DJORGOVSKI: So let us first start with neutron stars and pulsars, which are a subset thereof. This is a picture of the Crab Nebula, which doesn't look like a picture of Crab Nebula you know and love because it's taken in x-rays, and the gas that's emitting in x-rays or rather electrons has a different distribution.

First about the origin of neutral stars, they always come from supernova explosions, and as you probably recall, the core of the collapsing star is more than the Chandrasekhar mass then even though the degeneracy pressure of electrons cannot sustain the gravity of the core. It has to collapse. But as it does that, temperatures, of course, in many billions of degrees. Gamma rays are overabundant. They dissociate any nuclei, helium, or anything else. So essentially, what you have is a lot of protons and electrons.

Now, that is such a density that actually electrons and protons combine producing neutrons and emitting neutrinos, and what you end up with then is a whole lot of neutrons, which are also fermions, following Pauli's exclusion principles. So now neutrons do what electrons did for white dwarfs. They create this new quantum mechanical pressure that sustains against gravity and stabilizes what's now a neutron star.

And those neutrinos will fly away. Well essentially, they're cooling off those collapsing core takeaway energy, actually take most of the energy in the supernova. The stuff that you actually see is maybe 1% of the total energy. Most of it is in neutrinos that are generated in this process.

So then essentially what you have is almost like a gigantic atomic nucleus composed of neutrons, probably some other exotica, and the density is the density of atomic nucleus because it's an incompressible degenerate fluid, and so it doesn't matter whether it's a handful of neucleons or a whole lot of them. And when you divide four solar masses by their density, you find out that the radius of such a structure is about 10 kilometers. So you get nearly 1 and 1/2 masses of solar masses worth of stuff compressed into the size of say less than the inner Los Angeles.

Well, is wonder this is pretty dense and there will be very strong gravity. We think we know what the actual structure of neutron stars is. These are from theoretical models, but they're confronted with observations of pulsars all the time, and interestingly enough most of this neutron fluid, if you will, is superconducting or super fluid.

Usually think of things that are really cold like liquid helium. It can go into super fluid state. But for nuclear matter, it actually can be in millions of degrees and because of that, the interior of neutron stars can be excellent conductor and that's why it can retain the magnetic field so well.

Now, it's possible, I'll says it's probably likely that in the central parts of a neutron star, you have more exotic stuff. People talk about a quarkonium liquid, but that's a whole another story. And the very surface of it may be composed of ordinary matter, well largely, those will be the iron group elements.

Remember those were kind of final product off nucleus synthesis, so whatever was retained within the collapsed core will tend to form this iron crust that encloses this gigantic drop of neutron super fluid. Of course, such things we can never do in a lab, so this is why neutron stars provide insight into extreme states of matter that just cannot do any other way.

Well, how did this all come about? Neutron itself was discovered in laboratory in 1932 and already two years later, to astrophysicists Walter Baade and Fritz Zwicky who were studying supernovae, which around that time they figured out they're not the ordinary novae but a completely different phenomenon. They speculated they come from collapse of a very massive star and the core of the star could become a neutron star. That's a prediction way ahead of its time.

Now, that was pretty much untestable for a while, and then with the birth off radio astronomy, a graduate student by name Jocelyn Bell was doing her thesis in

Cambridge, and she used a radio telescope that looks like this. It's a whole bunch of wires and sticks, but those are actually dipoles, and for some other reason, they're probing solar stellar radio emission millisecond time scales looking for scintillation. And so she discovered there was a periodic signal coming from some directions, some tens of 4 hundreds of milliseconds, and it was a rotating like a sky, at a sidereal rate.

So this was completely unexpected because it was rotating at a sidereal rate, clearly had to be somewhere out there in the universe. There was nothing ever predicted like this, and all kinds of models advanced including those could be signals of extraterrestrial civilizations. But then her adviser Anthony Hewish figured it out that these are actually rotating neutron stars. The key to this was that the pulses themselves are very narrow, millisecond or less and the flight time or 4 milliseconds covers only a couple 100 kilometers, so the region from which those pulses are coming couldn't be more than a few 100 kilometers.

Now, white dwarfs are more like several 1,000 kilometers in radius, and they cannot be compressed any further. That's why they are white dwarfs. And so this could only be something else, and the only other thing that was anywhere in the literature would be neutron stars.

So this is what pulsars really are. In addition to inheriting all this mass and achieving high density, they inherit two other things from the progenitor star, the angular momentum, which as you recall cannot be radiated away, so it has to be retained, and because it's collapsed by a huge factor, then they'll start spinning really, really fast, and also the magnetic field, those trapped in the plasma, will be pull down in that collapse highly concentrated, and the prevailing dipole magnetic field can serve as a particle accelerator.

