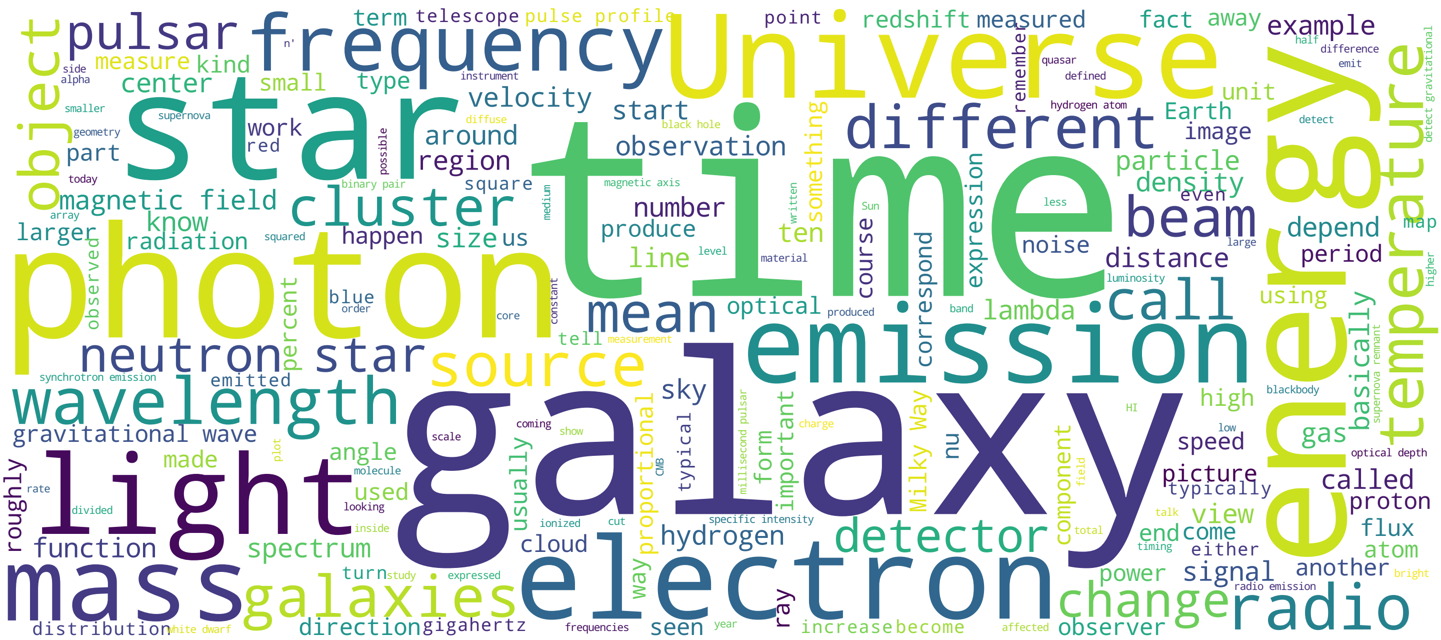
Pulsars

The Universe At Radio Wavelengths

Griffin Foster

One dish of the MeerKAT radio telescope

Image: SKA South Africa



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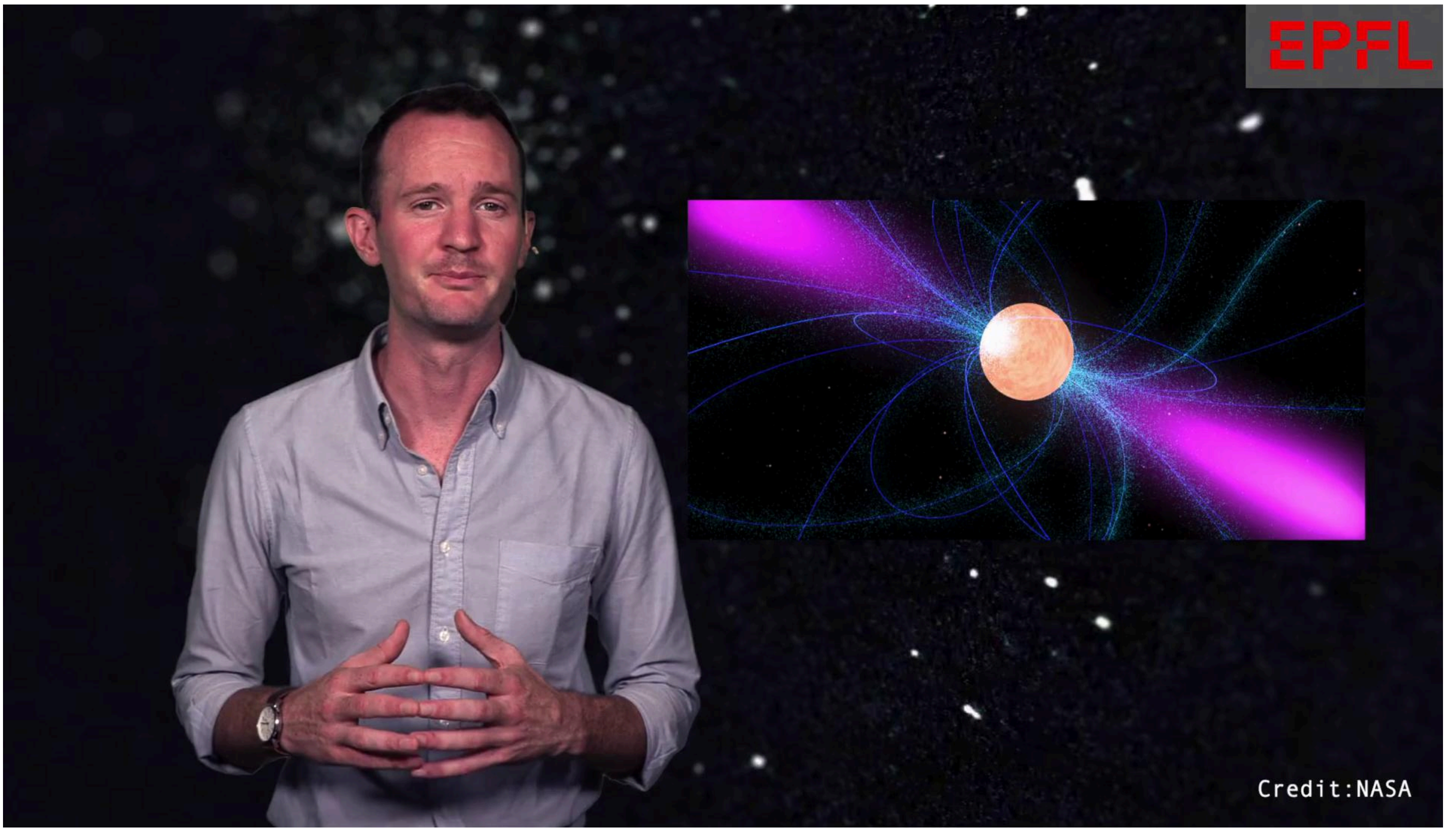


