DJORGOVSKI: All right, so let's see how stars evolve after their main sequence. This is a picture of Eta Carinae, which is a very massive star and has a nice nebula around it. That nebula is composed of the gas that was ejected from the star. It's driving a very strong stellar wind.

And it's got this bipolar shape probably because there is rotation. And so this is a good living example of Eddington limiting action. The star is going to explode sometime soon-- maybe tomorrow, maybe a million years from now-- but soon in astronomical terms, and it's going to be spectacular.

OK, so stars with given mass have different evolutionary tracks. Now these are not isochrones. Isochrones are for the whole collection of stars. So solar luminosity star-- there it is in the middle-- will make this little jigger and then collide the red-giant branch. Other mass stars will have slightly different shape. These evolutionary tracks are computed from theory and they seem to work fairly well.

You notice that some stars, massive stars, make some strange loops up there. And that's because they go through a wider variety of thermonuclear reactions. Eventually cores of stars become white dwarfs.

So let's take a look at this. A central point to remember here is that each of these components of HR diagram, each of these sequences, corresponds to a different stage of thermonuclear burning in stars. So each of them is a little main sequence, but for a different energy source.

So main sequence is when hydrogen burns in core. When you have hydrogen burning in shell and nothing in core, this is what you get, is a red giant. Red giant shrinks. When it reaches a certain amount of density and temperature in middle, helium can ignite in core.

And then star very quickly goes into the horizontal branch, which is the horizontal branch of helium burning, where helium burning in the core, creating carbon. And then there is shell hydrogen burning into helium around that.

And then, depending on its mass, it can do this all over again. It can become a red giant again. It's called asymptotic giant branch. And then you have carbon flash. And depending, again, how massive star is, it can do this several times, which obviously is somewhat destabilizing.

For example, during the helium flash ignition, the star has luminosity that's larger than the entire galaxy, but it doesn't explode. That energy's captured by the envelope still. So this is the key physical reason why these things happen.

OK, so as star becomes red giant, core shrinks-- temperature, luminosity, and so on. Envelope cools because it's expanded, and because it's bigger, star gets more luminous. And this process ends when helium ignites. That's the end of the red-giant branch. The red-giant branch begins at the main sequence and at the helium flash.

And so this is essentially kind of a schematic crosscut of what it might look like. So there is helium burning in the core. Hydrogen burns in the shell. And then there is a thick envelope which, depending on the mass, is conductive or radiative.

And burning helium into carbon is the more important source of energy. Even though in terms of thermonuclear reactions, burning hydrogen and helium is most efficient per nucleon, this hydrogen-burning shell is not very thick. And so most of the energy in helium-burning star is generated by helium burning.

Well, how does helium burn? OK, well. Turns out that stars more than 3 solar masses will then ignite. Less massive stars may or may not actually have helium flash. May just lose their envelope. But for those that do, the helium flash-- which is never seen as flash on the surface, as far as we know-- is an event that signifies the end of it.

Usually its ends with the expansion of explosion of the envelope. It gets all its energy, and that can become a planetary nebula. And then what there is left of the star that burns now. Helium and hydrogen goes on the horizontal branch.

The reaction that's needed here is so-called triple-alpha reaction. The two nuclei of helium will collide and make very quickly beryllium. And then third one will come in, and they can make stable nucleus of carbon. And then they can absorb one more and make nucleus of oxygen. This is where carbon and oxygen comes from. All the carbon and oxygen in the universe comes from this, essentially.

Now this is not an easy reaction to achieve. That's why it needs such a high temperature-- hundreds of millions of Kelvin. But another thing is that carbon nucleus has to have exactly the right kind of energy level so that at these temperatures, it can actually form.

And it turns out it does. This was predicted theoretically. And so there is this resonance level of carbon that enables this reaction to happen. And if it wasn't there, chemical evolution would stop at helium or beryllium.

