Rotating Liquid Helium to Simulate Glitching in Neutron Stars

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Neutron stars have long been known to emit beams of radiation that periodically pass the Earth's line of sight as they rotate. However, astronomers have observed sudden jumps in rotational velocity over the course of months or years called glitches. It is unknown exactly what causes these, but the two-component model, where a neutron star has a hard outer shell and neutron superfluid interior, is the current theory behind their occurrence. We aim to confirm this by modeling neutron star rotation with superfluid helium. The summer, we focused on building the experimental apparatus that will allow us to measure the rotational velocity of superfluid helium as it spins freely on a magnetically levitated axis. We confirmed a proof of concept for rotational data collection, which consists of a CD divided into equally spaced black and reflective sections that will spin with the superfluid helium. An LED light will reflect off of the CD and travel back into a photodector to record the voltage and timestamp at which the light is detected. From these pulses of reflected light, we can record an accurate period and rotational velocity. Additionally, an induction motor was built to rotate the superfluid helium setup on a magnetically levitated metal rod axis. The magnetic levitation device is built and is close to performing sustainable levitation on a steel ball. These components will combine to form the final experimental setup. Rotational velocity data obtained from this experiment will hopefully allow us to observe glitches and give astronomers a better understanding of the internal structure of neutron stars.

Introduction

In the 1960s, Hewish et al. were studying radio sources coming from deep space. These signals came in regular, rapid pulses and were fittingly named pulsars [6]. Today, we know them to be the remnants of supernovae called neutron stars, which rapidly rotate while emitting beams of radiation directed along their magnetic axis. Since the magnetic axis of these stars is commonly tilted relative to the axis of rotation, we observe the radiation beams as pulses when they pass Earth's line of sight. The radiation beam must cross the Earth to be detected, so the majority of pulsars cannot be observed directly.

The explosion of a sufficiently massive star creates a nebula of expelled gas with an extremely dense neutron star at its center. The neutron star is called such because it is so dense that almost all the nuclei break down, leaving a remnant of almost entirely neutrons, with some protons and electrons. The density of neutron stars is on the order of 1000 g/cm^3[6]. To put that in perspective, their density is similar to that of something a couple times the mass of the sun, shrunk down to the size of a small city. Due to this extreme density, neutron stars also have incredibly strong gravitational fields, around 10^{10} times Earth's gravity. Pulsars also have some of the strongest magnetic fields of any known objects, with fields ranging from 10^4 to 10^{11} tesla [6]. We can compare this to the strongest magnets man has created, which have just now reached strengths of 100 tesla.

Over time, neutron stars decelerate extremely slowly as they lose energy. However, astronomers have observed sudden accelerations in the rotational velocity of neutron stars, called glitches. These accelerations are not regularly timed, but usually happen on the order of months to years. The jumplike acceleration is followed by a long period of relaxation where the
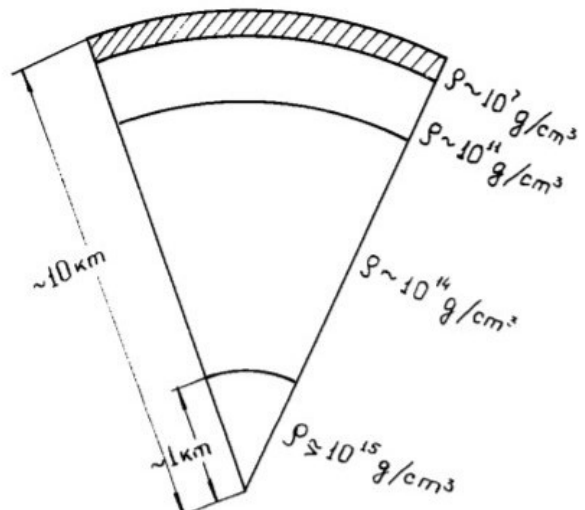

Figure 1: This is a diagram of the interior of a neutron star from Tsakadze et al. (1973), following the two component model. Underneath a solid iron shell, there is layer of neutron superfluid with neutron-rich iron nuclei. Further inside, the neutron superfluid also contains superfluid protons and electron impurities. In heavy neutron stars, there may also be a solid neutron core [6].

pulsar slows to its pre-glitch rotational velocity and continues to slow as normal [4]. It is not entirely understood why this happens, but the current theory is the two-component model of a neutron star. This model suggests that neutron stars are made of a hard outer shell with a neutron superfluid interior [6]. A rough diagram of this model, proposed by Tsakadze et al., is shown in Figure 1.

