DJORGOVSKI: So our own very star, it turns out to be fairly typical. And this is x-ray image from one of the satellites. I forget which one. I guess if you have x-ray eyes, the sun looks green.

And the reasons to study the sun are, well, kind of obvious. First of all, it's the nearest star. So we'll learn more about stars by studying this one nearby than those very distant ones. And we can test theories about stellar models and composition and convection, whatever.

And, of course, it does have some importance for life on Earth. And in addition to the obvious positive consequences of existence of sun, there also could be negative ones. Solar activity can actually be very detrimental in some cases.

And one new thing about it is that it's the first celestial source observed in neutrinos. It became a gateway to neutrino astronomy. So far there are only two sources in the sky that have been detected neutrinos ambiguously, sun and the supernova 1987A. Nevertheless, people are working on it.

Because the production of neutrinos is from thermonuclear reactions, it's highly sensitive to the structure and temperature in stellar cores. And neutrinos have very low interaction cross-section with everything. So they zip out. Unlike photons which have to diffuse by scattering many, many times, neutrinos just go through whole sun and come to the Earth. So they give us a way of measuring temperatures inside stars. And it turns out they really led us into a generally new piece of physics, which is neutrinos oscillations.

So, roughly speaking, in our sun the fusion happens all the way up to maybe quarter of solar radius. At which point it gets to be too cold for anything to happen. And then diffuses radiatively for most of the volume. But near the surface, when gas becomes opaque, it starts to boil. So sun is like radiative sphere of thermonuclear-fusing incandescent gas surrounded by an envelope of boiling gas.

Now, how can we possibly figure this one out, since we only observe the surface? It turns out we can do the equivalent of what geophysicists do with planet Earth where they study propagation of earthquake waves through the earth. And on the basis of that, they can infer the density structure of the Earth.

Same thing can be done with stars. If you measure oscillations, it turns out all stars vibrate, usually in scales of minutes. Some variable stars pulse at a much longer time scale.

But our sun has very prominent period at about, I think, five minutes, five minutes, something like that. There's a whole bunch of others. And this was also studied very prominently at Caltech while we still had a solar astrophysics group. Ken Libbrecht made his name doing this.

And what's shown here is a model of Doppler cross-section of the sun, with red and blue indicating velocities. And you can see there are all these nodes of waves in the sphere. So this is how we actually can probe stellar interior just by measuring dynamics of what happens on the surface. And from that, we could infer how sun is rotating inside. We can observe surface rotation by looking how sunspots move.

But do you do it in the middle? It turns out that, actually, there's a fairly complicated picture of internal rotation of the sun. And, remember, we neglected completely things like rotation when we were figuring out how stars were made.

So the surface of the sun has a bunch of interesting phenomena associated with it. The photosphere is the part that you actually see. That's why it's called that way. It's surrounded by a very thin, very low density layer of hot gas of tens of thousands of Kelvin. And that is surrounded by a much bigger, fluffy, very low density envelope of gas of millions of Kelvins. That's solar corona.

So if you look at the sun, what you're looking at is a layer of the photosphere of some finite thickness. Just like if you look at a cloud, there is certain fuzziness to it. Right? And as a consequence, the sum will look the brightest in the middle of the disk. And it will be a little dimmer towards the edges because you're looking through a thicker layer of the solar atmosphere, if you will. But, overall, when you integrate the whole spectrum, it is well-approximated black-body of temperature 5,800 Kelvin.

Now, I mentioned that there's a convective envelope. And we can directly see this. The solar surface shows us a whole bunch of these convective cells, which are called granule. And you can actually observe surface of the sun boiling slowly.

Sometimes, depending on magnetic fields, there is a larger region that gets together. And those are the sunspots. Sunspots are simply cooler parts of the solar photosphere. They look dark only in contrast to higher-temperature surroundings. If you were just to carve out a sunspot, it will still be pretty bright. And there is core region that is much darker, called umbra or shadow, and then surrounded by fluffier part called penumbra, same half-shadow.

And these are the spots where magnetic fields from the sun emerge, which is related to way they cool. So by looking at sunspots moving, we can tell about solar rotation, which is 20-odd days, intermediate latitudes. And usually sunspots start at high latitude and go towards the equator, where they move faster.

So sun has a differential rotation. It rotates fastest on the equator, slower towards the poles. This is part of the processes that lead to a solar dynamo that creates the magnetic field.

So if you count spots and plot them as a function of time in solar latitude, then you get what's called the butterfly diagrams for the obvious reasons. And they repeat every 11 years. So sun has an activity cycle that is really 22 years. Because every 11 years polarity of the magnetic field switches from north to south. And then the whole thing happens again. But surface manifestations are the same.

And so sunspots and other forms of solar activity-- I'll show you pictures in a moment-- follow the same cycle. There are probably longer cycles involved, as well. We just haven't been around long enough to really establish.

Other stars have similar things. This is a very subtle effect, comparatively speaking, because, maybe, just 0.1% of the stellar luminosity. In some stars it could be a much higher percentage. And it's uneven, as you can see. It kind of goes up and down. And that's another probe of how structure of the sun could be. And this one is useful especially because it's directly addressing the magnetic fields.

