In the year 1967, graduate student Jocelynn Bell and her research advisor, Anthony Hewish, laid down an array of radio antennae in England to study radio emissions from far off galaxies. Using a chart recorder to document radio signals, Bell noticed an inexplicable and reappearing "scruff" in her recordings. After switching to a recorder with even faster timing resolution, Bell was able to determine that the scruff was a series of regularly spaced pulses precisely 1.337 seconds apart from each other. *Such exact intervals from an astronomical object were entirely unheard of.* At first, the signal was jokingly (or maybe not?) referred to as "LGM", short for "Little Green Men", until Bell managed to find another strangely precise signal coming from a different location in the sky. With the alien hypothesis debunked, it was soon determined that the object responsible for the signal was a ***pulsar*** – a rapidly rotating, highly magnetized neutron star, with beams of radiation spouting from its magnetic poles and sweeping across our field of view like cosmic lighthouses. Since its initial discovery, over 2,000 pulsars have been found, with most being found by radio telescopes.

Pulsars are exceedingly strange – they are typically 1-2 times the mass of our Sun and yet their radius is typically comparable to that of Manhattan, making it *extremely* dense. How does such a star come into existence? A pulsar is formed when a massive star (around 10 to 25 times the mass of the Sun), in its dramatic throes of death (AKA a supernova explosion), begins to collapse in on itself. Depending on the initial mass of the dying star, the compression affecting the core of the star can result in the formation of a black hole or a neutron star. Following the supernova explosion, the resultant neutron star will retain the angular momentum of the collapsing parent star but with a much smaller radius. This results in the neutron star having a very high rotational speed. For the neutron star to be observed as a pulsar on Earth, its magnetic poles then need to be misaligned with the rotational axis of the star and pointed in our direction. From these magnetic poles, beams of radiation extend out and away from the star, allowing us to observe the blips of light that pulsars are so well-known for.

Pulsars possess two fundamental observables: **(1)** their period and **(2)** how quickly their period is changing, which is also referred to as their spin-down rate. From just these two observables, astronomers can infer other characteristics of the pulsar, such as the strength of its magnetic field and whether or not it possesses a binary companion. This is possible due to the incredible accuracy with which we can measure a pulsar's period and spin-down rate.

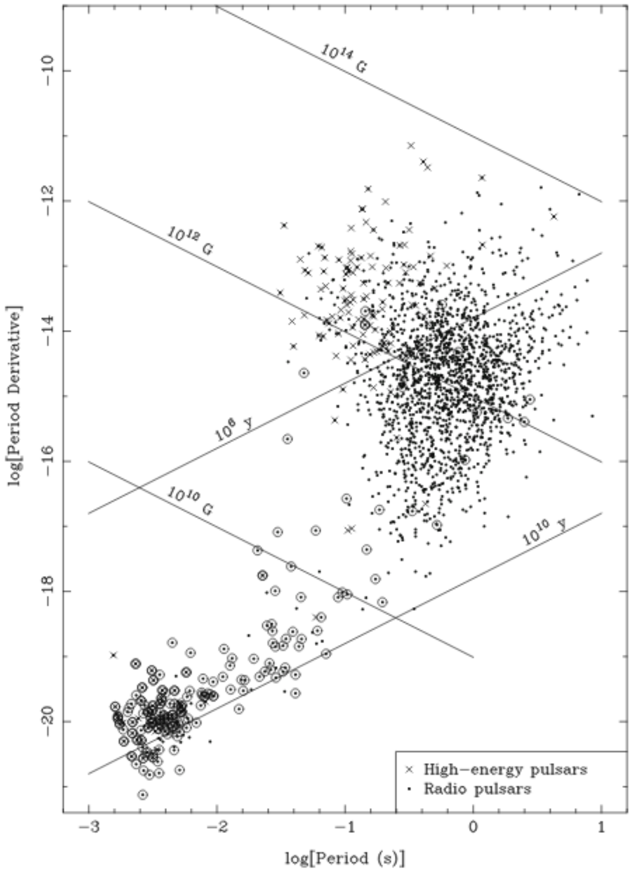


Figure 1: A "P-Pdot" diagram. Plot of period spin-down rate versus pulsar period for Galactic disk pulsars. Binary pulsars are indicated by a circle around the point. Figure from "Millisecond Pulsars, their Evolution and Applications", R.N. Manchester, 2017.