Pulsars are rotating neutron stars which emit a beam of light primarily in radio just like a lighthouse. To the observer they appear to pulse. Hence the name. These are incredible physical objects to study and understand. They are incredibly dense objects with strong magnetic fields. They rotate so precisely, their periods can be measured to nanosecond accuracy. Incredibly the stability of these objects means we can use them as instruments to study other phenomena in the universe like gravitational waves and the interstellar medium.

Notes

Summary

0m 05s

Discovery

Jocelyn Bell discovered the first pulsars in 1967

Image: J. Bell

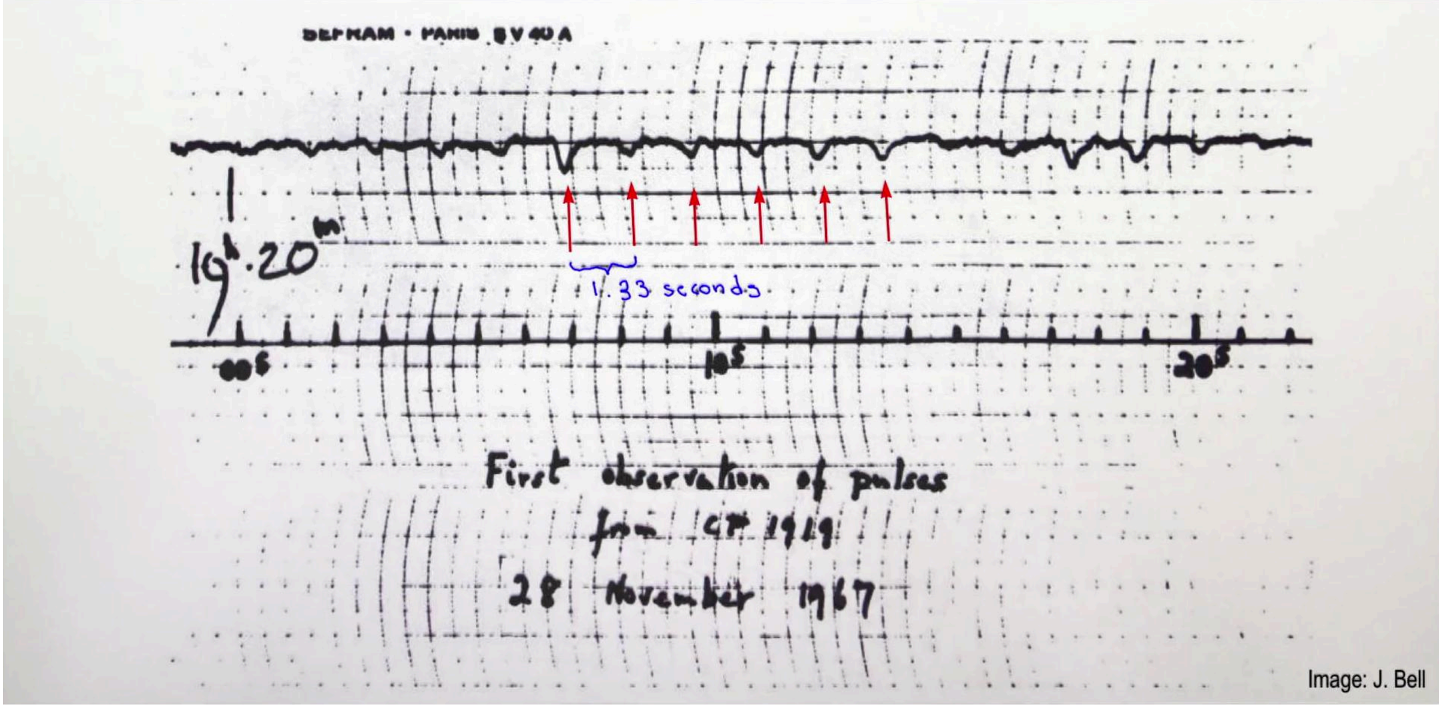
Pulsars were first discovered by Jocelyn Bell when she was a PhD student in 1967 while she was studying scintillation events.

