S GEORGE DJORGOVSKI: So first, let's consider white dwarfs, which are the end state of the evolution of low-mass stars, like Sun, and also some interesting things that they can do if they're paired up with another star. This is the actually image of Sirus-- naked eye star-- and its companion, Sirius B, which was probably the first white dwarf discovered. They form a binary, but sufficiently far apart that they do not affect each other. Obviously, Sirius' disk is apparent just because it's so burned in.

So to refresh your memory, stars-- a mass like Sun, give or take a little bit-- certainly lower mass stars have all often maintained sequence, climb to a red giant branch, undergo helium flash, go to horizontal branch, may do this again to a synthetic giant branch, shed the envelope. The envelope becomes a beautiful planetary nebula. It's the remaining core, which is now not burning anything because it could not ignite further nuclear synthesis because of the low mass. Ionizes this nebula, it dissipates.

So what happens to that former stellar core? It simply cools off. It moves like this on the HR diagram. It's hot, so it's still at high temperature, but it drops dramatically in the luminosity.

And then from then on, once it reaches approximately 1% of its former radius, it just passably cools on for many billions of years. And in principle, it can go down to what we call a black dwarf, although we've never actually seen one. But such things could exist. The intriguing thing is now, so here we have a star-- although it's not burning anything in its core-- which still has a lot of latent heat in it, and it's the size of planet Earth. That right away tells you it's going to be very dense, and there's going to be very strong gravitational field on the surface, and that can have interesting consequences.

As a white dwarf cools, it can actually crystallize. The plasma may be still very hot, but it's under such pressure that in the face base-- themodynamical face base-- it can actually become solid. So really, the star would be a hot, frozen, gigantic crystal of carbon oxygen and whatnot.

Now the important part of physics about white dwarfs, and also neutron stars, is the concept of the generated gas. And this is something that's particular to quantum mechanics. It does not have a counterpart in classical physics.

So as you know, for regular gas, molecules bounce around. Kinetic energy is expressed as their motion. There's pv equals rt, and so you can translate increase in pressure into either temperature-- it can decrease volume in translating fission pressure or temperature.

So here we have ionized plasma. It gets to be sufficiently dense. So now, ions and electrons are in very close proximity.

This is where quantum mechanics comes in play. There is a thing called Pauli's exclusion principle, which states that in a given quantum system, no two particles can have-- oh, sorry-- spin of one half can have identical quantum states, including energy levels. So if you have two electrons somehow pressed close together, it could not be done in any way. They cannot have the same energy.

So you can think of this whole star as a gigantic quantum system with many, many, many energy levels. And they get up to be filled up one by one. And that tells you just how close you can put the particles together.

So that creates a new kind of pressure of degeneracy pressure. This is called degenerate gas, because of this reason. And yes, you can compress it further with enough gravity that opens up more energy levels because the potential well gets deeper. But essentially, you have a new kind of pressure that can counteract gravity, at least in certain conditions. The same kind of reasoning applies to neutron stars, except there, it's the neutrons and not the electrons that cause this pressure.

So summary of the properties of white dwarfs. Unlike normal stars, where gravity is balanced by plain old thermal pressure, here it's balanced by the degeneracy pressure. This is why the core doesn't just go in straight collapse into a black hole or something. And typical sizes of the white dwarfs are about the size of planet Earth.

And give or take solar mass, this is about 1% of the solar radius. That means the density is going to go by a factor of 1 million. And indeed, the densities of white dwarfs are, on average, some millions of grams per cubic centimeter.

One interesting thing is that there is an upper limit to their mass, and that's called a Chandrasekhar mass, as it was first discovered by Subrahmanyan Chandrasekhar, a famous astrophysicist. He got a Nobel prize for this, and everything that he has done. And that's about 1.4 solar masses.

Essentially, for white dwarfs of a higher mass than that, even degeneracy pressure cannot sustain gravity, and they have to collapse into something else. So the highest mass a white dwarf can have, if it's supported by electron degeneracy pressure, it is Chandrasekhar mass. There is an equivalent of this for neutron stars, which are supported by degeneracy pressure of neutrons. And then, you go into black holes.

One interesting thing about objects supported by degenerate pressure is that if you increase their mass, they don't get bigger. They get smaller, because the gravity is pulling things closer in. And so, this is the opposite of normal things where, say, radius involves cube root positive cube root of mass.

Since these are remnants of relatively low mass stars, those are stars that are going to synthesize helium into carbon and oxygen, but did not have enough mass to go beyond that-- into magnesium and silicon and iron and whatnot. And their envelopes, which are stratified or shed away as a planetary nebula, what you have left is the core that's mostly carbon and/or oxygen.

Now in principle, lower mass stars could have only helium cores. Those are like really dwarf stars. They have shed their envelope. They could not ignite helium, and you have a helium white dwarf. And there may be such things.

And then after a white dwarf becomes a white dwarf, it just radiates this heat forever essentially. So those are some of the oldest stars we see around. And actually, they provide us with the means of age dating star clusters or solar neighborhood, because you can see what are the coolest white dwarfs that you can find, and that gives you essentially the limit.

Now, interesting things happen if you put white dwarfs into binary stars. First, we didn't talk much about binaries. The concept is obvious-- two stars will orbit each other or their common center of mass. If they're far apart, nothing particularly exciting will happen.

