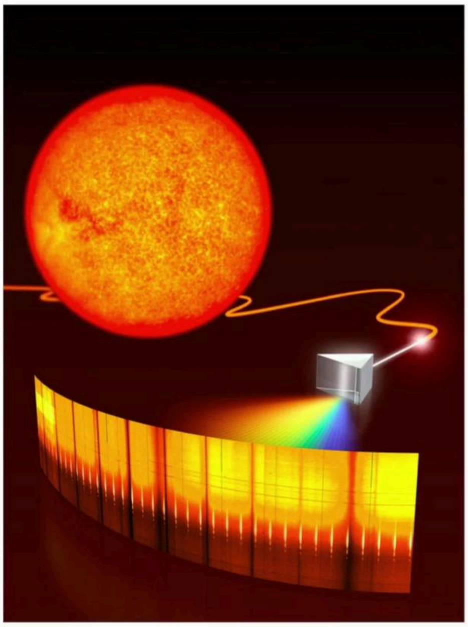
Spectral Lines (part 1)

Kim McAlpine



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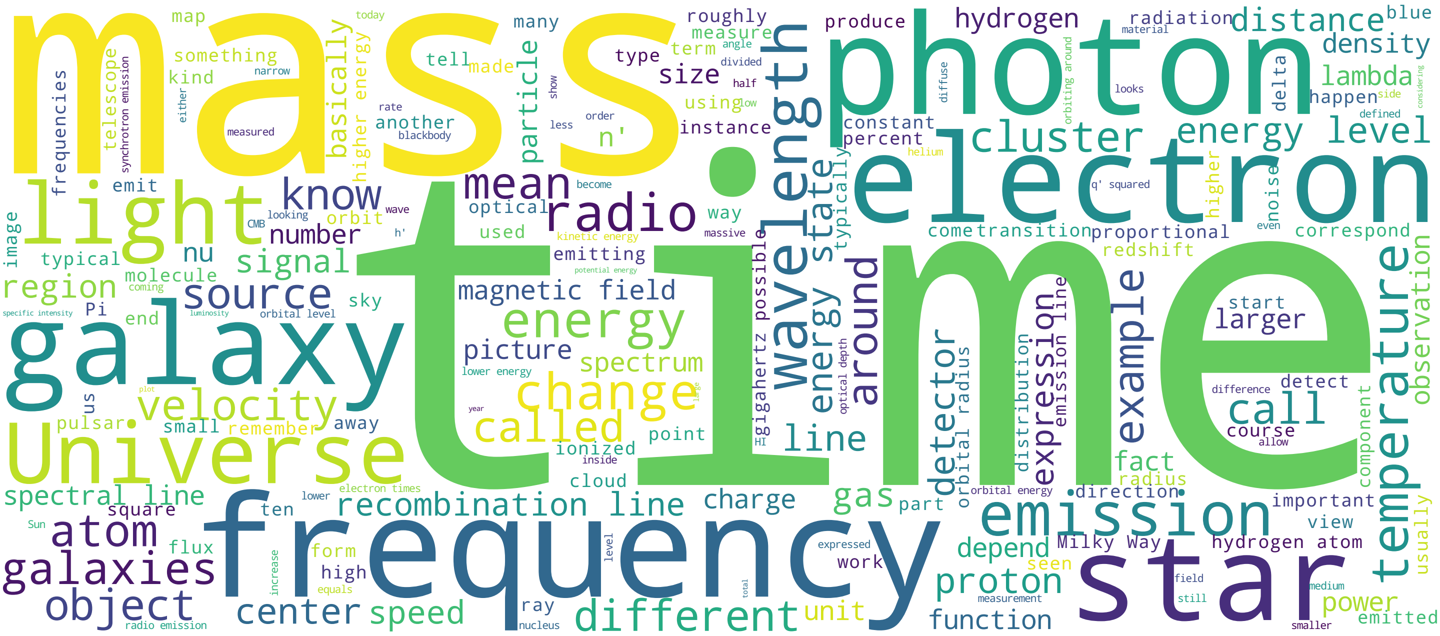