Before we can understand why this would cause sudden jumps in rotational velocity, we first need to understand the unique properties of superfluids. Superfluids are liquids that have zero viscosity and do not freeze at 0K. They are coherent quantum systems that can be described by single-particle wave functions. Liquid helium is a common example of a superfluid. At 0K, liquid He is entirely a superfluid. From 0K to 2.17K, thermal excitations appear in the superfluid component, and liquid He becomes a mixture of normal fluid and superfluid. Above 2.17K, the thermal excitations take over the whole volume, and liquid He becomes an entirely normal fluid [6]. Whenever there is non-zero circulation imposed externally on a superfluid, vortices form [4]. These vortices are quantized, meaning their circulations can only be specific, indexed values. Superfluid helium vortices have been observed experimentally, as they are entirely macroscopic formations.

with it [6]. This means there is a difference between the angular velocity of the vortices and the angular velocity of the neutron superfluid. Eventually, the discrepancy causes enough force on the vortices that they become unpinned. There is then a mechanism that transfers the angular momentum from the superfluid to the shell, causing it to accelerate, which we view from Earth as a glitch. A relaxation period then occurs as the vortices re-pin [1]. Since there is no definite time frame that the vortices will unpin, the glitches occur in irregular jumps in time.

To simulate these glitches on Earth, Andronikashvili, Tsakadze, and Tsakadze (a group from the 1970s) used liquid helium. They rotated a magnetically levitating, cylindrical vessel of liquid helium cooled to 1.46K in order to experimentally create glitches. An example of their glitch data is seen in Figure 2. They recorded the period of the rotating vessel by pointing a light beam at a mirror that was attached to the rotating rod. This gave them an accurate period to 10^{-3}s [6]. The full experimental setup can be seen in
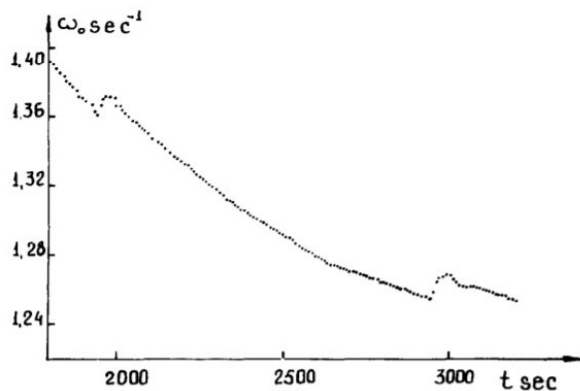

Figure 2: A sampling of rotational data from Tsakadze et al. (1980). "Time dependence of the rotation velocity of a light vessel containing superfluid liquid. T = 1.52 K" [6]. The jumps in rotational velocity around t = 2000s and t=3000s are glitches, similar to those observed in neutron stars.

