Measuring the Acceleration of the Milky Way with Pulsar Timing

Statement of Interest:

In my final three semesters at UConn, I will explore the question of how I can use my knowledge of pulsar timing to study different topics in astrophysics research. This will allow me to enter graduate school with a specific and informed focus about my interests in the broader field. I will begin to accomplish my goal by studying cosmology in the next semesters as I measure the acceleration of pulsars in the Milky Way and interpret these values. Additionally, a possible next step of this project involves the study of dark matter, another interest of mine. I also hope to become familiar with General Relativity this summer via an REU opportunity, thus incorporating a third topic.

My interest in exploring different sub-fields began while working at the Center for Computational Astrophysics at the Flatiron Institute this summer. Through an internship program, I was able to meet with pulsar timing physicists both inside and outside of my advising professor's Gravitational Wave group. Simultaneously, I began work on a formal paper for the Astrophysical Journal which detailed my research on improving the sensitivity of pulsar timing arrays (PTAs). A significant portion of my paper was dedicated to the importance of PTAs in different branches of astrophysics. The applications spanned from gravitational wave and dark matter detection to tests of general relativity, all topics which are on the cutting edge of astrophysics research. I thus have made it my goal to develop an understanding of what doing work in these different sub-fields would be like given that I plan to earn a PhD in astrophysics as the next step in my career and want to make the most informed choice when selecting a topic to study.

I am well prepared to explore this question because of the research I have already conducted (Moran, Mingarelli et al. in prep). I began my research with a geophysics professor where I analyzed Martian seismic data from NASA's Project Insight. As a freshman, this gave me the opportunity to conduct independent research and report my results to the rest of the group. I thus learned the importance of having strong verbal and written communication skills. In addition to this, the project involved working with a very large set of data, which is crucial to pulsar timing astrophysics, as are the coding skills which I acquired when calculating and creating a model of the interior structure of Mars.

In my sophomore year, I transitioned to Professor Mingarelli's group where I began my pulsar timing research. My project objective was to determine more precise distances to pulsars in PTAs to improve array sensitivity. I utilized computational methods to identify binary systems of stars in the *Gaia* catalogue and International PTA pulsars and ran a series of tests to determine if the matches were false alarms (Mingarelli et al. 2018). Finally, I calculated the most probable distance to each pulsar (see Figure 1 for example) using a geometric distance prior and the parallax measurement of the *Gaia* object, which was reported in a paper where I am the lead author, to be submitted in the next few months..

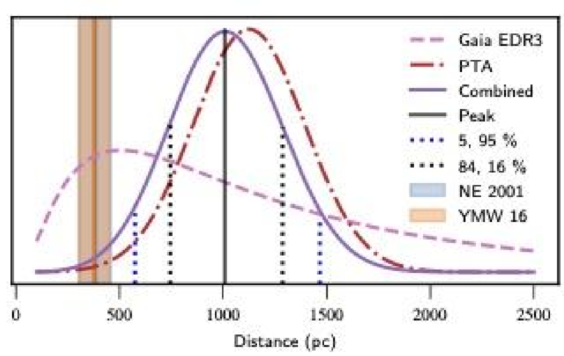

Figure 1: Distances to the system of one of the pulsars in my previous research. The peak of the combined curve was reported with asymmetric error bars representing the 84th and 16th percentiles of the distribution. The "Combined" curve takes into account all available distance measurements.

My study of applied mathematics as a double major has many applications in research using pulsar timing, such as the probabilistic analysis which was necessary in calculating the updated pulsar distances. I first added the double major because of an experience I had at the Conference for Undergraduate Women in Physics at Yale University as a freshman. When a speaker was asked what she wished she had done differently as an undergraduate, she replied that she wished she had taken more math classes because of how ubiquitous the applications are in physics research. This inspired me to officially add a double major in Applied Mathematics, something I had already been considering. Now, with classes covering topics such as mathematical modeling and complex numbers, as I progress in my learning plan, I will be able to expand the quantitative side of my research.