Notes

Summary

0m 39s

Discovery



She found a 1.33 second pulse repeating at the same sidereal time in the sky indicating that the source was astrophysical. It had been previously theorized that rotating neutron stars could exist as a product of a supernova but this was the first time there was observational evidence for that theory. The initial discovery quickly led to the development of new instrumentation and discovery of new pulsars. Today there are approximately 2,600 known pulsars.

Notes

Summary

0m 47s

Discovery

EPFL

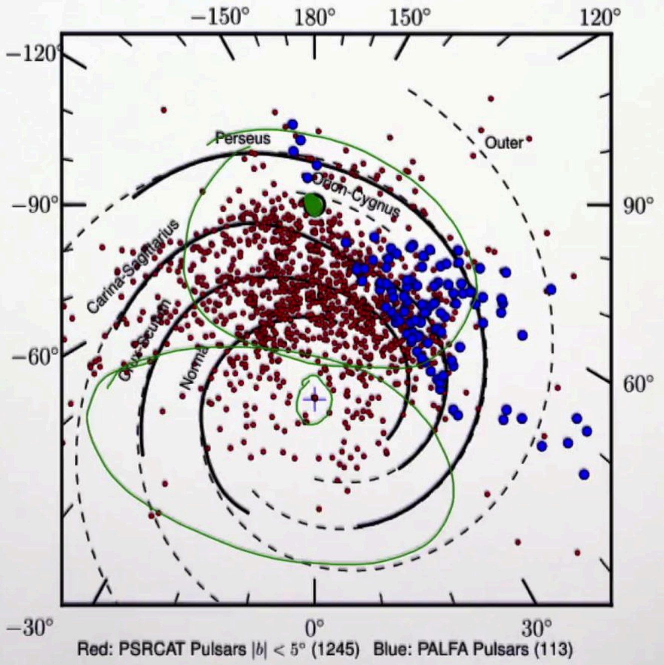


Image: PALFA

This is a top-down view of the Milky Way. These black lines are the arms of the galaxy. All these red and blue points represent the known pulsars. The Earth is located here while the center of the galaxy is here. We expect the galaxy to be filled with pulsars. We have a discovery bias for pulsars closer to Earth that is why it's so much denser here compared to this region here.

Notes

Summary

1m 17s

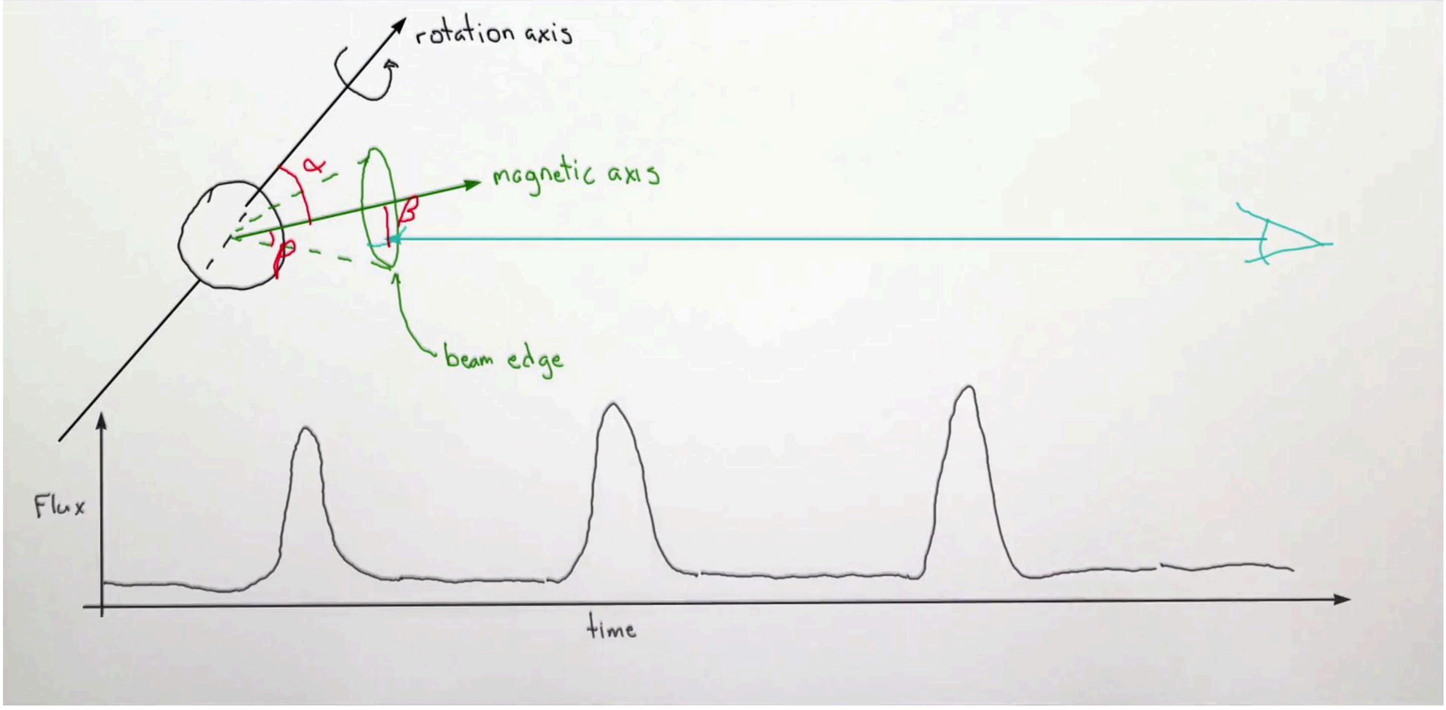
The basic structure of a pulsar is that the neutron star rotates along a rotational axis, there's an offset magnetic axis in which the beam emits light. As the neutron star rotates for a fixed observer's point of view, the neutron star appears to pulse.