Since neutron stars spin, Ginzburg and Kirzhnits (1964) suggested that quantized vortices exist inside the neutron superfluid interior. According to the two-component model, the outer shell slows while superfluid interior does not. The vortices within the superfluid are pinned where they meet the crust and slow
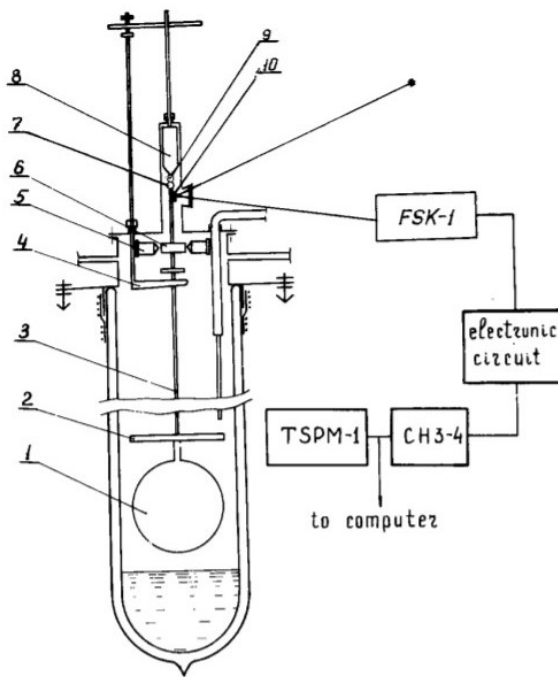

Figure 3: This is a schematic of the first apparatus used by Tsakadze et al. [6]. A glass sphere (1) containing liquid He is attached to a stainless steel axis (3) which ends in a steel ball (7). When the electromagnet (8) is turned on, the steel ball is attracted to another (9). The balls are the only point of contact suspending the apparatus, so when it spins, there is very little friction. A second setup built by Tsakadze et al. was similar, but magnetically levitated the system instead of using the balls as a contact point.

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Figure 3. While some glitches were observed, not many were recorded, especially with the precision that can be achieved with the technology of today. While the millisecond period accuracy is not bad, Tsakadze et al. only took measurements every few seconds, which is an interval we can greatly improve upon.

We hope to run a similar experiment to that of the Tsakadze group in order to find more abundant and precise glitch data that astronomers will be able to use to compare to data from pulsars. Using observational and experimental data will give a more accurate understanding of the interior structure of pulsars.

The Experimental Setup

The experimental setup will be similar to those of other rotating helium experiments, one of which is diagrammed in Figure 3 [3][5][6]. The goal of the apparatus is to simulate the spin of neutron stars by rotating liquid helium and recording how the angular velocity of the system changes as it slows, hopefully observing some sudden upticks in velocity or glitches. The majority of the apparatus will be contained inside of a dewar, the schematic of which is shown in Figure 4. We will magnetically levitate a steel ball connected to a metal rod which will be attached to a spherical vessel at the bottom. The dewar will contain the cooled liquid helium which the spherical vessel will be dipped into and filled through a small hole at its top. An induction motor will rotate the metal rod and, therefore, the vessel of helium. We plan to rotate the vessel at an angular velocity of about 1 revolution per second, although this may vary as we perform various runs of the experiment. The vessel will be rotated up to this initial velocity, then the induction motor will be turned off, and the angular velocity of the vessel will be free to decay naturally due to friction from the evaporated helium contained within the dewar. The experiment will be left to run for hours or up to a day at a time. To record the period and angular velocity of the vessel over time, we will use a mirrored disk, likely a blank CD, attached around the metal rod. The disk will be divided by black, evenly spaced lines marked on a transparency, the design of which is seen in Figure 5. The disk must be less than 4 inches in diameter in order to fit inside the dewar. The light from an LED will be directed onto the disk as it rotates, and a photodetector will keep track of the flux of the reflected light coming off