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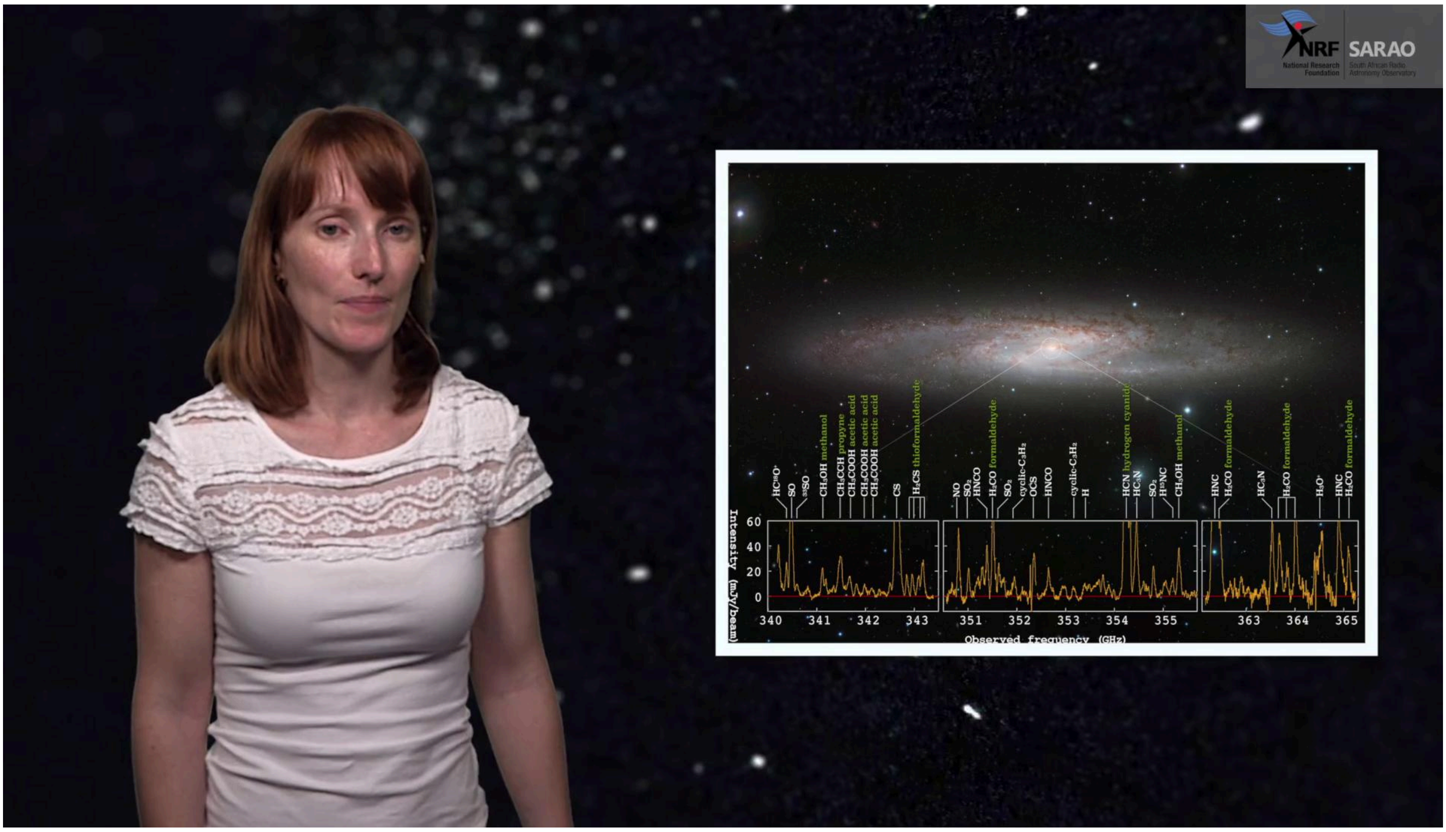
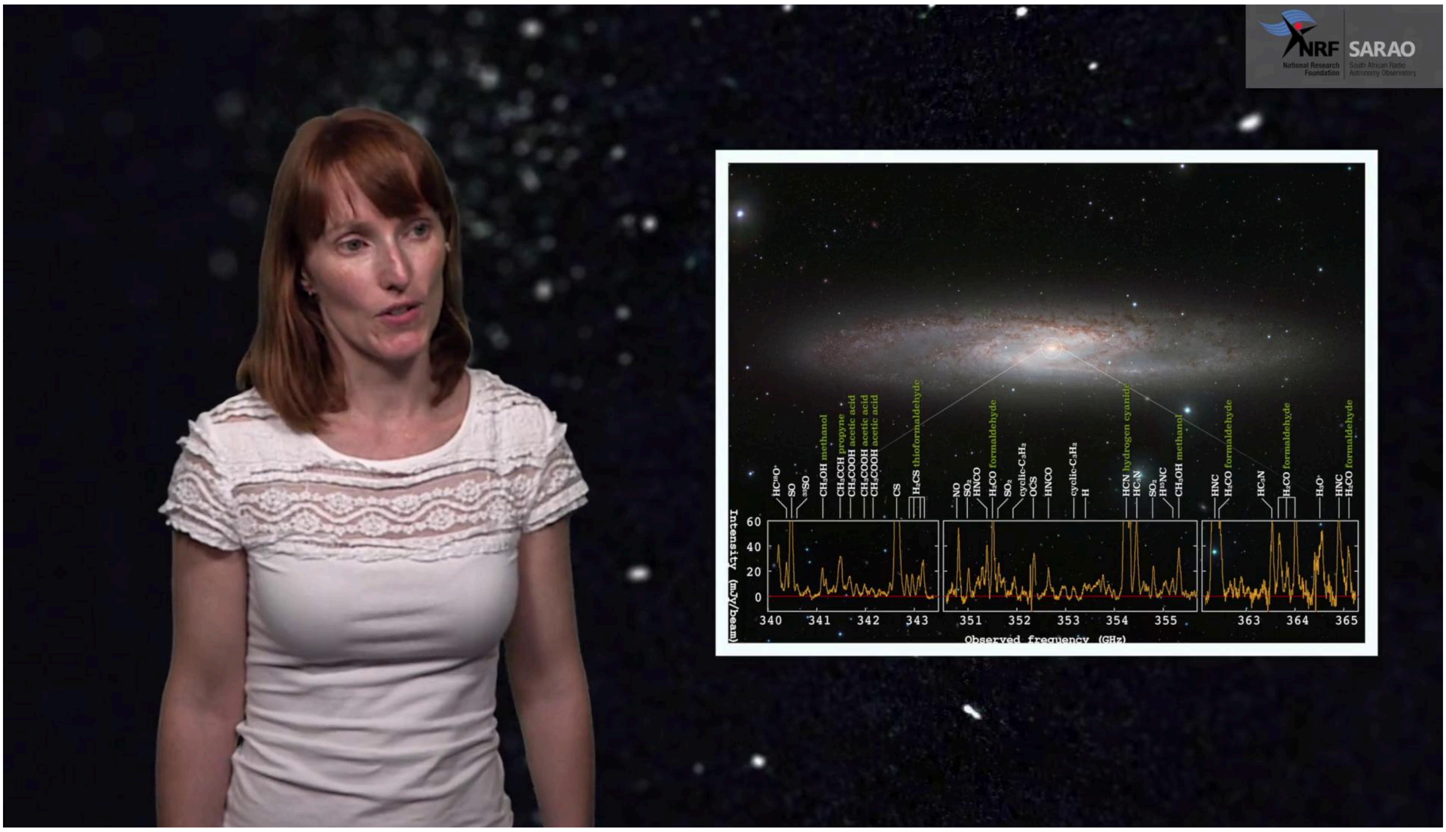