Learning Plan:

My learning plan is focused largely on building a theoretical basis for the physics in my research. Astrophysics is not a stand-alone field, and most of the subjects I am interested in require knowledge of more basic concepts. The study of cosmology and observations of large scale galactic motion for example are dependent on a strong understanding of dynamics. Another example is that an understanding of emission mechanisms in astrophysical objects like pulsars requires a foundation of quantum mechanics. On a more fundamental level, the electromagnetic properties of pulsars are what allow us to use pulsar timing in the first place, and thus knowing more about electricity and magnetism will allow me to understand more applications of pulsar timing.

Another objective of my learning plan is to further develop my understanding of mathematical concepts in geometry, modelling, and linear algebra which are integral to work in computational astrophysics. General Relativity, for example, is a very math intensive subject. I have already seen a need for strong mathematical skills when studying Gravitational waves via pulsar astronomy and I am confident that developing my mathematical skills will continue to benefit my research.

My final learning objective is to develop my communication skills, particularly in physics writing. Communication is completely essential to an astrophysicist's career, from presenting at poster exhibitions to writing research papers. This learning objective will be largely met by my additional learning opportunities each semester. The *Frontiers* poster exhibition, NANOGrav conference, and presentations at meetings with the Center for Computational Astrophyics's Gravitational Wave group will give me a chance to improve my verbal communication. I am also looking to develop my own voice in my papers in order to prepare myself for a career in research. This can be achieved during the revision process for my paper "Improving Distances to Binary Millisecond Pulsars with *Gaia*," and in the process of writing the journal article which will report my findings from my University Scholar project.

I have selected courses for my final three semesters with these objectives in mind. Some of these courses, such as "Stars and Compact Objects" are very directly related to my goals. Others are related in a less obvious, but equally important manner. In particular, "Quantum Mechanics" I and II are important to the theoretical basis of my studies, as is "Electricity and Magnetism II." "Introduction to Complex variables," "Introduction to Mathematical Modelling," and "Differential Equations for Applications" are all courses which are focused on topics in mathematics directly applicable to physics. "Mathematical Modelling" and "Differential Equations for Applications" are especially crucial to my understanding of how to approach real world problems and represent observed phenomena mathematically. Finally, "Undergraduate

Research" and "Research Thesis in Physics" will give me the opportunity to develop my skills in physics writing through the development of a formal research paper.

Project Proposal:

In my remaining three semesters at UConn, I propose continuing my work with pulsar timing astrophysics. My previous work focused on improving pulsar timing array (PTA) sensitivity with a novel technique of measuring pulsar distances. These new and improved distances can now be used to measure the acceleration of each pulsar, and through mathematical deduction, the acceleration of the Milky Way.

Neutron stars are formed when a very massive star runs out of light elements to use as fuel and explodes in a supernova, leaving behind a small and dense object. These remnants tend to be highly magnetized and thus spin on an axis. As they spin, the stars eject charged particles, creating radio waves that we receive as pulses of energy on Earth. These rapidly rotating neutron stars are hence called pulsars (see Figure 2). Millisecond pulsars (MSPs) are of particular interest, since they are very stable, making them the best natural clocks ever discovered (Backer et al. 1982).

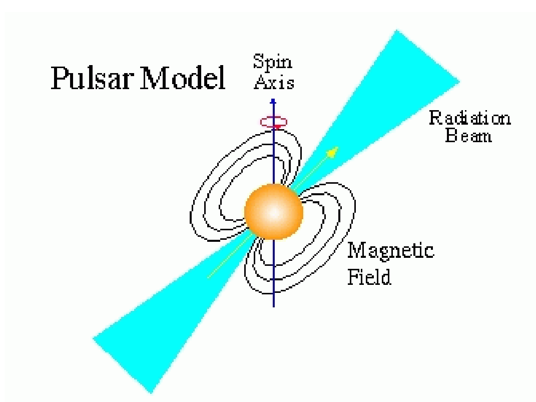

Figure 2: The basic structure of a pulsar. The orange sphere at the center is a neutron star with its spin axis misaligned with its magnetic field. The other basic components are labelled accordingly. When the radiation beam sweeps out in the Earth's direction, it is possible to detect the pulsar (Ryden 2003).