Now in general, the magnetic poles and rotational poles did not coincide. This was the case in planet Earth. Our magnetic pole is not nor geographic pole, but it's a little off. And so that means that this magnetic dipole will keep rotating, and if it accelerates particles along the magnetic lines of force due to Lorentz force, then the beam of those particles and any synchrotron radiation they emit will be sweeping around the sky in a cone.

And so if we happen to be in the beam, we're going to see pulses. So it's just like a lighthouse although in radio waves. But that also means there are many, many more pulses out there than we see because we only see those that happen to be pointing at us. But that all fits with our estimated rates of supernovae and what have you.

So that's the basic model of how pulsars work, and they were all discovered in radio. The new preferred model of discovery is through gamma rays with the Fermi emission, and there are few that there are also seen as visible light pulsars. Crab Pulsar was the first one on them. They're too little stars in the middle of Crab and they're south, western one, is the pulsar itself. And so a pulsar that's shown here on the right is a sequence of video frames and you can just see it come and go.

And then it does the same thing in x-rays, and this was measurements with chatter satellite. Doesn't have the same angular resolution, but you can see the point source come and go at the exact right pace. So the Crab is probably the best studied pulsar amidst its all wave lengths. It's bright relatively speaking. It's one of the youngest we know, and it served as a milestone for many of the other studies.

So this is what happens when you take the light curve and fold it by a period and the period is indicated there in the upper right corner. You can see from the number of significant digits that these things are measured with an exquisite precision. It's not that their calculator has 10 decimal places so they just wrote them all down, they're actually that precise. And because of that, those are really precise clocks.

So now no period can fold the data again and again and again, and you get beautiful curve like that. You can see there's a big pulse and there is smaller pulse since the beam goes around orbits. So the pulsar timing then became a very useful tool because pulsars have humongous moment of inertia. You guys can compute those Friday, say. Then they'll be very stable in their spin period, and they are as good or better than the atomic clocks we have on planet Earth.

So actually one point, there was power interruption in Arecibo, and they tuned their atomic clock according to the pulsars they were monitoring. Well, all right. So they radiate. That radiation has to come out of somewhere and the only or the main source of energy that's available is the rotational kinetic energy of the neutron star. So that's 1/2 moment of inertia time the angular frequency squared, and that will be inversely proportional to the square root of period.

Now, luminosity is the change of energy per unit time because energy is going down. It's negative, so might as well have to compensate with a minus from derivative, just a simple derivation and luminosity will be directly proportional to the period derivative in time, which you can measure using pulsar timing and shown here is somewhat schematic representation of how people actually observe periods of pulsars slowly growing.

Now occasionally, there is a glitch. It drops down a bit, and since the only way it can do this is by changing its moment of inertia, essentially pulsar rearranges itself a little bit. It's the starquake. So that goes into slightly lower energy states of rotational motion and then continues doing the same thing again.

So these are probably starquakes that are with amplitudes of some millimeters. The biggest mountains of these neutron stars are probably millimeters high, but nevertheless, they can be observed very easily. You may also remember that this enabled people to discover planets around pulsars because you have very precise clock going around, and you can measure Doppler shift to the arrival of pulses just like you do with radial velocity, and this was how the first extra solar planets her found.

But the really cool thing happen when the first binary pulsar was found. Since a lot of stars are in binaries sometimes you're going to get massive star binary both of them will explode and both of them will leave a neutron star. And those new neutron stars will orbit around common center of mass.

So the first one of those was found by Joe Taylor and Russell Hulse. Russell was a summer undergraduate student, so who knows, one of you doing SURF today might get Nobel prize some time in the future. So they found this binary pulsar with a period of, I think, seven-something hours, and they can time it very precisely.

Now, what happens when you have such massive binary at such close separation relativistic effects start coming in play. One of them is that two masses rotating will start creating gravitational waves, and those gravitational waves have to come at the expense of something. They come at the expense of the orbital kinetic energy just like pulsar emission from internal rotation of the pulsar, this is from the rotation of the binary, and when they compare that with predictions of theory of relativity, they saw this.

You never see such fantastic fit in science. This is amazing. Because of this, this was essentially the first detection of gravitational waves. They could have closed LIGO shop right then, but they didn't. These guys got the Nobel prize for this stuff.

And something else interesting can happen with pulsars. So there are these binaries. they can be creating, well, just like with white dwarf binaries, you can have x-ray binary that contains a pulsar and those are seen and called x-ray bursters. But in some cases, or maybe most cases, what happens is this material is being accreted onto the neutron star and it comes with some finite angular momentum, so neutron star soaks up not just the mass, but also the angular momentum and spins up.

And it turns out you can do this in some circumstances to speed them up to about millisecond period, which is phenomenal. So that then became a whole new industry of precise pulsar timing because it's even more precise clock with shorter period.