This next lecture in our series on the production of radio waves will focus on spectral lines. As we've already discussed, emission can be emitted or absorbed continuously at all wavelengths or be confined to a narrow range of wavelengths. The narrowness arises because spectral emission is generated by change in the energy state of an atom or a molecule. And energies in these quantum systems can only take on specific discrete values. As these allowed energies are highly specific to a particular atom, the frequencies of the observed spectral lines can be used to diagnose the chemical composition of the material emitting the lines. You could say that the spectrum of an element is a fingerprint which identifies it uniquely. For example, in the image behind me, the ALMA telescope has used spectral lines to identify a variety of complex molecules in the center of the starburst galaxy NGC 253. The relative intensities of lines at different wavelengths can also tell you about the relative number of atoms in specific energy states giving insights into the physical conditions of the gas producing the lines.

Notes

Summary

0m 05s

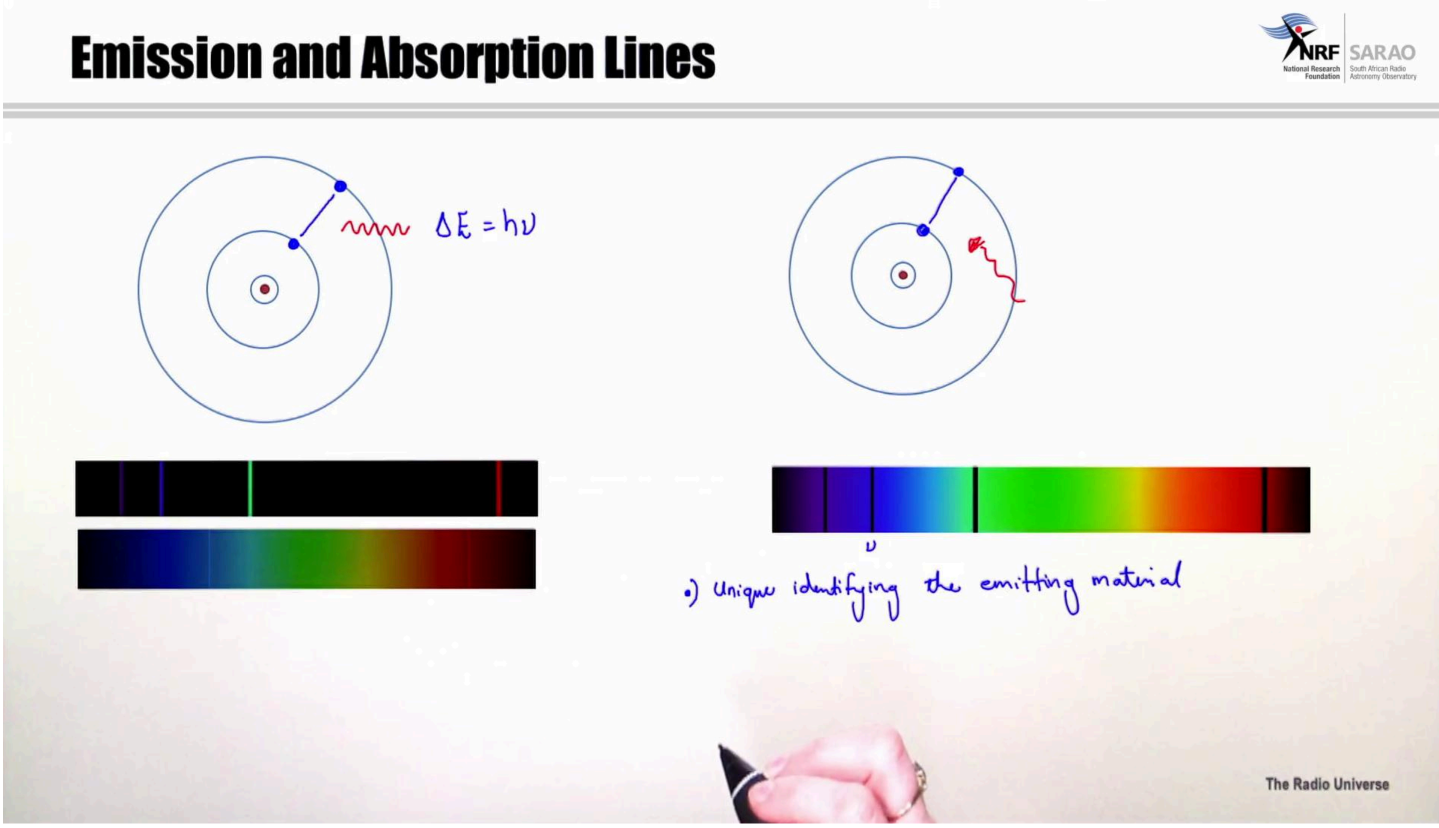


As spectral lines are narrow and located at specific wavelengths, it's also possible to detect Doppler shifts from the rest wavelength and use this as a probe of the radial velocities of a system. Something which we're not able to do using continuum emission alone. Spectral lines, therefore, have a really important role to play in studying the dynamics of galaxies and the dynamics of the universe.