Within the population of known pulsars, an interesting subpopulation has emerged since its discovery in 1982: the millisecond pulsar (MSP). Figure 1 shows the bread-and-butter plot of pulsar science – the spin-down rate versus the period of the pulsar, lovingly referred to as the **P-Pdot diagram**. As can be seen in the figure, MSPs occupy a region on the P-Pdot diagram of short periods and small spin-down rates. In other words, MSPs are incredibly fast and incredibly stable. Their stability implies their longer lifetimes, as a pulsar's rotational energy will be depleted by its radiation energy over time, resulting in larger and larger periods until the pulsar inevitably "turns off". A typical pulsar lifespan is around a million years, whereas MSPs have typical lifespans of *10 billion* years. It should also be noted that MSPs tend to have weaker magnetic fields than regular pulsars, as can be seen on the diagram by the constant lines of magnetic field strength.

These P-Pdot diagrams of pulsar populations display a wealth of interesting correlations and phenomena. In particular, it can be seen in Figure 1 that a large majority of the MSP population exists within binary systems, whereas the regular pulsar population has a scarcity of binary systems. From this observation, one can begin to infer the *formation histories* of MSPs as compared to their slower counterparts on the P-Pdot diagram.

Formation History

In general, pulsars are formed as a result of the supernova explosion of the primary (heavier) star within a binary system. In the simplest of cases, a binary system will become disrupted if more than half of the initial mass of the exploding star is expelled in the explosion. *In the case of a binary disruption*, the newly formed pulsar and it's companion star will be separated, leaving us with a young radio pulsar and a runaway star. Below are several cartoons I have recreated from [1] to illustrate the lifecycles of a neutron star.

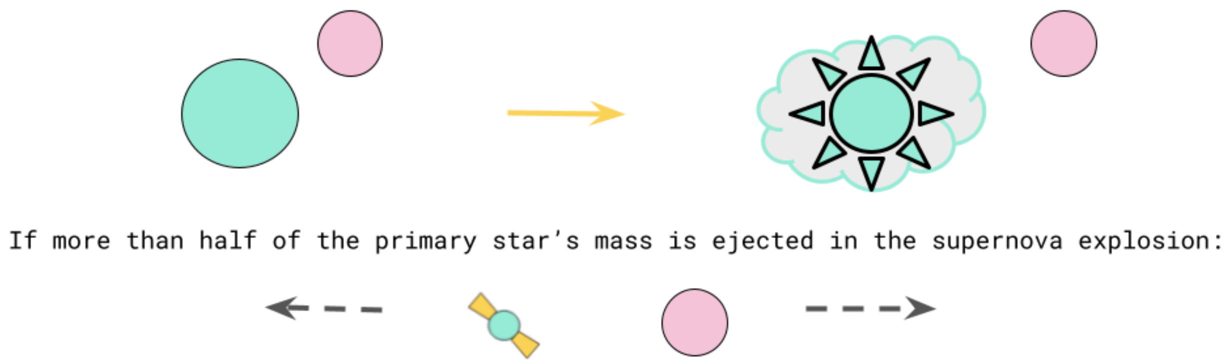


Figure 2: The birth of a pulsar first begins with the death of a massive star in a binary system. If the dying star loses enough of its initial mass in the supernova event, the binary system is disrupted and the newly-formed neutron star will not become a recycled millisecond pulsar unless it enters into a new binary system with a new star. Adapted from D.H. Lorimer.

For those systems that do survive, if the secondary star is sufficiently massive, the star will eventually start on its path to death and begin to expand. As it expands, the pulsar will begin to collect, or "accrete", material from its companion. As the material is accreted, the pulsar will gain more angular momentum resulting in a decrease in its period. This process is referred to as the pulsar being "spun-up" or "recycled". As material from the companion star is accreted onto the pulsar, the infalling material can experience frictional heating, leading to the emission of x-rays and the observation of the pair as an *x-ray binary system*. What happens next depends on the mass of the companion star.

