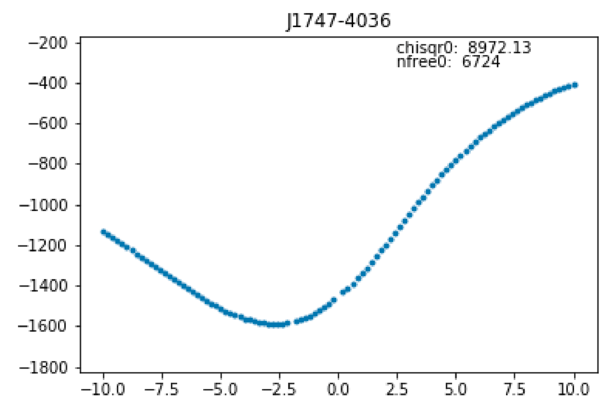


XMX Parameters

Adding XMX parameters to the traditional timing equation is a way of trying to come up with models to quantify the ISM's effect on pulse timing.

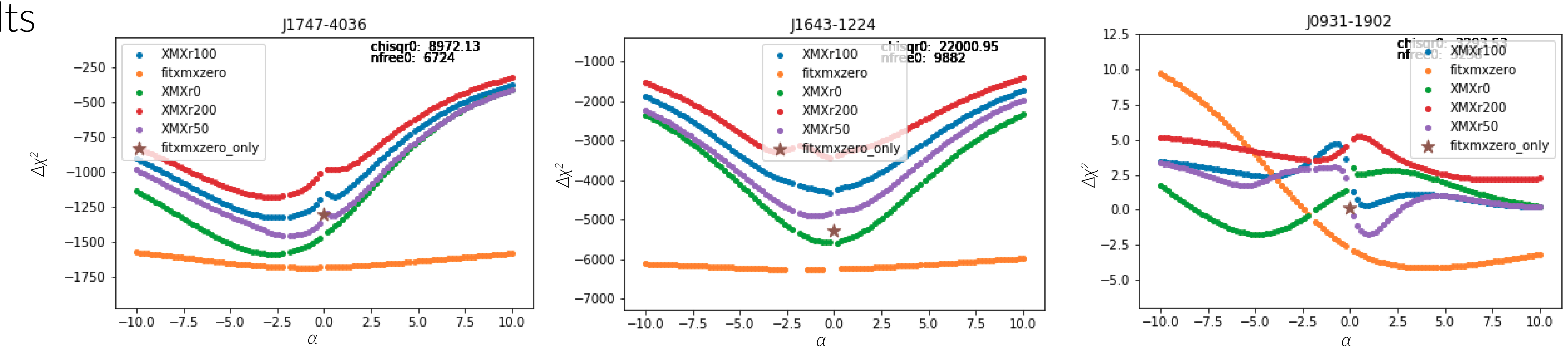
$$t_{\text{observed}} = t_{\text{emitted}} + \underbrace{\Delta t_{\text{solar system}} + \Delta t_{\text{binary}}}_{\text{Distance-related components}} + \underbrace{\text{DMX}_i\left(\frac{\mathcal{D}}{f^2}\right)}_{\text{Traditional DM model}} + \underbrace{\text{XMX}_i\left(\frac{f}{f_0}\right)^{\alpha}}_{\text{Our addition to the model}}$$

- Analyzed times of arrival (TOAs) from NANOGrav's 12.5-year dataset.
- Fit timing models incorporating the XMX parameter to the data.
- Predicted TOAs and compared them to the experimental data; the difference is called a "timing residual."
- Compared the χ^2 value (indicating the goodness of fit) to another fit that did not include the XMX parameters.
- Used a range of values for α.



Above: A χ^2 plot for the pulsar J1747-4036 over a time scale of a few days, the same time scale used for DMX.

Results



From left to right: $\Delta\chi^2$ plots for pulsars J1747-4036, J1643-12124, and J0931-1902. J1747-4306 and J1643-1224 are pulsars for which the model is improved (more distant pulsars) as is seen by their significant negative $\Delta\chi^2$ values. J0931-1902, the rightmost pulsar, is an example of a pulsar for which adding XMX terms does not improve the model. The different colors on each plot are analyses in which the timescale over which an XMX value is held fixed is varied from a few days to 50, 100, and 200 days. We expect the model to be similar over these differing timescales. The x-axis on the plots above represents the exponent used on the XMX parameter in the equation; the y-axis is the $\Delta\chi^2$ value.

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