Notes

Summary

1m 20s

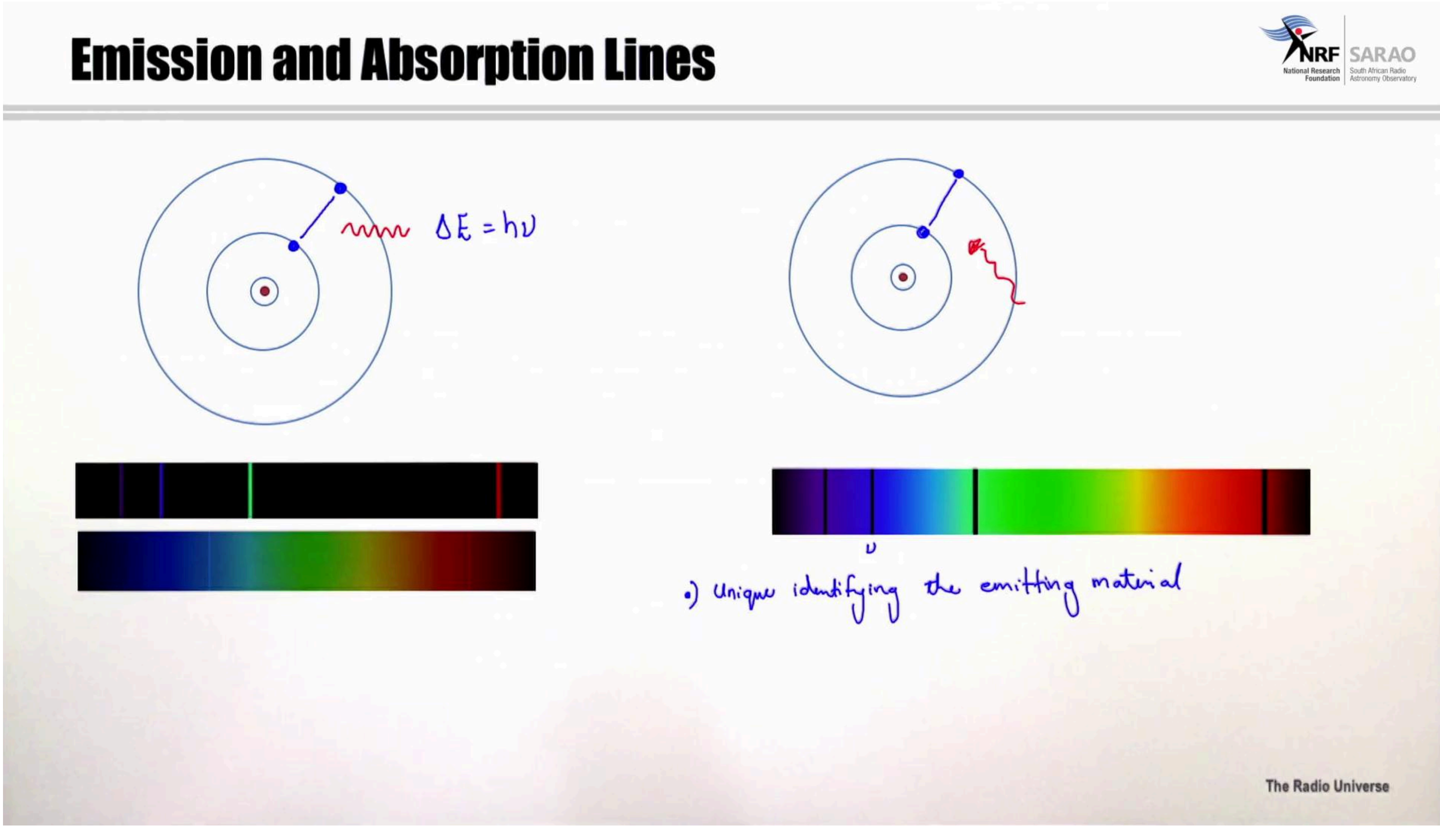


As we've already discussed in one of our previous videos, we have if you have a narrow feature in frequency or wavelength space then that feature is called a spectral line. The spectral line can be an emission so it can emit light or it can be an absorption so it can absorb light. As we've already discussed, the emission line happens when an atom drops from a higher energy state to a lower energy state and that excess energy is then emitted in the form of a photon which has a frequency given by change in energy in the system equals the Planck constant times the frequency of that photon. Similarly, in the inverse process you can have it that a photon is absorbed by the system and that allows the the atom to go from a lower energy state to a higher energy state. Because these energy levels are unique to the atom that you're studying, the frequencies of these lines act as a unique fingerprint that allow you to identify the molecule or atom that is emitting those lines. So this gives us a unique way of identifying what is emitting. The emission tends to happen when your molecules are radiatively or collisionally excited.