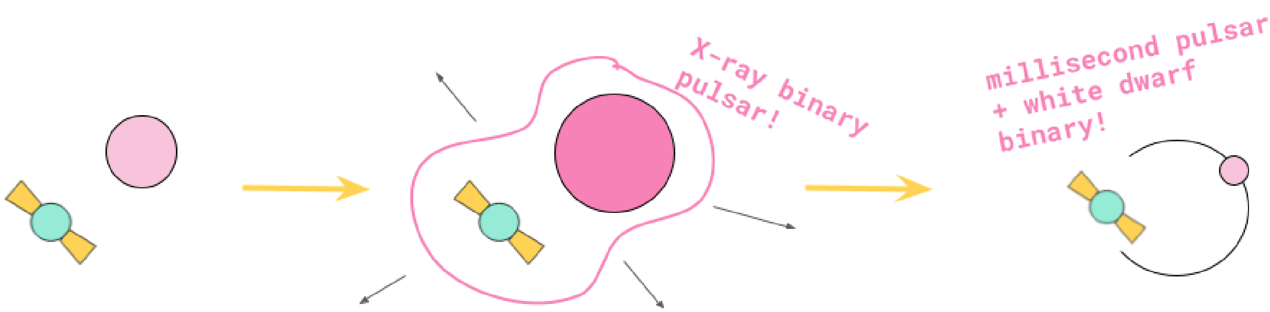


Figure 3: If the binary system remains intact. Adapted from D.H. Lorimer.

In the case of a high mass companion, the companion may very well go supernova and become a pulsar itself. With our symmetric explosion assumption on hand, the binary system will again disrupt if more than half of the mass of the star is expelled in the explosion. If more than half the mass is expelled, the two pulsars go their separate ways, with one having been spun up before the second supernova event and the other just newly born. The extent to which the first-born pulsar is spun-up depends again on the mass of the companion star in the system. The more massive the companion, the more quickly matter will be accreted and so the pulsar will be only mildly recycled leading up to the death of the companion. If the binary system remains intact, we are left with a double neutron star binary system. To date, only nine such systems have been found [1].

The pulsars lucky enough to have surviving lower mass companions will accrete material more slowly than if the companion were more massive, and so the system will survive for a longer time and the pulsar will have a better chance to spin up to millisecond period speeds. Thus the MSPs are born, and with them, the final resting form of the companion star as an orbiting white dwarf. This is a standard explanation for the formation of MSPs, and it does a great job at explaining the high number of MSPs found in binary systems just like the one described. However, there are anomalies which have been observed, such as isolated MSPs and MSPs belonging to triple systems! Most of these outlier systems have been observed in globular clusters, and so they can easily be explained by the high stellar densities found in these objects; however, 16 out of the 72 MSPs found in the disk of the Galaxy are without a companion [1] -- an observation which begs a different explanation. One favored explanation is that these isolated MSPs are the result of the companion star being destroyed by the strongs winds of a pulsar at the center of a supernova remnant -- such systems, in which the companion star is destroyed by the pulsar, are aptly referred to as “black widow” systems.