Pulsar timing arrays are a collection of these ultra-stable millisecond pulsars, and can be used in a variety of topics in astrophysics research, such as to study dynamics on the galactic scale. The sensitivity of the array can be improved if the distance to the pulsars is known. Although this distance can be difficult to determine directly, indirect methods such as kinematic distances and associated distances can be used. In my paper "Improving Distances to Binary Millisecond Pulsars with *Gaia*" (Moran, Mingarelli et al. in prep) I describe how I used the latter method to calculate new pulsar distance measurements with the goal of improving PTA sensitivity.

To continue my exploration of pulsar timing astrophysics, next semester I will be using PTA data and pulsar distance measurements to study the acceleration of the Milky Way galaxy. I hypothesize that using the spindown rate of IPTA and NanoGrav MSPs, the acceleration of the galaxy is measurable, and is within three sigma of the expected value of each galactic region. It is possible to do this because of pulsar spindown. Pulsar spindown (Lyne & Graham-Smith, 2012), denoted $\dot{P}$, is the increase in time between successive radiation bursts from a pulsar over time. The increase that we observe on Earth is the result of several factors, as shown in Equation 1 (Verbiest et al. 2008).

$$\dot{P}_{obs} = \dot{P}_{GW} + \dot{P}_{Gal} + \dot{P}_{kin} \quad (1)$$

The first term that contributes to the observed spindown of a pulsar is $\dot{P}GW$. This is the decrease in period is the result of gravitational wave emission from the binary, and since these are millions of years from merging, we can approximate $\dot{P}_{GW}=0$. The third term is $\dot{P}_{Gal}$, or the decrease in a pulsar's period as a result of galactic acceleration; this is the term we want to isolate. The final term, $\dot{P}_{kin}$ is the decrease in a pulsar's period due to kinematic effects. Dubbed "the Shklovskii Effect," this consequence of time dilation is directly proportional to the pulsar's distance from

Earth (Shklovskii, 1970). Therefore, it can be calculated once the distance to a pulsar is known. Thus, we are able to isolate $\dot{P}_{Gal}$ for pulsars with a measured $\dot{P}_{obs}$ and distance.

Indeed it is theoretically possible to isolate the effects of galactic acceleration from the other spindown terms. I will begin the process of measuring galactic acceleration by collecting data from the International PTA (IPTA) and NANOGrav's 12 year dataset (both are publicly available), keeping data only on the binary pulsars that have $\dot{P}$ measurements. I require that each $\dot{P}$ value is a 3 sigma measurement, that each pulsar has a measured proper motion, and that the pulsar has a distance measurement in IPTA. The two latter requirements ensure that only the dynamical effects of the galaxy are taken into account and that it will be possible to isolate $\dot{P}_{Gal}$. I will then plot the coordinates of the pulsars on a skymap to determine where we will be able to measure the value of galactic acceleration (i.e. how far from the center of the galaxy) and determine the expected acceleration values accordingly.

Next, in order to subtract the effects of $\dot{P}_{kin}$ from $\dot{P}_{obs}$, I must calculate a combined distance measurement to each pulsar from the solar system barycenter (if this was not already done in "Improving Distances to Binary Millisecond Pulsars with *Gaia*"). Based on this distance, I can calculate the the expected $\dot{P}$ from the Shklovskii effect alone. Additionally, using mass estimations for the pulsar and companion object, I can also calculate the energy loss due to Gravitational Wave emissions for the pulsar (Peters & Mathews 1963). From this, the increase in period due to these emissions can be calculated. Thus, assuming the $\dot{P}_{int}$ term is indeed negligible, I will have isolated the galactic acceleration term.