Notes

Summary

1m 45s

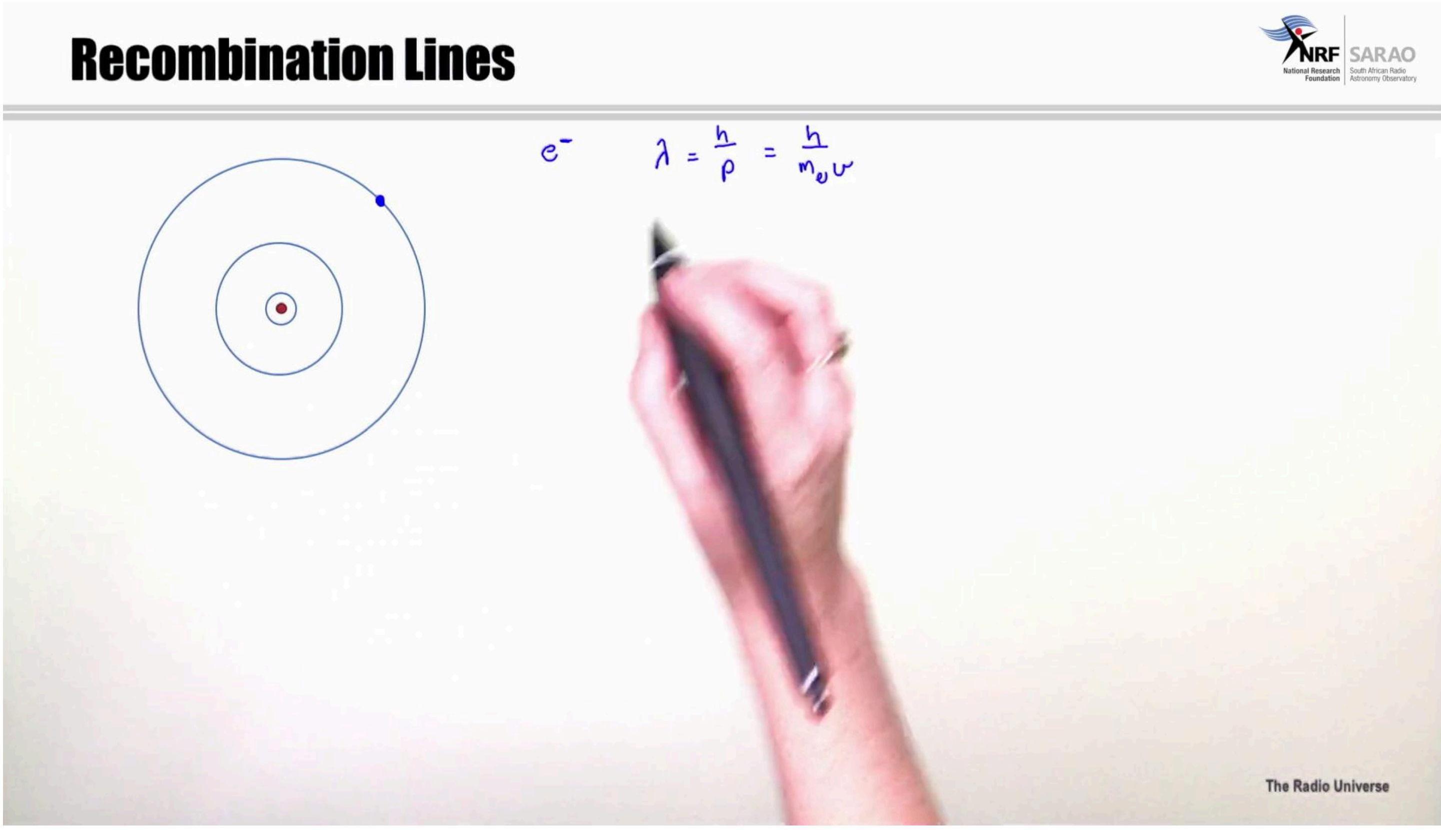


So if they're collisionally excited, it's because these atoms are bumping to get against each other and transferring energy that way or they can be radiatively excited if they're in some incoming radiation field which is then exciting the atoms to a higher energy level.