of the disk. As it spins, the light will sequentially hit reflective and black sections of the disk, resulting in pulses of light and dark data, converted into high and
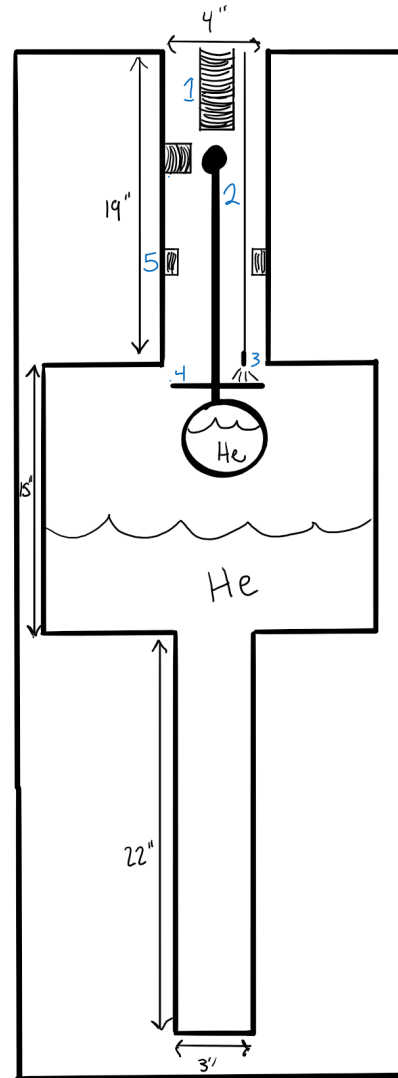

Figure 4: This is a diagram of the future experimental setup within the dewar. The measured dimensions outline the interior of the dewar, which has a thin top, wide middle, and thin bottom. The bottom and most of the middle portions of the dewar will be filled with liquid helium. The main experiment will be in the top and middle of the dewar. 1) The magnetic levitation device that will hold up the steel ball and entire rotating apparatus. 2) The rotating apparatus. A steel ball is attached to a metal rod, ending with the container of liquid helium. 3) The optical fiber that will transport LED light to the reflective CD and out to the photodetector. 4) The CD, divided into reflective and black sections. 5) The induction motor that will rotate the metal rod and therefore the bucket of helium.

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low voltages by the photodetector. The times between each pulse will allow us to determine an accurate period of rotation and angular velocity. A more in-depth description of this process will be described in "Optical Data Collection". With liquid helium contained inside of the vessel, we expect to see sudden jumps in angular velocity over the course of the gradual slow-down, which would support the theory that glitches in neutron stars are caused by an internal neutron superfluid.
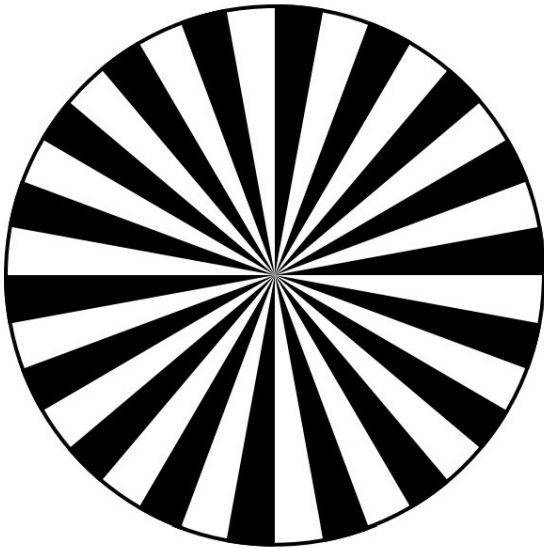

Figure 5: This is a sample image of the transparency that sits over the CD. The black and transparent lines are equally spaced around the CD, so an accurate measure of the period of rotation can be made.

Magnetic Levitation

Magnetic levitation was chosen to hold up the rotating vessel because it will allow for frictionless rotation of the system, better simulating the conditions of neutron star rotation. To cause magnetic levitation, a steel rod was wrapped in magnet wire to create an inductor. The steel rod acts to amplify the magnetic field through the magnetization of the steel. When a current runs through the wire, it induces a uniform magnetic field vertically through the rod. The magnetic field strength can be controlled by changing the current through the wire using a DC power supply. For testing purposes, we are currently trying to levitate only the steel ball that will be at the top of the ball-rod-vessel system. We set an arbitrary distance from the magnet to be the location for the ball

to levitate. A sensor is positioned under the magnet with the ball in between. The sensor will detect the position of the ball, and if the ball is not in the specified location, the sensor sends a signal to the voltage source to change the voltage, changing the current running through the magnet wire, and therefore the magnetic field strength. This way the ball will be shifted closer to the ideal levitation location by the changing magnetic field. Because of the way this system works, we expect the ball to slightly oscillate before settling on the levitation location.