And as you keep going through this, remember star kinetics and giant branching can become asymptotic giant branch. It's fully convective, and so now it dredges up all these products of nuclear synthesis to the surface. And so if it loses envelope in the end, this is how these newly-minted light elements can get into the interstellar medium, right? So asymptotic giant branch stars are one of the major ways in which enriched material returns into interstellar medium.

So how long does this take? So here is a rough diagram of how solar luminosity will change as a function of time. It's gradually increasing while in main sequence-- not much. Then it increases rapidly as it ascends the red-giant branch.

So it takes more like 200, 300 million years for the whole red giant episode to end, even though it took 12 billion years to begin ascent to the red-giant branch. So all these subsequent phases of stellar evolution are much, much faster than what happens in a main sequence.

This is why most stars are in a main sequence, because that's the most likely time to find them, at the random moment. And all these other stages that we talked about, they happen rapidly after that. Different mass stars will have some different curves of this, but this is the basic idea.

So then how can star end? Again, mass determines everything. Relatively low-mass stars, less than 8 solar masses, will shed their envelope in one of these flashes. And that is being expelled and becomes so-called planetary nebula. Now the core cools and becomes white dwarf. Is star doesn't burn.

More massive stars than about 8 solar masses explode. And this is how the rest of the chemical elements get out. What's left there is a neutron star or black hole, and we'll talk about that in some detail later.

Well, let's talk about low-mass stars now. Because like end of the massive stars, it's very spectacular. That will require more explanation. And essentially you have dramatic brightening. This energy is conveyed into the envelope. Then envelope essentially pushed out.

There is usually some instability involved while the star is rearranging itself. But this stellar envelope that's now been expelled then goes into the vacuum, becomes a planetary nebula. And usually like 20%, 10% of the massive star is expelled in that fashion.

So what you have there now is central core, where all nuclear reactions are going on, which is very, very hot. It generates a great deal of ultraviolet radiation. That radiation can fully ionize the material that's been expelled and thinned out, and this is why you have these nice shining recombination nebulae.

So here is a set of pictures from Hubble Space Telescope of some of the more famous planetary nebulae. By the way, they're called planetary nebulae because people originally thought they may be planets, because they have disk. But of course, they had nothing to do with planets. And there is a striking variety of geometries, which depend on how progenitor star was rotating, how the ejection happened, and so on. Only rarely do you see this simple kind of quasi-spherical structure.

And this process of hotter core, igniting ever heavier thermonuclear reaction keeps going on until you start creating iron group elements. As you recall, this is the bend over of the binding energy per nucleon curve. And to create heavier elements, you don't generate energy. You have to put energy in. And so this is where natural chemical evolution, thermonuclear evolution of a star must end.

So in the end, you have this super giant star. It's been through a whole bunch of these things. And it has iron core, and then burns silicon into iron run around that, and oxygen, neon, carbon, and all the way to hydrogen, if there is any left at that point. And once that star explodes, it releases all this freshly made material, chemical elements, in the interstellar medium.

So here again is rough sequence of how long these interactions take. Now we have to look at the really massive star in order to get all the way to iron. So in the main sequence, it only allow lasts millions of years. But as a red giant, 10 times less, and so on and so forth. By the time it starts making silicon, that phase of stellar evolution lasts one day. And then it's essentially a fraction of a second before you get into the explosion of supernova. So towards the end of thermonuclear evolution of a massive star, things happen much, much faster.

And in the end, this is essentially life cycle of stars. Smaller stars puff up, become red giants, shed the envelope. The core cools off. As a white dwarf, stays that way essentially forever.

Massive star explodes, and the remnant is either neutron star or a black hole. In either case, the envelope is now released back into interstellar medium. It now carries all these chemical elements that have been produced through thermonuclear fusion. And that's the material that makes the next generation of stars.

And this is why sun has 2% of its mass in elements heavier than helium. Original stars, so-called Population III stars, were only made out of primordial hydrogen and helium. Everything after that incorporated some of these products of chemical evolution from the first supernovae onward.