Notes

Summary

3m 15s

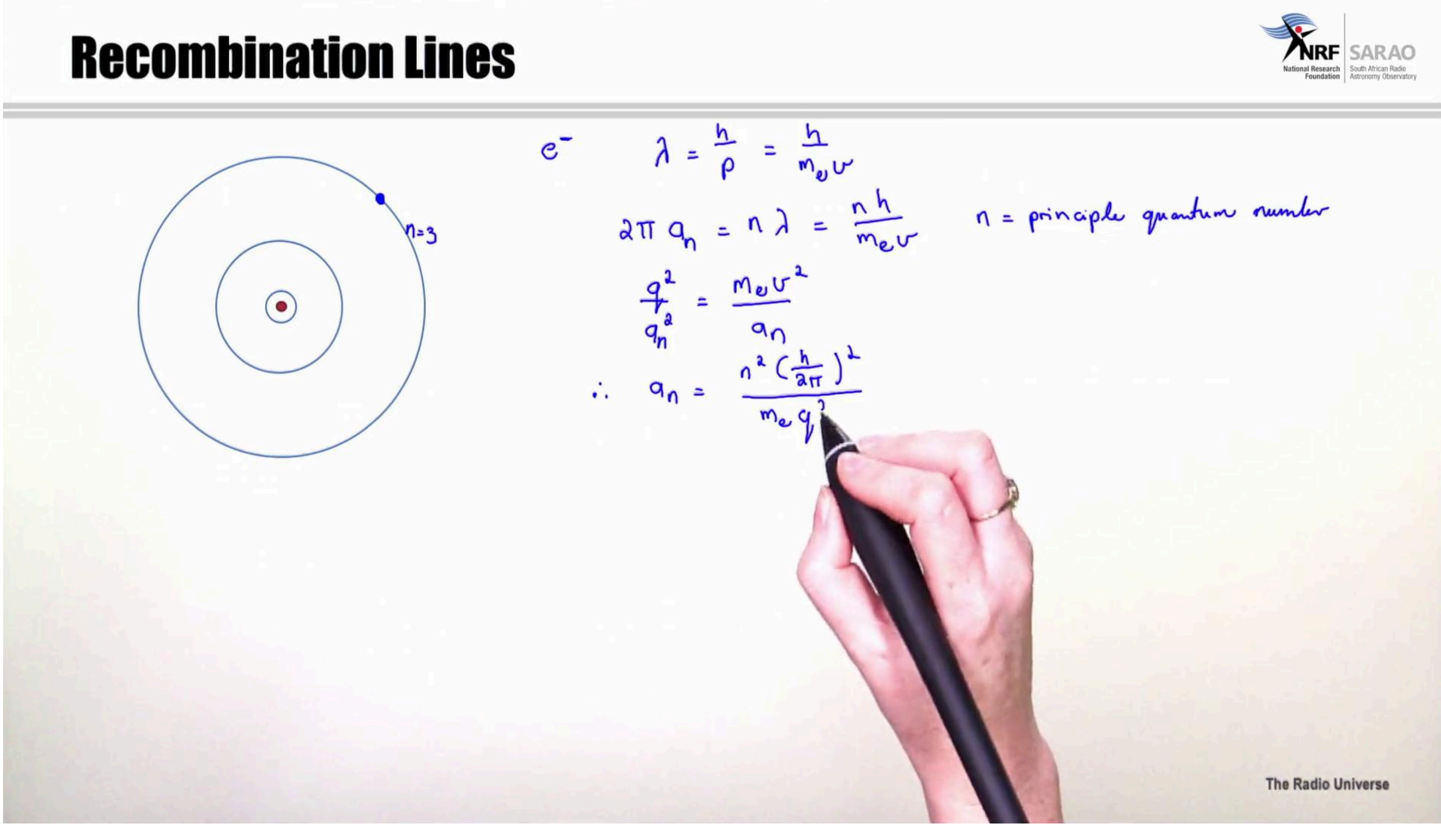


We'll start our discussion by talking about recombination lines for the hydrogen atom. This is because the hydrogen atom is one of the simplest atoms and so it's the easiest to understand and because it's also the most abundant element in the universe so it's the one that we study the most frequently. Recombination lines are called recombination lines because they happen when a free electron that has been ionized is captured by a proton, a nearby proton and rebound to it as an atom. When this happens the captured electron quickly transfers from the outer higher energy states to lower and lower energy states to eventually reach the ground level and as it's cascading down all of these energy states, it's emitting these emission lines which is why they're called recombination lines. In in the semi-classical model of the Bohr atom, what you can say is that an electron in some orbital energy level here has a wavelength which is given by the expression 'h' over its momentum, the Planck constant over its momentum which means that its wavelength is equal to 'h' over its mass times its velocity. In the quantum approximation here what we can say is that the only allowed orbital energies are those which have a circumference which equals a whole number of wavelengths.