As of the present moment, magnetic levitation of the ball has not been achieved, but oscillations have been felt, indicating that the setup is close to working. The current belief as to why it is not working is that there is too much noise around the circuit that controls the inductor's current. This noise may create an incorrect signal that the magnet adjusts to. These adjustments could push the ball far enough from its equilibrium that it cannot recover. We will be testing whether putting a box around the circuit to block the noise will lead to successful levitation.

The Induction Motor

In order to rotate the system without friction, we are using an AC induction motor. An induction motor uses alternating magnetic fields to spin a rotor that is positioned in the middle of the coils. In our setup, there will be four coils of 250 turns of magnet wire around metal cores to increase inductance. They will be arranged in a square, and opposing coils produce magnetic fields in the same direction at the same time. The circuit for this is seen in Figure 6 where two opposing coils are in series with each other so the current running through them is always the same. The other two opposing coils are placed in parallel with them, but are also in series with a capacitor. For testing purposes, we used an AC power supply set to 60 Hz, so the current through the coils has a strength that increases and decreases in the form of a sine wave.

In the circuit, the capacitor acts to offset the current between the two sets of inductors. When two opposing coils have a strong current (and magnetic field), the others have a weak current (and magnetic field). Ideally, the currents are 90° out of phase so the rotor feels the greatest difference between the magnetic field strengths as they oscillate. Through our trials of building the induction motor, we found that a 1000μF capacitor created a 76° phase difference be-

tween the 250 turn coils, making it close to the optimal 90° offset. This offset was calculated using an oscilloscope that showed the sinusoidal wave function of the voltage across each set of coils, and we could calculate the degree of separation between their wave functions based on their measured separation.
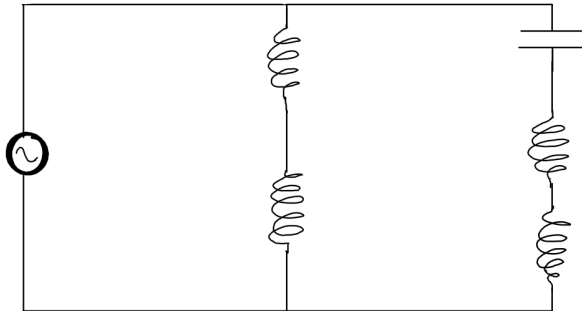

Figure 6: The is the basic circuit for the induction motor. Two 250-turn coils of magnetic wire wrapped around metal cores are in parallel with another set of two coils, and with an AC power source at a frequency of 60 Hz. A 1000μF capacitor is in series with one set of inductors. The capacitor offsets the current between the two sets of inductors, causing their magnetic fields to be out of phase by 76 °.

Our final setup will have the induction motor surrounding the metal rod on all sides, so we tested various metal rotors to make sure that they would spin under the influence of the induction motor. Holding a steel ball in the middle (the same steel ball we will be using for the levitation), we felt the oscillations as the magnetic field between the coils was changing. A steel rod suspended from a string did rotate, but it was difficult to keep it from directly attracting to one coil vs the other, so cardboard barriers were put in place to keep it in the middle. This suggests that the real setup will need to be close to perfectly symmetric for the rod to stay completely in the middle of the system. The best rotors we tested were the lids of pasta jars. These required the least amount of voltage to begin rotating and rotated at the fastest rate. It is still not clear why they are the best rotors, but we are currently exploring this in order to incorporate their properties into the actual metal rod system.

Optical Data Collection

Since past setups of rotating liquid helium all used some sort of laser-mirror-photodetector system for data acquisition, we decided to use something similar.