Notes

Summary

1m 49s

Geometry

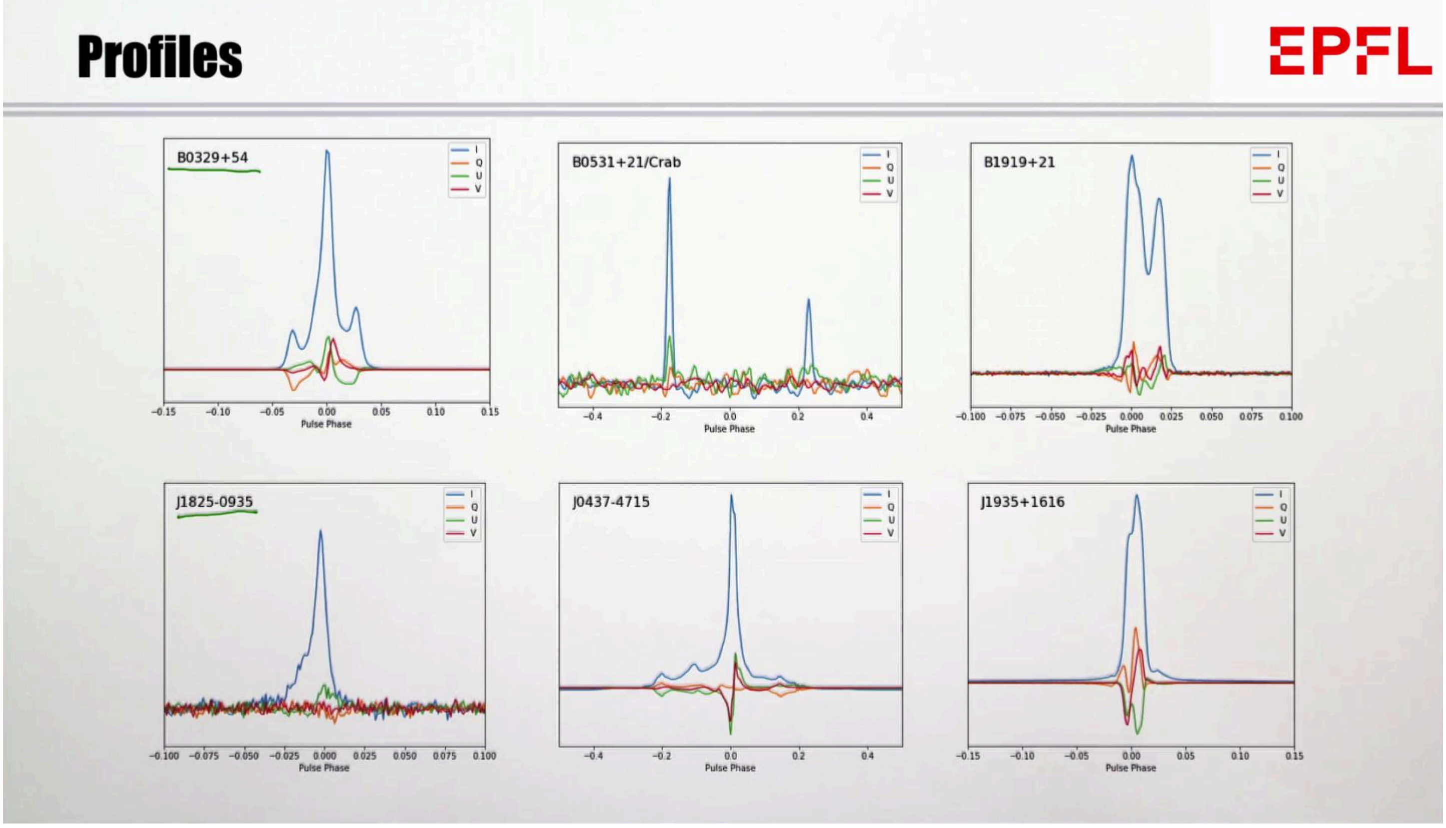


The actual emission mechanism is not well understood though many theories have been developed so we'll draw this model. We have a neutron star which rotates on some axis. We also have a magnetic axis offset from the rotational axis. There's some emission beam. The offset between these axes, the rotation axis and magnetic axis is alpha. Then we also have an observer. This observer sees a cut through the beam. So as the beam rotates, there's some arc which the observer sees. The angle between the magnetic axis and the observer, the line of sight of the observer has an angle which we call beta. We can talk about the opening angle of the beam. We use the angle rho. From the observer's point of view, a pulse profile is observed. This is a cut through the beam. So if we make a plot in time and then this is flux. As the pulsar rotates, the beam will come into view so there'll be no flux until there's an increase in flux because the observer can see the beam, see the emission of the beam and it'll drop off again and then at a predictable time later the beam will return. It'll be flux again so continue.