Notes

Summary

3m 32s

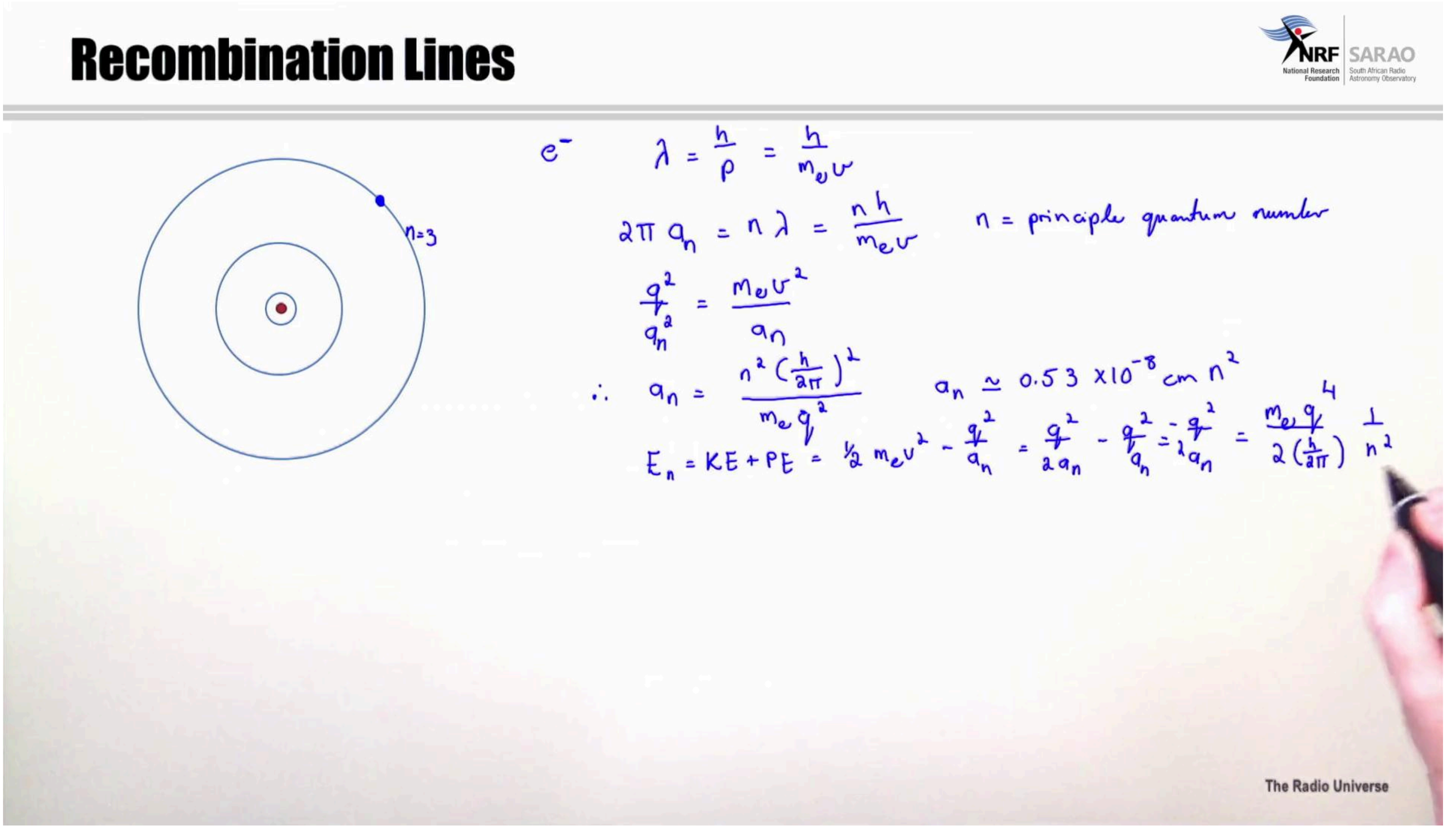


So if you set the radius of an orbital energy level here then you can say that the circumference of this orbital energy level has to be equal to a whole number of wavelengths, where in here is the principal quantum number. If we imagine for the moment now that the the mass of the proton is very much larger than the mass of the electron, so much so that we can assume it's stationary and the electron is orbiting around it then we can say that the electron will remain stable in this orbit only if the centripetal force associated with its velocity exactly balances the attraction, the Coulomb attraction between the positive proton and the electron in its orbit and its orbital level. So we have to say that we think that the that the Coulomb attraction here which is given by the multiplication of the charge of the electron times the charge of the proton which we give here as 'q' squared over the square of the radius gives you the Coulomb force and it has to balance the centripetal force which you get from the mass of the electron times its velocity over the radius. If you rearrange this equation then what you can get is an expression for the orbital radius which is given here.