However, we hope to improve upon the accuracy of past setups by increasing the number of datapoints collected and the precision at which they are measured. In this experiment, we are looking to measure the period of the vessel's rotation as it slowly decays over time. The main components of our setup include an LED light source, an optical fiber, a mirrored disk or CD, and a photodetector. We positioned a 660nm, 13mW LED on a breadboard, and using a DC power supply to power the LED, the light is directed into one end of an RP20 Fiber Optic Reflection Probe Bundle. That branch of the optical fiber sends the light out the bottom to reflect off of the mirrored surface of a CD below. The CD is divided into black and reflective sections by laying a transparency with the pattern shown in Figure 5 on top of it. We determined the optimal number of lines by measuring the spread of the light when it hits the CD from about 0.1 inches away. The cone of light would spread to a diameter of about 0.08 in. Using this value as the smallest width a black line could be and estimating that the radius at which the fiber will sit will be about 1.5 in from the metal rod axis, we calculated that about 40-50 black lines would be the most we could fit onto the CD.

The CD rotates with the metal rod and He vessel system, so the light from the optical fiber will hit alternating black and reflective lines as they pass by. This will send pulses of reflected light back up the fiber in time intervals that correspond to the speed of the passing lines and, therefore, the period of the system. The reflected light will travel up the other branch of the fiber and into a Si Fixed Gain Photodetector. The photodetector will convert the luminosity of the light it receives into a corresponding voltage. We connected the photodetector to an Arduino for the main analysis. The Arduino records the voltages and assigns a time to each one. We optimized the code so the Arduino would only store the times when the voltage changed by a significant amount (the beginning and end of each pulse of light). These values are the only ones necessary for calculating a period from the data because just the time interval between each pulse is needed.

When testing this setup for proof of concept, we set the CD on a motor that rotated it at a certain speed depending on the voltage powering it. This was a crude setup, so the CD wobbled on its axis due to it not being perfectly level on the motor. This meant that the voltage data collected by the Arduino was not entirely regular: some light vs dark pulses had a much larger voltage difference than others. There-

fore, it was difficult to set a threshold for large versus small voltages to track the beginning and end of each pulse without missing any or including any that were not real pulses. This variance in voltage differences can be seen in Figure 7. The data set clearly shows the periodic wobble of the disk in addition to the regular pulses. We were able to level the CD enough to get data for proof of concept. This data can be seen in Figure 8. Using all of the data points shown in Figure 9, which consists of the first 150 data points from Fig. 8, we averaged the time difference between each pulse and multiplied by the number of lines on the disk. This gave a period accurate within 1% of the actual period observed using a stopwatch. Even using just 10 data points gave a period accurate within 2%. The data points are also collected at much smaller increments as compared to Tsadadze et al. A data point was collected about every 3ms, while Tsadadze et al. only took one data point every few seconds. Example data is shown in Table 1. The rotational velocity can be calculated using this period and the circumference of the disk. While the stopwatch timing was likely inaccurate, this was enough of a proof of concept that we are confident the method will work to give an accurate period for the real system, especially since we will be able to attach the CD more carefully to limit any potential wobble.

Table 1: Example Data	
Timestamp (μs)	Time between pulses (μs)
5246260	N/A
5284564	38304
5321464	36900
5358900	37436
5396436	37536
5435244	38808
5472932	37688
5509212	36280
5546108	36896
5583148	37040

