DJORGOVSKI: The first subject that we'll bring up is some basics about photons and electromagnetic radiation and Kirchoff's laws, which were the first insight as to how one might use spectroscopy. This picture here is of Joseph Fraunhofer-- that's the young guy-- showing his spectrograph to senior scientists back in 19th century. He was the first person to take astronomical spectrum of the sun. And he saw lines which were then called the Fraunhofer lines. And you will see them shortly.

So as you probably know, energies of photons are proportional to their frequency. Frequency and wavelength multiplied together give the speed of light. And the constant of proportionality is Planck's constant. Values given here.

Now, we often use energies expressed in electron volt units, which is the energy electron gets if it's accelerated with the potential 1 volt. And it's this many ergs or joules. Typically, spectroscopic transitions or energies of photons of visible light. There are a couple electron volts, a few electron volts. In the x-rays, we're talking about kilo electron volts and up. And gamma rays will be mega electron volts.

So there are two important things to note here. First, even in classical physics, if you have charged particle like electron moving, if it's somehow accelerated or decelerated, that is going to cause it to radiate in electromagnetic waves. And then when you look at quantum systems such as atoms, they have discrete states of energy that comes in well-defined quantities, depending on what their internal structure is.

So electromagnetic radiation, then, comes, really, in two flavors-- as continuum spectrum, that there are photons of all different frequencies; and as discrete ones, which are spectroscopic lines. It could be absorption or emission, depending on what happens.

There are several different ways in which continuum spectrum can be produced. The most common one is thermal spectrum. Any body with temperature greater than absolute 0-- that will be all of them-- emits radiation over all frequencies. And we'll discuss the spectrum shortly.

But there are also other mechanisms, like free-free transitions or breaking radiation and Cherenkov an synchrotron. We'll come up to this. Now, the important thing is that different processes in nature generate electromagnetic signals at different wavelengths. And because of that, we can use what we observe as a diagnostics of what's going on.

So if you look at global electromagnetic spectrum like this-- and this is in logarithmic scale, obviously-- and so you can look where do different phenomena play a role. And typically, atomic levels, energy levels that correspond to most transitions are around visible light, give or take-- UV, near infrared. So isn't that very fortunate? Because we happen to live around the star that peaks right there.

Now, as you go toward higher energies, then you start to see energy transitions of innermost shells of heavy elements, and then deeper yet, into nuclear energy transitions-- annihilation, things like that. On the other side, as you go to lower energies or longer wavelengths-- this is spectra of molecules and such-- they're eventually just waves generated through different plasma processes.

So you can see there is a broad range of different physics that plays a role here. And so by observing it a different wavelength, then you can learn something about the source. The way we measure things is with spectra graphs. And everybody's seen pictures of them with the prism making the rainbow spectra.

There are almost no prism spectrographs that are being used anymore, because the much better way to do it is with diffraction gratings. And skipping over a lot of details, the way this is done is that diffraction grating is a piece of glass or metal on there are little parallel grooves, each of which acts as a little mirror. And then bouncing light off of a diffraction grating at different angles, you see light of different frequencies will be phased by different amount.

So a given wavelength from diffraction of different grooves will have constructive interference and some spot in a focal plane. But a different wavelength will be a little off, because the wavelength's a little shorter. Now, this can be worked out great detail. But intuitively, this is what's going on.

So typically, what we have some sort of entrance aperture, otherwise everything would be smooshed together. And usually, a slit is used so you get spatial resolution along one axis. And then there is an interplay. The wider the slit, more light you get, but lower spectral resolution you have.

And that's colimited. That is there is a set of lenses that makes this converging beam from telescope into parallel beam. It's the parallel beam of light that has to get bounced off the grating. And that has to be focused onto a camera-- detector such as CCD. So essentially, that's how spectrographs work today. And when we go to Palomar, you will see one of them.

So what are Kirchoff's laws? These come from 19th century, before there was any atomic physics, before people understood any about this stuff. They played with Bunsen burners, putting different materials in, and looking what the spectrum looks like, dispersed to prism. So if you had a hot flame or a hot body that radiates thermally, then there will be a continuum. There will be light of all different wavelengths.

But now, if you pass this light through a cloud of some gas or vapor and you look at light that passed through, you'll see that there are some wavelengths that are missing-- that there is light that's been absorbed in particular wavelengths, which are characteristic for a given element or compound. And the other hand, if you don't look at the continuum light, but look at the hot cloud of gas from side, you'll see it shining at those exact same wavelengths.

And so the Kirchoff's laws-- and the name is ker-koff, not ker-choff-- are these. So first, any hot and opaque body emits in a continuum. And then a hot gas that's transparent will shine in particular set of wavelengths, the emission lines, whereas a cooler gas or a gas that's been transpiring, if you look through it through some continuum source, shows absorption spectrum. And those wavelengths are characteristic of a given element or compound or ion.

Now, we, of course, completely understand where does this come from, but back in 19th century, nobody knew. And until Bohr figured out how atom of hydrogen works, spectroscopic lines were a complete mystery. There was a lot of empirical data and people just didn't know where they came from.

So typically, what we do is we take spectrum of something-- it could be a star or a galaxy or what have you that's dispersed-- and then we compare that with a spectra of laboratory source, like arc lamps and such, to calibrate it. And then we can compare depth of different lines, which then tells us about physical conditions in the source itself.

So things that you can get from a spectrum are temperature and composition of the source-- say, solar photosphere. But also, you can measure velocities, because you can compare wavelengths of the observed lines with those that would be addressed. And simple Doppler shift formula would apply.

So spectroscopy, then, tells us about the physics of what's going on. It also tells us how fast things are moving in radial direction. And that has great applications in cosmology, because that's proportional to the distance.

So here are some of the typical spectra they can see with emission or absorption lines superposed in continuum, depending on what lamp they used. And every element, again, has its own characteristic signature. But the relative strengths of these lines will depend on the temperature and other physical conditions.

So here is the solar spectrum. Now, this one is really folded many times. You can think with this zigzag spectrum. The way this was done is with a so-called echelle spectrograph, which is a way to do a lot of high resolution spectroscopy with a single detector. And the black blotches are Fraunhofer's lines. He couldn't resolve the very faint ones with his apparatus, but he's certainly seen the big ones and have them names-- A, B, C, D, and so on. And sometimes, we actually use some of his names, like H and K lines with calcium are Fraunhofer's. A and B bands are not from sun. They're actually from Earth's atmosphere. C is now known as H alpha and so on.

We'll speak about how they came to be in a moment. But there is one other important question. Is something going to be transparent or opaque? And here, we talk about optical depth. Optically thick is a medium that is opaque-- that photons are just scattering so much that you cannot see through it. So fog would be a really good example of that. Optically thin is medium, through which photons can fly with just a minimum amount of scattering of interaction, like the air into this room, for example.

Generally speaking, optical depth tends to be proportional to the density. So denser plasma will tend to be more opaque. And that governs a lot of physics of what happens inside of stars. So typically, a star is a ball of hot gas, or plasma. And in its interior, it's optically thick. So when you're looking at a star like the sun, you're seeing a continuum source that has certain temperature surface, like 6,000 degrees Kelvin. And then the outer most layers are radiating away. So they're cooler. And so that cooler gas, according to Fraunhofer's laws, will be imposing an absorption spectrum.

So the spectrum of the sun is the spectrum of the outermost thin layer of plasma on the sun. And the same is the case for just about every other astronomical source.