Notes

Summary

2m 05s



Most pulse profiles are made up of complex components. You can see that in the Stokes eye of B0329 plus 54 where there's three bright Stokes eye components and some complex polarized flux going on here. As a note about notation, note this notation here. There are two types of notation for pulsars. One that starts with the ‘B’ and one starts with the ‘J’. ‘B’ means B1950, ‘J’ is J2000. Typically the labeling scheme for a pulsar is the RA and then declination so B0329 plus 54 is that a right ascension of three hours 29 minutes a declination plus 54. At least in B1950 coordinates these have changed and oftentimes a 'B' pulsar name is additional 'J' pulsar name. Famously there's the Crab pulsar which is quite a young pulsar, has a narrow component, has narrow main component. There's actually a secondary component. Because of the geometry of the pulsar we see both of the beams so we have the primary pulse and then the off-pulse separated by half a pulse phase. B1919 plus 21 was the original pulsar discovered by Jocelyn Bell. We can see that there's two components here and again some polarized complex polarized flux. J0437 has a significant polarization swing as it's cut through the beam.

Notes

Summary

3m 58s

Profiles

6.7: *Successive pulses from the first pulsar discovered, CP 1919, are here superimposed vertically. The pulses occur every 1.337 seconds. They are caused by a rapidly-spinning neutron star.*

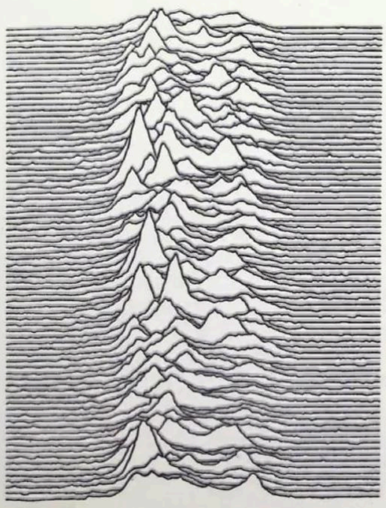
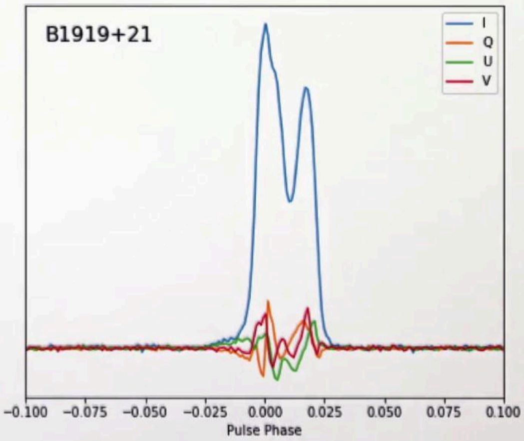