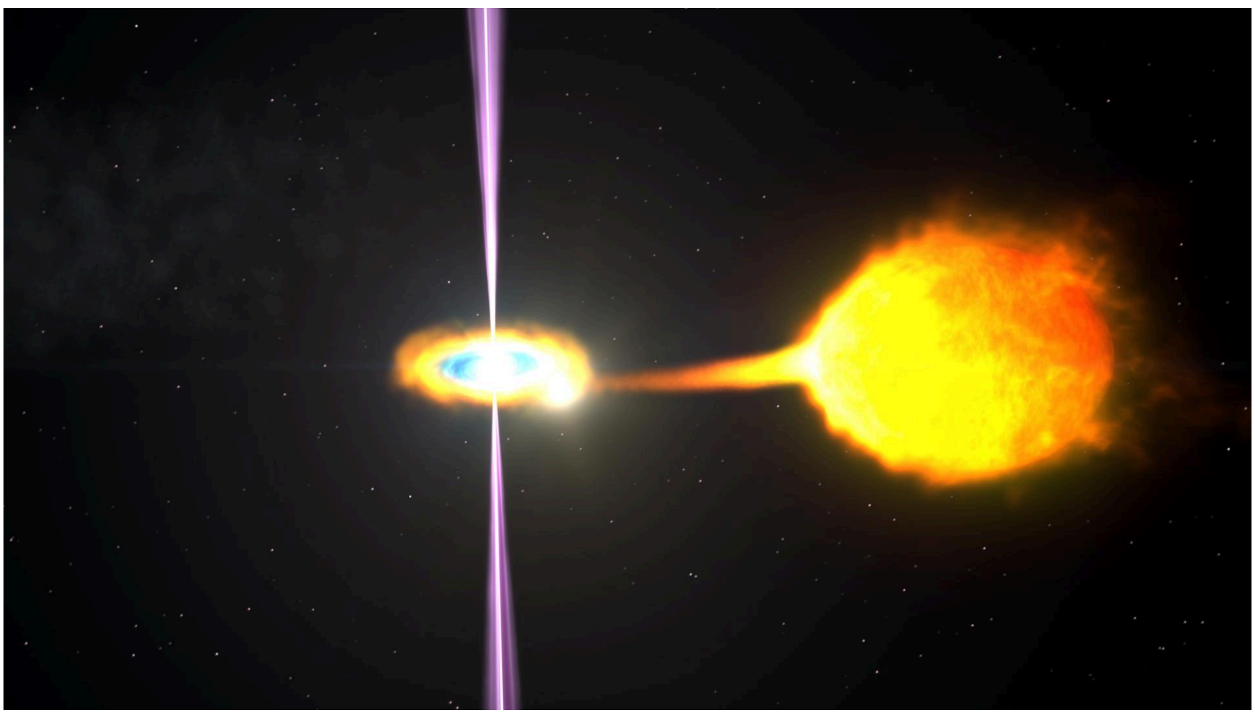


Figure 3: An artist’s concept of a pulsar accreting mass from it’s companion star, from NASA Space Flight Center.

Pulsars as Cosmic Timekeepers

One of the most remarkable characteristics of MSPs is their incredible stability. With such quick periods and such small spin-down rates (Figure 1), we are able to observe a single MSP over and over again to derive a period with an accuracy of up to one part in 10 trillion or even better [2]! In this section, I will describe, to the best of my abilities, the basics of pulsar timing. The essence of pulsar timing lies in measuring an accurate Time of Arrival (TOA) of an averaged, or “stacked”, pulsar pulse. The TOA is typically taken in reference to the start of the observation time at the given observatory as measured by atomic clocks and monitored by GPS signals [3]. Below is a cartoon I have recreated from [1] to better illustrate how pulsar timing works. As the pulsar spins, the magnetic poles (and therefore beams of radiation) will pass through our field of view. Radio waves from the poles will be impacted by the interstellar medium as they travel towards us, causing a dispersion in the pulses that may vary from pulse to pulse.