So you take a picture of sun in, say, narrow-band filter, centered on H-alpha line of hydrogen. It looks something like this. There is this kind of wrinkly surface is the boiling surface of the sphere of the sun. There are these dark filaments, which are just slightly cooler gas. And there are bright spots, which usually are associated with sunspot groups. Sometimes there are flares associated with them.

And there are prominences, which can get very big. Now, remember, sun is a hundred times bigger than planet Earth. So this prominence up there is many, many times larger than our entire planet. This is how stuff is accelerated through magnetic fields, pushed out into solar corona. And sometimes there are larger mass ejections.

And some of the plasma can be then pushed out into the interplanetary space. It is a highly ionized, usually accelerated, piece of plasma. So it's a radiation-dense package.

When it reaches planet Earth, it can disturb are own magnetic field. And that can have interesting consequences. In addition to having something like aurora, some of these coronal mass eruptions, ejections, can also disturb electric power grid. And there were at least a couple of cases in the past where one of these has basically blacked out a good part of the North America. I'm sure there were even bigger ones in the past.

Now, you see how all this shiny gas goes into these filamentary loopy circles. Essentially, it's falling up magnetic lines of force. Ionized gas is trapped by the magnetic field and vice versa. And so this is just like magnetic lines of force. You have a whole bunch of little magnets coming out of the interior of the sun popping up at the surface. And depending on how these lines collide, you can get flares.

So sun's been actually studied by a whole bunch of satellites, UV, x-ray, and visible.

There are I don't know how many of them in the orbit now. And they monitor solar activity in a range of frequencies. And we now much more about sun than we ever had before. So we're getting pretty good insight into it.

Incidentally, those coronal mass ejections, they may represent the biggest danger for interplanetary travel. If one of those happens when you're out, say, in spaceship between Earth and Mars, that can have really bad consequences for the astronauts. And there is no way of protecting against.

So one last piece of this is the neutrinos. Again, this is a unique way of probing physics in places where we can never look in any other way. And for many years, detections of solar neutrinos were happening. But they were about three times lower than theory predicted. And that was called a solar neutrino problem.

Now we know why this happens. But there are many different theories, including the sun has turned off its nuclear reactions for some reason. But, remember, it takes a quarter million years for radiation to come out. So the sun could have stopped producing energy, but we're still seeing it shining for awhile. Thankfully, that's not the case. And we think we know what's happening.

So where do these neutrinos come from? Well, they're there because of the conservation of leptonic charge in thermonuclear reactions. And in addition to the usual proton-proton cycle, then there are a few other reactions which can generate neutrinos. Some of those are continuous energy spectra. Some of those are like spectroscopic lines but in neutrinos.

And there are different ways of detecting them depending on what energy they are. But here is an interesting tidbit. So, remember, we get 28 megaelectron volts per one helium production. Right?

We know what solar luminosity is. Divide solar luminosity, or solar flux right here, by 28 megaelectron volts. And you find out that flux of solar neutrinos right now is something like 60 billion per square centimeter per second.

Now estimate your surface area that intercepts the solar neutrinos. So there are many hundreds, let's say trillions, of neutrinos going through every second. Fortunately none of them stay. Because a neutrino can go through light-year of lead without any problems. The probability of any neutrino interacting with anything is very low. So you need a lot of neutrinos in order to have detectable number of interactions.

So this was first done in 1960s. And the first detector was this tank of cleaning fluid, which is tetrochloroethylene, which is, well, used for dry cleaning. But it was also the safest and easiest way to put a lot of chlorine atoms together in a liquid form. And it was done in the Homestake Mine in order to shield from all other particles.

And it was looking for this particular nuclear reaction, that neutrino absorb with chlorine nucleus turns it into argon. And argon is a noble gas. It does not interact with anything. And so if you integrate for a while, you generate some number of atoms of argon, usually a few tens. And then you pump this whole volume through apparatus that will extract argon from it. And you find out how much you got.

So they've done. This is an amazing experiment. And they found that the number of detected neutrinos was about 1/3 of what was expected. This was then confirmed with a whole bunch of other experiments.

Now, more modern ways use Cherenkov radiation. This is the inside of Super Kamiokande, which is this gigantic cavity filled with super-pure water and a lot of photomultiplier tubes. That's each one of those, these guys in rubber after replacing. And they're looking for flashes of Cherenkov radiation when a high-energy neutrino interacts with one of the electrons in the water.

So the solution on the solar neutrino problem was that neutrinos undergo a cycle of quantum oscillations. This is a phenomenon associated with electroweak interaction. That certain types of families of particles, in this case there are three kinds of neutrinos-- electron, muon, and tau-- turn into each other in an oscillatory process.

This was predicted by our understanding of electroweak interaction. And I don't know if it was actually ever tested in accelerators in some direct way. But it was an immediate and obvious way to solve the solar neutrino problem. Because if they oscillate, then at any given time, you're only going to catch exactly 1/3 of the originally-produced number. And so that basically solves the problem.

The interesting thing about this is that in order for neutrinos to do this, they have to have a rest mass. And it's very small. We actually don't know how much. But it's not zero. And so this was an important fundamental physics discovery in itself.