Image: H. Craft

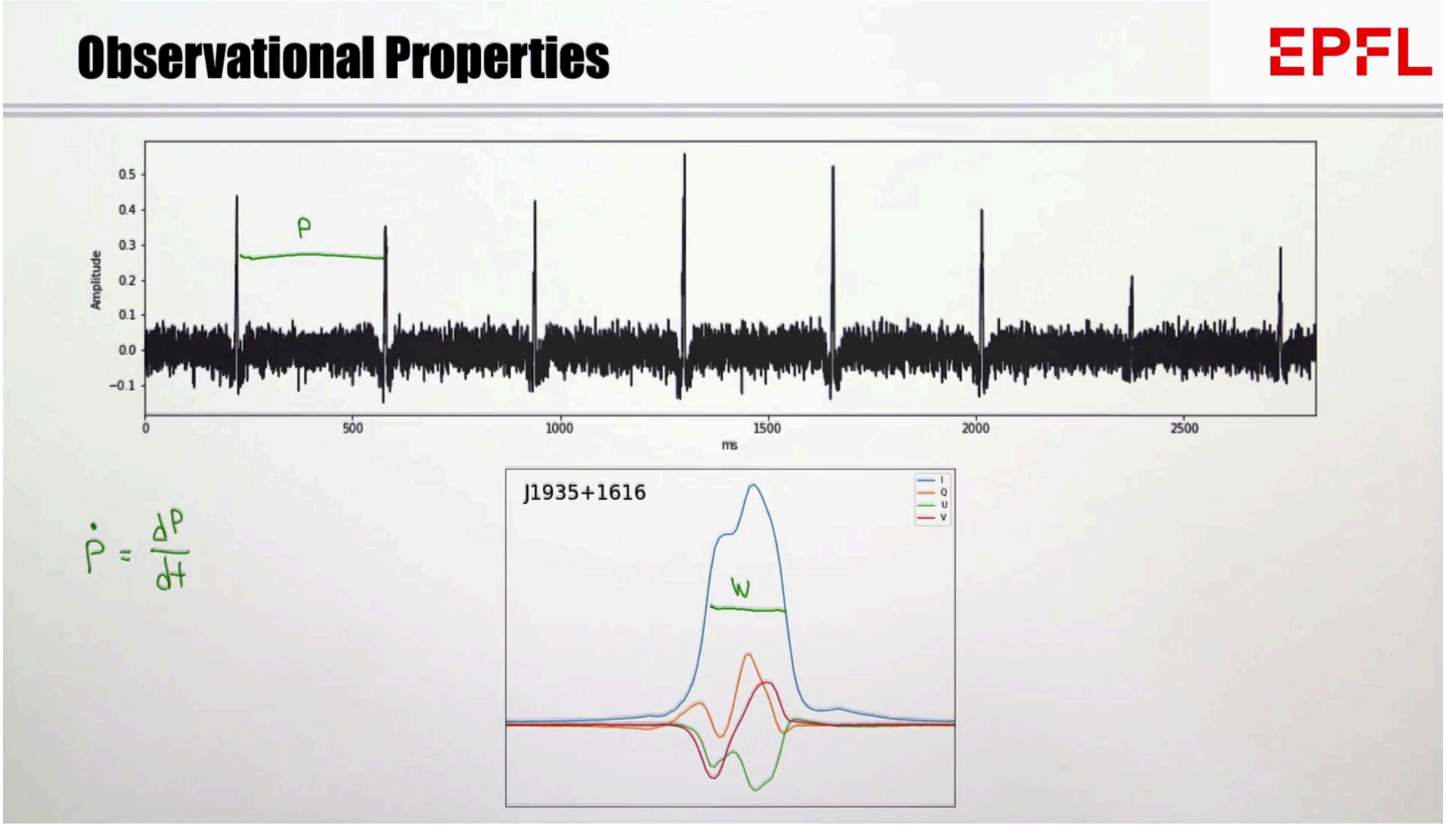


Now if we look at the individual pulses of a pulsar they don't look like the average pulse profile. They vary quite significantly from pulse to pulse but when you take the average, you produce the same average pulse profile which is stable on long time periods.

Notes

Summary

5m 44s



The period of a pulsar can be measured very accurately. In fact, the period derivative known as 'P-dot' can also be measured. The period and 'P-dot' along with the profile width are the main observables. We can derive a lot of quantities about the about an individual pulsar and the pulsar population just from these simple quantities.

Notes

Summary

6m 07s

P/P-dot Diagram

EPFL

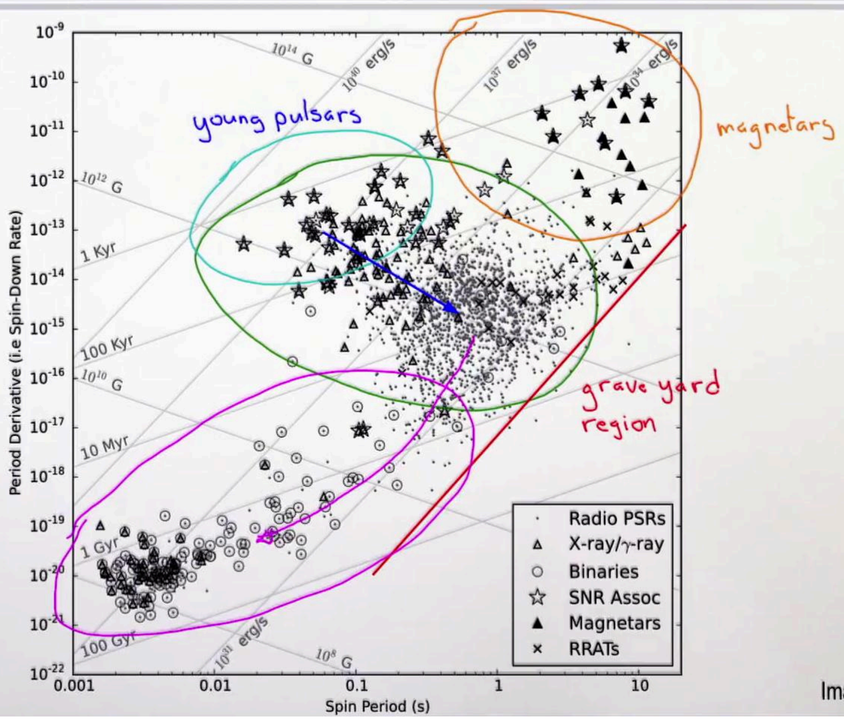


Image: Condon and Ransom

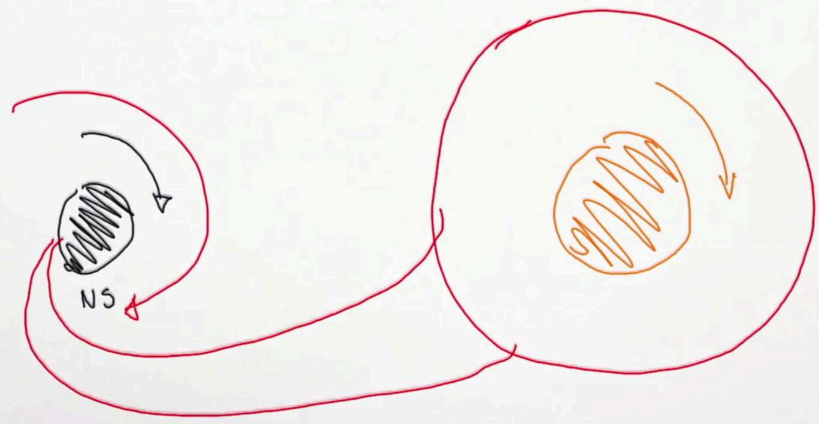
As 'P' and 'P-dot' are our main observables, we can build what's called the P/P-dot diagram. This is like the HR diagram for pulsars. Most pulsars sit in the central region. Young pulsars like the Crab and Vela pulsar start over here. In time they slow down and move into the central region. Old pulsars eventually move to what's called the graveyard zone where they turn off and can no longer be observed. There are a number of slow pulsars with very high magnetic fields in this region. These are called magnetars. These sources are often discovered at X-ray and Gamma-ray. Now there's a region down here. The pulsars down here are known as Millisecond Pulsars or MSPs. What's going on is that normal pulsars are being spun up by accreting mass from a binary pair. They're often called recycled pulsars. These millisecond pulsars, very short periods and are incredibly stable. These turn out to be the very interesting ones we use for timing and when we talk about timing we want to time them to incredible accuracies. The main goal of timing is to use them as an array of observables to try and detect gravitational waves.