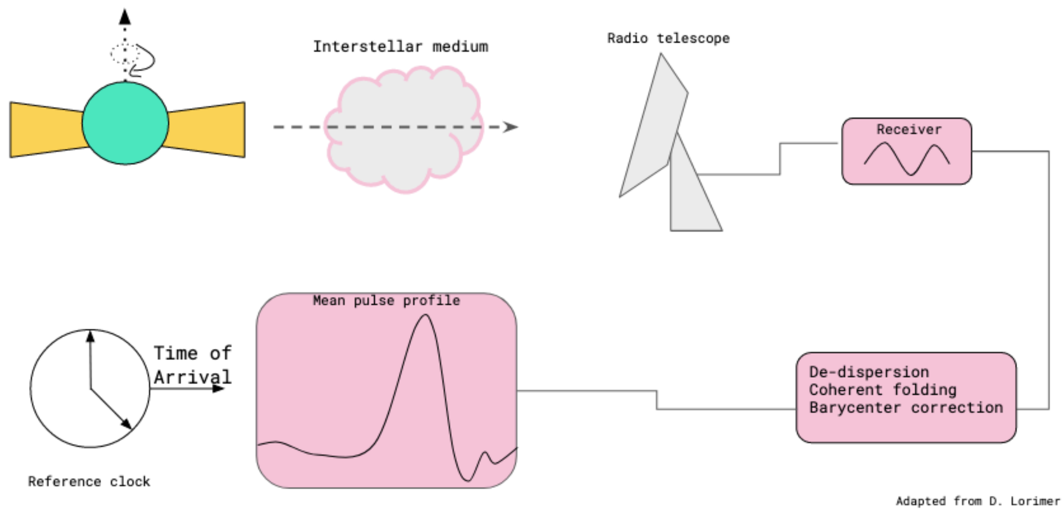


Figure 4: A cartoon to give the reader (Rob) a general feel for the complexities of pulsar timing.

Once the radio waves have been received, there are many steps taken to ensure the measured TOA of the pulses are accurately timed, starting with stacking all of the received pulses to calculate an averaged pulse profile ("coherent folding"). The pulses of a single pulsar can vary quite a bit (see Figure 5), but nevertheless the average profile of a pulsar is stable. For MSPs in particular, thousands of pulses can be averaged together in just a few minutes, resulting in extremely stable profiles [3]. Once these pulses are stacked, the TOA is then taken to be the difference in time between the start of the observing period and the peak of the averaged pulse profile.

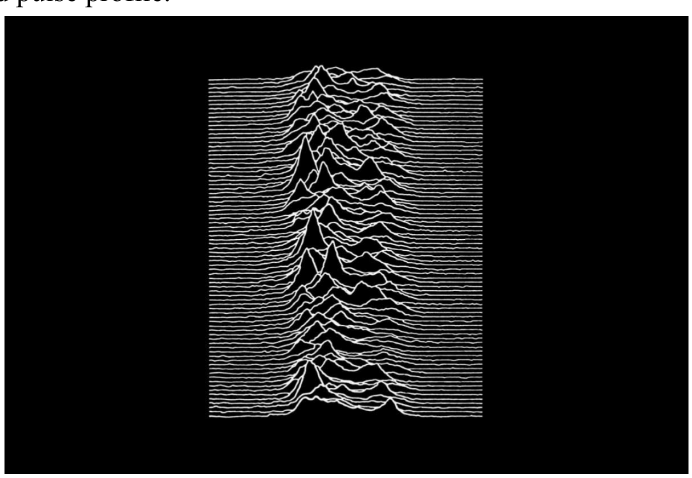


Figure 5: The iconic cover of Joy Division's album "Unknown Pleasures" (1979), which also turns out to be the radio pulses of the first ever pulsar discovered by Jocelyn Bell, PSR B1919+21. This image does a good job of showing how different individual pulses can be despite being from the same star.

As can be seen in Figure 4, stacking pulses is just the beginning of pulsar timing. There are several other factors that have to be taken into account before a true TOA is obtained, known as "clock corrections". The first such obstacle to correct for is the dispersion that the radio waves undergo as they travel through the interstellar medium. A pulsar emitting a beam of radiation, with all frequencies peaking at the same moment, will be stretched out as the radiation interacts with charged particles on its journey to Earth. In other words, since the radiation is frequency dependent, the interactions with charged particles will delay the propagation of the waves according to the waves' initial frequency, causing a smeared effect on the pulse profile, as can be seen in Figure 6.

I should actually correct myself for calling pulsar dispersion an obstacle to overcome; in fact, the dispersion of pulses can tell us the distance to the pulsar with an assumption made about the density of electrons along our line of sight to the pulsar. In practice, astronomers can use models to determine an estimate for the Galactic electron density distribution [4] to derive accurate distances.