But once they're separations get to be comparable to their radii, interesting things do begin to happen. And you may remember when we talked about star clusters in our galaxy, there are two gravitational potentials. There is one due to the cluster itself, and there is one due to the galaxy. And if a star crosses the boundary where one of galaxy is overcoming the one from cluster, it will just evaporate away.

So the same thing would apply for any two gravitational sources. In this case, those will be two stars. And there will be a surface around the 2 stars on which the gravitational potentials of the two are equal. And that's called a Roche lobe, or Roche surface, and has this funny shape that there is a point somewhere between the two stars. The position depends on the mass ratio of where the two touch. But then there's this kind of elongated quasi-spheroidal things.

And so, if a star swells, say, by becoming a red giant, and crosses its threshold boundary, that material will no longer be bound to the star. It will have to be bound to the other star. And it turns out that this is exactly what happens, and the mass flow goes through this Lagrange point in between them-- it's like a little funnel-- so the mass can siphon from one star into the other.

If the companion is, say, a regular mass main sequence star, again, nothing much exciting will happen. I mean, they do have some phenomenon associated with them. But if the companion is one of these compact objects, be it a white dwarf or a neutron star or a black hole, interesting things begin to happen.

First of all, the material loses energy and collapses to the smaller radius, deeper into potential well. It loses energy, and that does two things. Well, first of all, that energy has to be radiated away somehow. The second thing is there is still angular momentum, which cannot be radiated away.

And again, you may recall from the discussion why there are such things as proto-planetary disks. This is the reason-- that you cannot easily get rid of the angular momentum. So the material that falls in into the white dwarf or neutron star, what have you, first settles into a disk.

And then from the disk, it can dribble in. That's called the accretion disk, and the accretion need not be smooth. It can come in blobs, and then cause some variability.

But this is essentially how all accreting objects are powered. The same reasoning applies to black holes-- even gigantic black holes that power quasars. Material falls in, kinetic energy that's acquired from-- starting from essentially zero potential energy down to a substantial potential energy at the bottom of potential well-- gets to be radiated away. But you cannot get rid of angular momentum, so you have to transfer it slowly through this gas leak.

This is an important process that we see over and over in astrophysics, not just for binary stars but, again, for active galactic nuclei in a number of different circumstances. In the case of binary stars, where a dense companion is a white dwarf or neutron star or black hole, the temperatures that are reached in these accretion disks go up to millions of degrees. And so, the kinetic energy that's being converted to thermal energy essentially is being radiated away, mostly in x-rays and some of in UV and some in visible light. But the disks tend to be fairly hot.

If the magnetic fields are present, then things get to be a lot more complicated and interesting, but this is the basic idea. And so if you ask, how much energy is there, if it comes from a large enough radius, essentially the change of the potential energy is equal to within a sign, to the potential energy it would have at a spot at which it's accreting-- somewhere in the disk very near the surface of the compact object. And so, the change is roughly equal to the potential energy there itself.

Now that's a simple formula. It's gravitational constant times the mass of the star onto which the thing is accreting times the radius to which it hits, which is two times stellar radius, for example. Now luminosity is time derivative of energy. And so, differentiate this, and you get that luminosity is proportional to the mass accretion rate m dot. It's dm over dt.

So this is how we can figure out how much material is being accreted. Now there is certain inefficiency in this process, so there's usually some efficiency factor that multiplies this formula, which could be as much as 10% in some cases where black holes are a fraction of a percent. But that's essentially what it is-- it's you're converting binding energy into luminosity.

Now when you're doing this for white dwarfs, there is only a tiny fraction of mc squared. The rest mass energy has been converted. If you start doing it with black holes, you can convert substantial fraction of the rest mass energy. And this is why accretional luminosities can vastly exceed those of thermonuclear sources, because as you may recall, burning hydrogen into helium converts 0.7% of the rest mass of those nucleons into energy. But here, it can go for 10%.

So when this happens, we have objects that we call cataclysmic variables. Those are binaries where you have one compact component-- mostly red dwarfs. They're more numerous and a companion-- could be may sequence star or red giant-- and there is variation in accretion. So they can change their luminosity dramatically and very quickly depending on what falls in.

And so, the plot here is of a cataclysmic variable. It's in magnitude so you can think of its log luminosity. So these things can easily brighten tens of time-- by factors of tens, even hundreds.

This is all from the variation of the accretion onto the disk itself. But eventually, some stuff can fall down right on the surface of the compact object, like a white dwarf or a neutron star. When that happens, it is under such pressure because of the high gravity, and it's got pretty high temperature, they can actually ignite thermonuclear reactions on the surface of the compact star, like white dwarf or neutron star.

So a gigantic thermonuclear war right on the surface of the white dwarf, and that creates a sudden release of energy that's even more than what these cataclysmic variables. And that's the phenomenon we call nova. Those have been noted many times.

Occasionally, there is naked eye novae. Amateur astronomers find them. But that's essentially what happens. You have critical amount of material gets accreted on the surface of a white dwarf. Thermonuclear burning occurs, and the thing kind of slowly decays over some weeks.

So now we have been known for a long time, just empirically even before people understood the physics. Super novae are indeed extra bright novae, but their physics can be very different. It is very different, and they're much more luminous.