With this value isolated, the pulsar's acceleration towards the galactic plane can be calculated via a sine relation (Nice & Taylor 1995). In addition to $\dot{P}_{Gal}$, this relationship depends on the pulsar's galactic coordinates (l,b), its distance to the galactic center, and rotational velocity, all of which are measured for all IPTA and NanoGrav pulsars which have a measured value for proper motion. Thus, using this relation I will be able to calculate the value of acceleration towards or away from the galactic plane at different distances from the galactic center (exactly where is dependent on what pulsars meet my criteria). Combining the values produced by this step geometrically for all of the pulsars will result in the acceleration of the Milky Way (Phillips et al. 2021). The relationship between acceleration and the previously mentioned sine function is expected to be linear, thus making this final step relatively simple. This method has been used in other similar projects, thus speaking to its reliability.

Note that while the Milky Way's acceleration has been measured before, and has even been measured with this method, because new pulsars are discovered and catalogued constantly, my study will include more data than any previous research. I am therefore hopeful that my work will produce results which are more accurate than past values.

I expect that this project will produce a formal research paper to be submitted to the Astrophysical Journal and a poster to be presented at the next NanoGrav meeting. Next steps in this research will depend on my results, but possibilities include mapping dark matter in the Milky Way or testing general relativity using pulsar timing.

References

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Learning and Project Plan

Student Name:

Spring 2022

Courses

Dept &Course#	*Course Title*	*Credits*
Phys 3202	Electricity and Magnetism II	3
Phys 3989	Undergraduate Research	3
Phys 3300	Statistical and Thermal Physics	3
Math 3710	Introduction to Mathematical Modeling	3

Other Learning Opportunities

Opportunity	*Location/Date*
Academic Writing: make revisions to "Identifying Binary Companions to Millisecond Pulsars with Gaia" according to ApJ feedback	January - March 2022
Apply to REU programs after discussion with professors about their work apply to programs relevant to my interests	January 2022
GRE preparation: review of material for physics and general GRE, begin taking practice exams	Throughout semester

Project Milestones

Key Tasks
Identify pulsars which meet the requirements of the project
Plot pulsars on sky map to determine where (how far form the galactic center) I will be able to measure the acceleration of Milky Way
Begin to calculate galactic acceleration values of the pulsars

Summer 2022(optional)

Other Learning Opportunities

Opportunity	*Location/Date*
REU	TBD/May-July 2022
GRE preparation: take practice exams for physics and general GRE	May-July 2022
Take GRE	TBD/August 2022

Graduate school applications: select schools, reach out to professors to discuss research	Throughout Summer 2022

Project Milestones

Key Tasks

Fall 2022

Courses

Dept &Course#	*Course Title*	*Credits*
Math 3510	Numerical Analysis I	3
Math 3146	Introduction to Complex Variables	3
Phys 3401	Quantum Mechanics I	3
Phys 4710	Stars and Compact Objects	3
Phys 3989	Undergraduate Research	3

Other Learning Opportunities

Opportunity	*Location/Date*
Graduate School Applications: prepare application materials	Throughout semester
Attend NANOGrav conference	October 2022

Project Milestones

Key Tasks
Calculate galactic acceleration values for all remaining pulsars
Combine these values to calculate the acceleration of the Milky Way

Winter Intersession 2022 (optional)

Other Learning Opportunities

Opportunity	*Location/Date*
Graduate School Applications: review, finalize and submit applications	December 2022

Spring 2023

Courses

Dept &Course#	*Course Title*	*Credits*
Math 3410	Differential Equations for Applications	3
Phys 3501	Modern Experimental Methods	3
Phys 3402	Quantum Mechanics II	3
Math 3511	Numerical Analysis II	3
Phys 4096W	Research Thesis in Physics	3

Other Learning Opportunities

Opportunity	*Location/Date*
Present Galactic Acceleration project at *Frontiers* exhibition	UConn/TBD

Project Milestones

Key Tasks
If possible, verify the galactic acceleration value using a second mathematical method
Write, edit, and submit formal research paper to the Astrophysical Journal