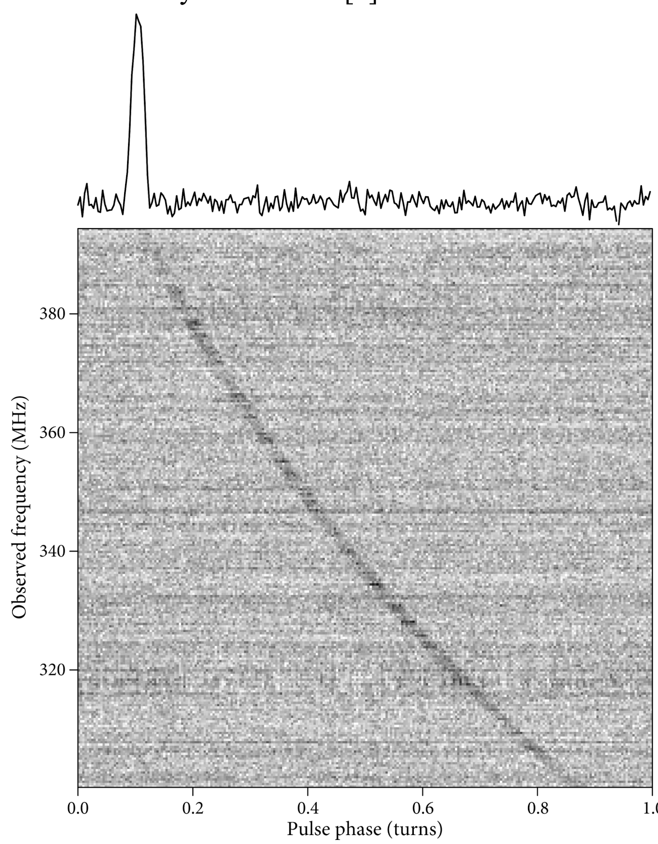


Figure 6: The observed frequency of the pulsar J1400+50 versus its phase. The frequency-dependent smearing of the signal can be seen as the dark grey curve. The averaged pulse profile is shown in the top panel. Figure from Chapter 6 of Scott Ransom's online Introduction to Radio Astronomy (reference [4]).

To fully reap the benefits of the timing precision that MSPs can offer us, a better method of dispersion removal is necessary than is typically used for pulsars with larger periods. More accurate dispersion removal from MSP signals is achieved by de-dispersing the signal with unique filter designs [1].

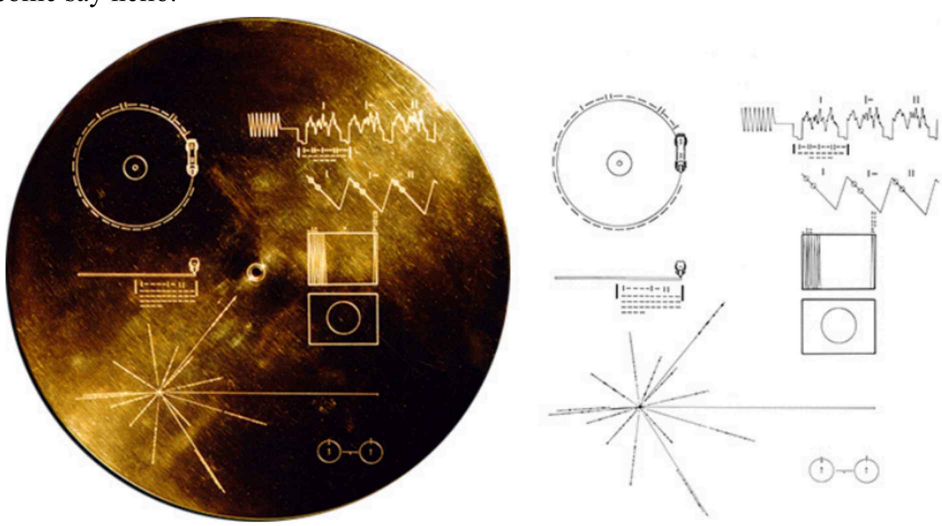
Lastly, a correction to transform the measurement to an inertial reference frame, a "barycentric correction", is required to achieve an accurate TOA. First, we must recognize that we are not in an inertial reference frame with respect to a pulsar being observed, as we are constantly experiencing accelerations due to the Earth's rotation and orbit around the Sun. The varying gravitational potential that is experienced on Earth affects even atomic clocks as they go along for the ride, and these terrestrial timekeepers must also be corrected in a similar way. To appropriately correct for this, astronomers transform the observed TOAs from the reference frame of an observatory on Earth to the barycenter of the solar system. To perform this transformation properly, several delay factors are taken into account, as described in [3]:

(1) The *Roemer Delay*, which accounts for the time it takes light to travel from the radio telescope in question to the barycenter of the solar system.
(2) The *Shapiro Delay*, which accounts for the space-time curvature of the solar system. Typically only the Sun is taken into account in these calculations, although Jupiter can contribute as much as 200 nanoseconds to the delay depending on the location of the pulsar.
(3) The *Einstein Delay*, which accounts for the variation in atomic clocks due to the changes in the gravitational potential experienced on Earth as it travels on its orbit around the sun.