Notes

Summary

6m 36s

Millisecond Pulsars (MSPs)

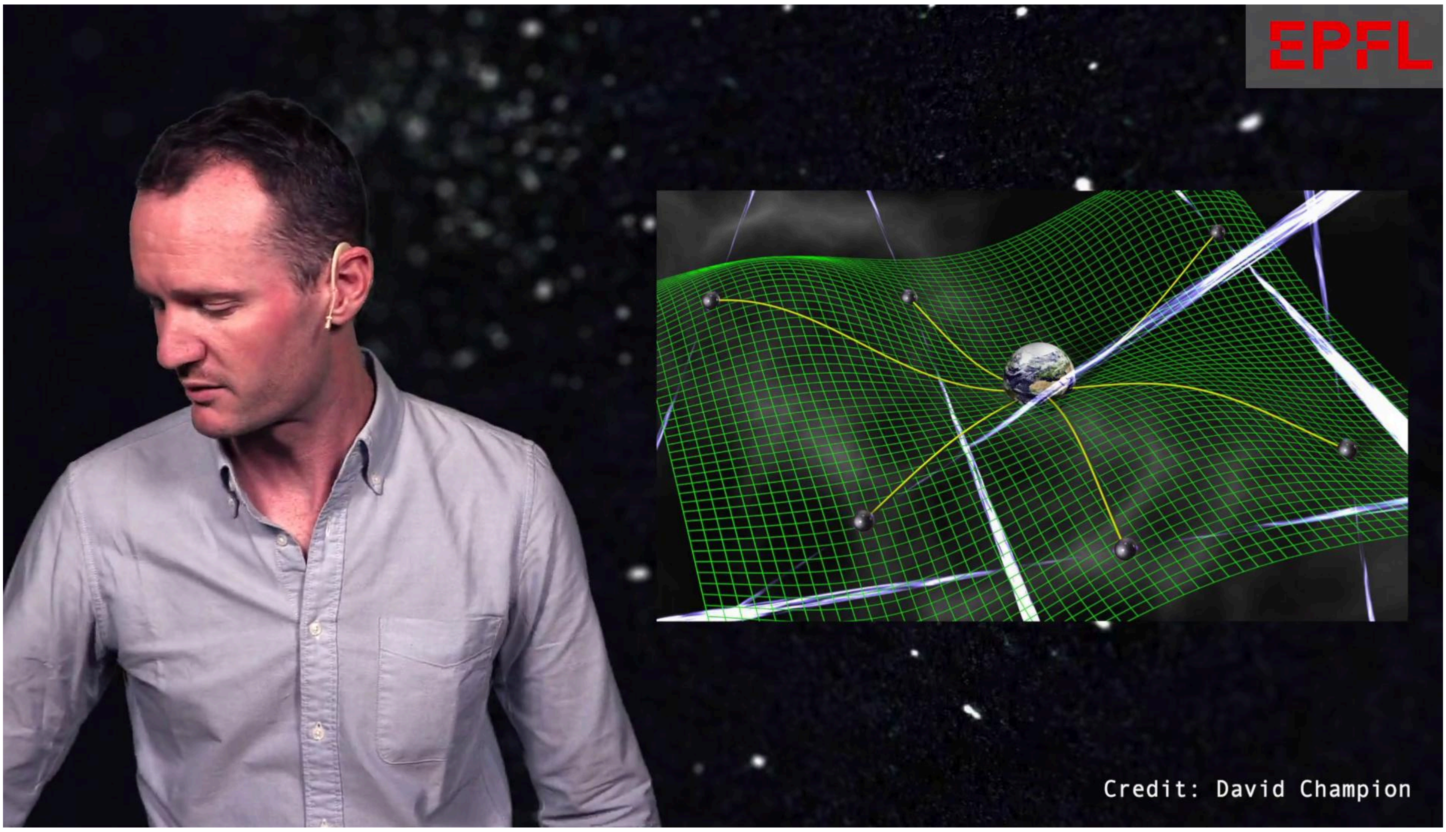


To form a millisecond pulsar we start with a normal pulsar. A little neutron star and it's spinning then we have some companion star which is also spinning. Eventually it begins to turn into a red giant, puffs up and this mass then begins accreting onto the neutron star and as it accretes it brings with it additional angular momentum and thus spins it up even faster unless we've spun up this older pulsar.