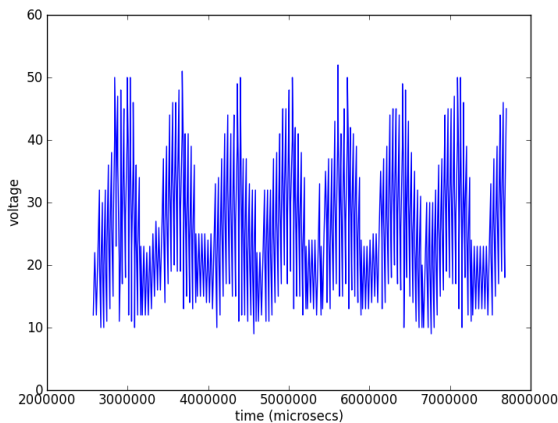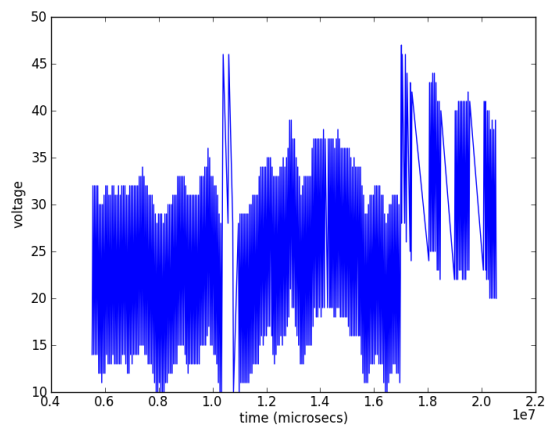Figure 8: Timestamp vs Voltage when the CD was leveled.

Figure 7: Timestamp vs. Voltage data. The "voltages" come directly from the Arduino which converts the analog voltage to a digital one by assigning it a corresponding number 0 to 1023 depending on its value. Each peak corresponds to a reflective section of the CD, while each minimum corresponds to a black section. A period is difficult to measure from this data due to the wobble of the disk. That wobble can be seen in the periodic oscillation of the voltage data. When the CD is closer to the optical fiber, a higher voltage difference between reflective and black sections is read. When it dips away, the voltage difference is smaller.
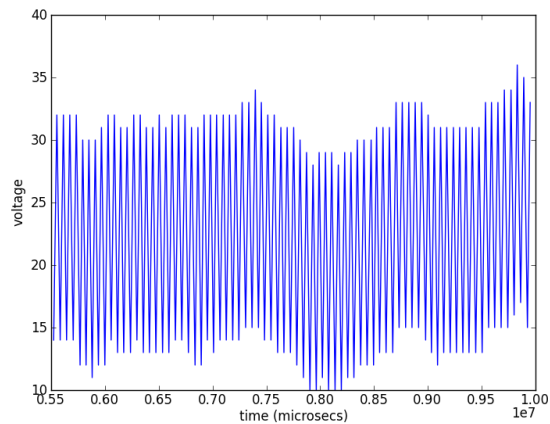

Figure 9: The first 500 data points from the Timestamp vs. Voltage sample in Figure 8. A period was calculated by averaging the time differences between each pulse and multiplying by the number of black lines on the CD. A rotational velocity was calculated by dividing the circumference by the period. The angular velocity of the data is 211.38 rad/s with a 0.46% error. The angular velocity measured from the ten data points in Table 1, is 167.86 rad/s with a 1.6% error.

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Concluding Remarks

The main goals of this summer were to design, build, and test the component parts of an experiment which rotates liquid helium. The data collection system and induction motor have been proved to work on their own in a testing environment that is similar to how they will function in the dewar. The magnetic levitation system has not been successful in its testing yet, but there is promise that the reduction of noise surrounding the circuit will cause the ball to levitate. Since these main components have been proved to function, the next steps for the experiment are to build everything for the dewar. This will include utilizing the machine shop to build the He bucket-rod-ball structure that will be levitated. In addition, a mechanism to lift and lower the bucket into and out of the He in the dewar will need to be designed and manufactured. We will also need to adapt the data collection and induction motor systems, so they work with the levitation component of experiment. Once the experiment is built inside the dewar, data collection can begin, and hopefully glitches will be detected. If glitches, or sudden increases in the angular velocity of the system, are detected, it will give us a greater understanding of why glitches are detected in neutron stars. Astronomers will be able to use our data to compare with observational data to verify whether neutron stars have a neutron superfluid interior and whether that superfluidity is the reason glitches occur.

Acknowledgements

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