Even more delay factors are necessary to include if the pulsar exists in a binary system (which we know to be the case for most MSPs!), such as the time it takes for light to travel across the binary orbit as well as relativistic effects within the system. The Keplerian orbital parameters of the binary system must then be solved for analytically in tandem with deriving a TOA to come out the other side with accurate numbers.

Pulsars as Celestial Lighthouses

In 1972, a plaque was mounted aboard the Pioneer 10 spacecraft depicting the figures of a man and a woman along with a pulsar map to guide an extraterrestrial reader to our location in the galaxy. This same map was included on Voyager's Golden Record, which is shown in Figure 5 below. The locations of fourteen different pulsars are shown with lines originating from the location of our Sun. The periods as measured on Earth are given for each pulsar, displayed using a binary code. Using the distance from our solar system to the given pulsars and their periods, a clever extraterrestrial reader could determine our location and come say hello.



The Golden Record cover shown with its extraterrestrial instructions. Credit: NASA/JPL

Figure 7: The Golden Record. I'd like a copy for myself someday!

Pulsars are often described as cosmic lighthouses due to the way their rotating beams of radiation appear to mimic the way light from a lighthouse will blip in and out of view. However, the similarities between pulsars and lighthouses don't necessarily end there; pulsars could someday be used as navigational beacons for spacecrafts, just as lighthouses act as beacons for ships at sea. Just as the pulsar map on the Golden Record utilizes the locations and periods of fourteen pulsars to describe the location of our solar system, we can use the locations of pulsars to guide a spacecraft from Earth to a far-off location in the galaxy. I will outline the general idea of how this could work, as described in [3]. The chain of events necessary for a spacecraft to use pulsars for navigation would go as follows:

(1) The spacecraft is launched with an intergalactic destination in mind. Three to four pulsars are chosen beforehand to act as navigational beacons for the craft.
(2) An initial assumption of the spacecraft's three-dimensional positions and velocities is made.
(3) To test the accuracy of this assumption, the spacecraft will be equipped with the necessary equipment to measure TOAs of the selected pulsars. In this case, the spacecraft will measure a pulse profile using x-ray data, so that no corrections need to be made for the dispersion of the pulses.
(4) As in the case of observing pulsars on Earth, barycentric corrections must be made to derive accurate TOAs.
(5) Once a final TOA is derived, the spacecraft's pulse peak can be compared to the expected pulse peak of the pulsar at the assumed position, as derived carefully on Earth. If these two values are shifted from each other, the spacecraft can correct its position accordingly.
(6) This process will continue iteratively until the pulse measured by the spacecraft matches the expected pulse for its location as calculated on Earth.

The method outlined above is especially well suited for MSPs with their highly precise pulsar ephemerides, with the additional benefit of ⅓ of known x-ray pulsars being MSPs [3].

Discussion & Conclusions

The mere concept of incredibly dense stars out in space rivaling the accuracy of atomic clocks is both amusing and awe-inspiring. I do not think even the best science fiction writers could come up with something like this. With there being hundreds of confirmed MSPs found just since the 1960s, and with upcoming radio telescopes such as the Square Kilometer Array to be built in the southern hemisphere, there are many more pulsars left to be uncovered in our galaxy and much more progress to be made in pulsar science. Stellar population models predict a total MSP population of anywhere from 10 thousand to 1 million MSPs in our Local Universe [7]. In particular, I look forward to advancements made in the area of pulsar detection at the Galactic center, from which an inexplicable excess of gamma-rays originates, which could be explained by an as-yet observed population of MSPs.

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