Notes

Summary

8m 06s



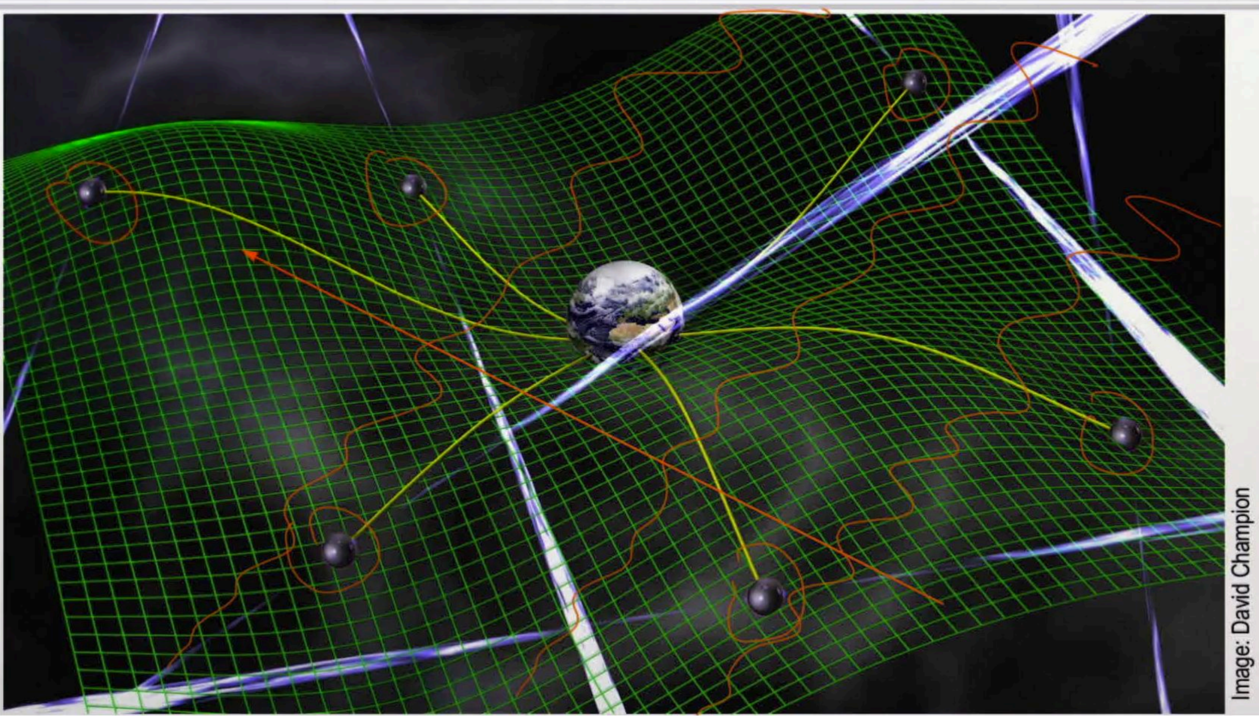
MSPs are extremely fast spinning and stable sources which we use to detect gravitational waves. The pulse arrival time from these MSPs are accurately measured over many years. The changes in the timing solution over many pulsars could indicate a change in space time due to the gravitational waves.

Notes

Summary

8m 43s

Pulsars as Gravitational Wave Detectors



So the idea here is we have a bunch of pulsars in our timing array. There are all throughout the sky and we monitor them regularly, you know, once a day, once every few days. Now if there's a slow moving gravitational wave, it'll come from some direction. With time they'll pass through Earth or pass through our array of pulsars so we have some movement of time. So in time the gravitational wave moves this way and what will happen at the beginning the first period of time this pulsar will be affected and none of the rest will be and as it propagates across, these pulsars will be affected and eventually this pulsar will be affected. And so we should be able to see this change, this very subtle change in the timing solution for the pulsars. But this is an incredibly difficult measurement to make and it's an ongoing process to detect gravitational waves with pulsars.

Notes

Summary

9m 03s

Tests of General Relativity

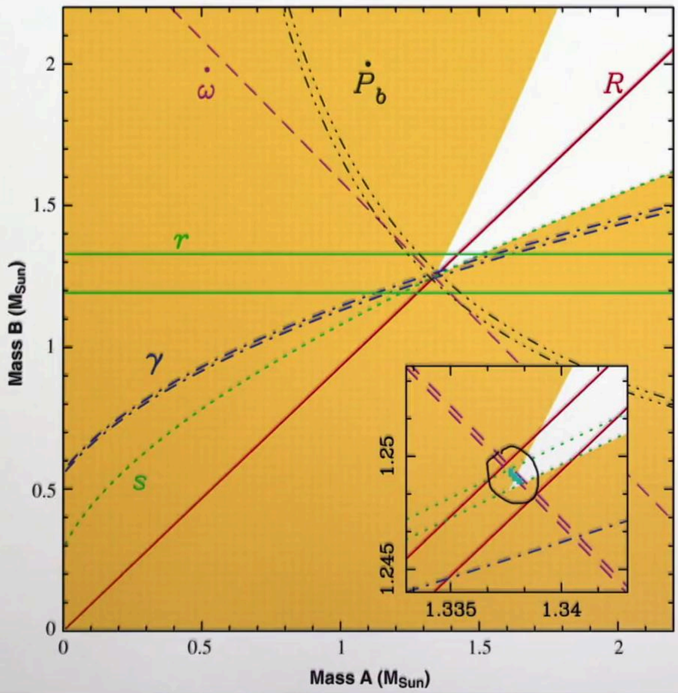


Image: *Tests of General Relativity from Timing the Double Pulsar*
Kramer et al. 2006

Many pulsars are also in a binary pair. Observations of pulsars in binary pairs has led to the strongest tests of general relativity so far. This has led to the limiting of the parameter space to this tiny region proving general relativity holds up in even the most extreme cases.

Notes

Summary

10m 14s

Though supernovae are the end-point of stars, they're often the beginning of new interesting physics in the formation of white dwarfs, black holes and neutron stars. These neutron stars is rotating objects have become some of the most interesting experiments in understanding the extreme environment of the Universe. Their incredible stability has provided us with an additional tool to help us understand some of the bigger questions.

Notes

Summary

10m 34s