Notes

Summary

5m 12s

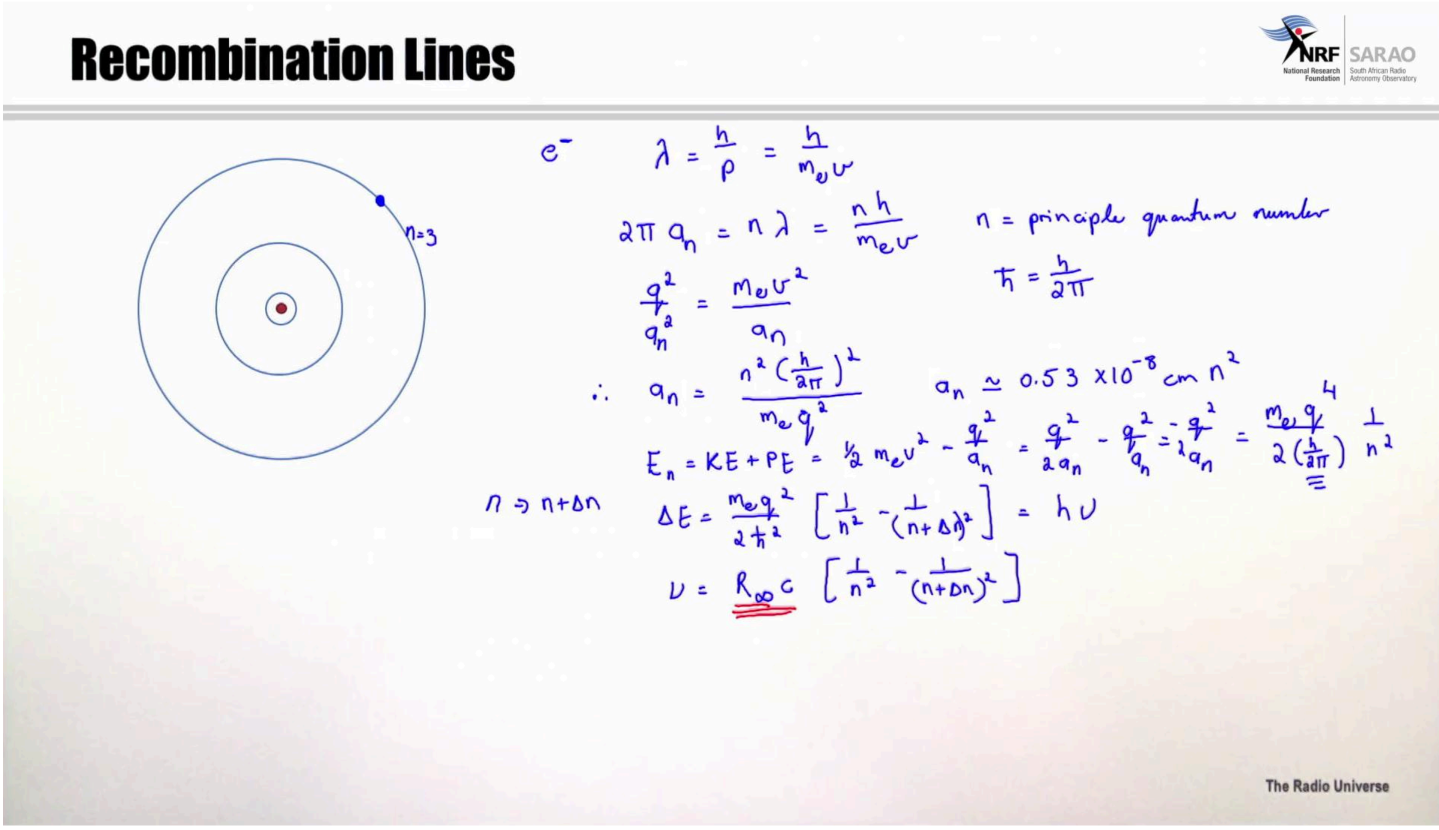


So here you have an expression for each orbital radius as a function of its energy level so in is one, in is two, in is three and 'a n' is, therefore, if you were to solve, if you were to calculate this where this is the mass of the electron, this is the charge of an electron, then what this works out to be roughly is 0.53 times ten to the minus 8 centimeters times the principal quantum number squared. So what we want to know is what is the frequency of the emitted photon as you change from one orbital level to another. So what we need to know then is what is the energy of each orbital level. Well. Energy of each orbital level is given by the kinetic energy plus the potential energy. We have the kinetic energy as the usual a half 'm e v' squared and the potential energy is given by the the charge squared over the radius. If you compare this equation here with this equation here, you can see that you can rewrite this as being equal to 'q' squared over two times the orbital radius which then minus 'q' squared over the orbital radius is equal to is equal to half 'q' squared over the orbital radius which then once again when you compare to this expression can be rewritten as the mass of the electron times the charge to the power four over two times 'h' over two Pi one over 'n' squared.

Notes

Summary

6m 49s

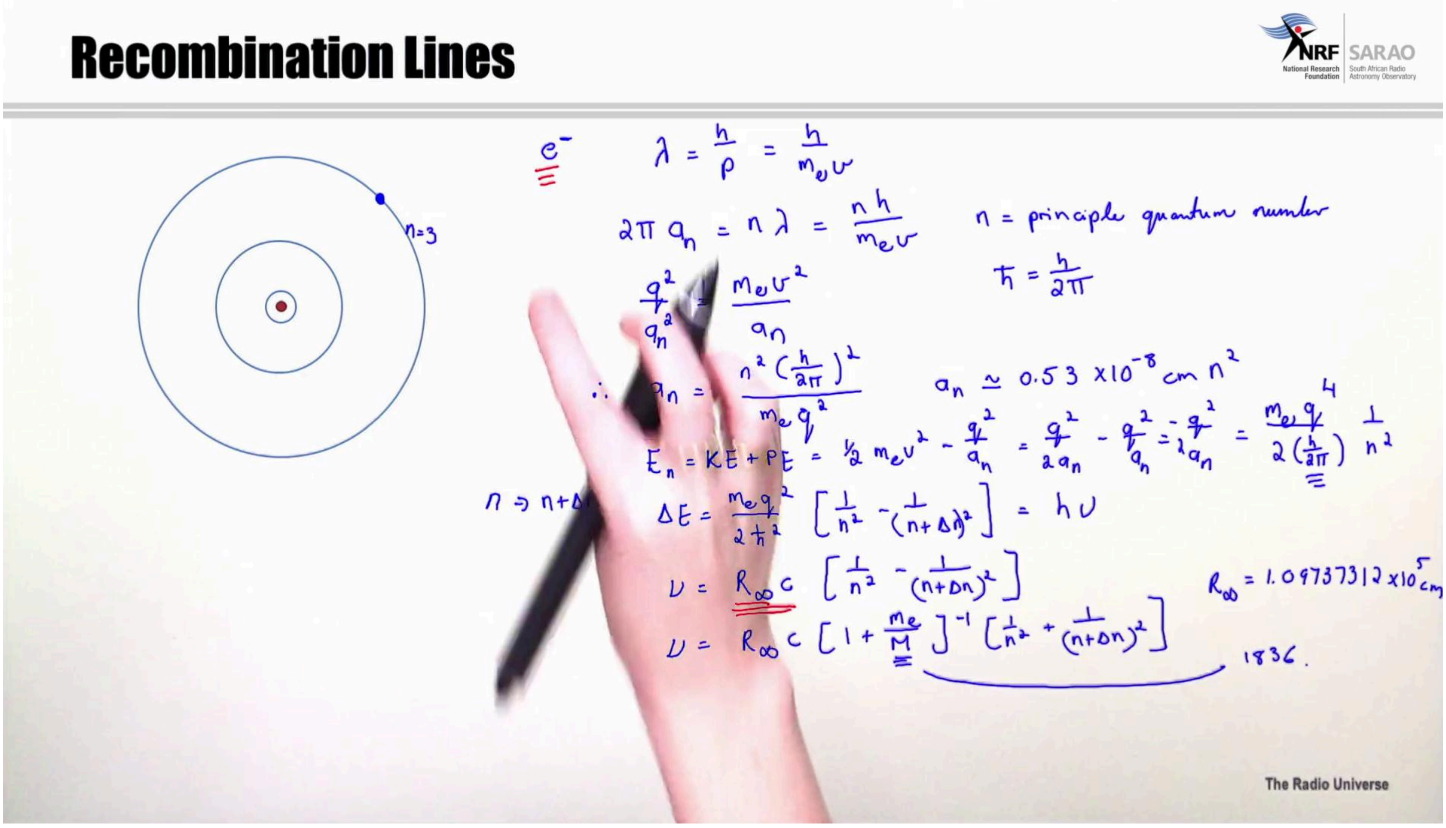


'h' over two Pi has a special name as it comes up more than once and it's called 'h' bar, a special name or a special symbol, 'h' over two Pi. So from this expression, it's fairly straightforward to see that if you were change from an orbital number 'n' to some other orbit with the number ‘n’ plus delta ‘n’, that the change in energy here would be equal to which then is equal to ‘h’ nu. So we can rewrite this equation so that the frequency is equal to a constant which you get from this constant in this equation and times by the speed of light over one over... So from this we can work out the frequency of any transition from one orbit to another. This constant here is called the Rydberg constant and it has units of per length and when it's multiplied by the speed of light then it's called the Rydberg frequency and has units of frequency.

Notes

Summary

8m 38s

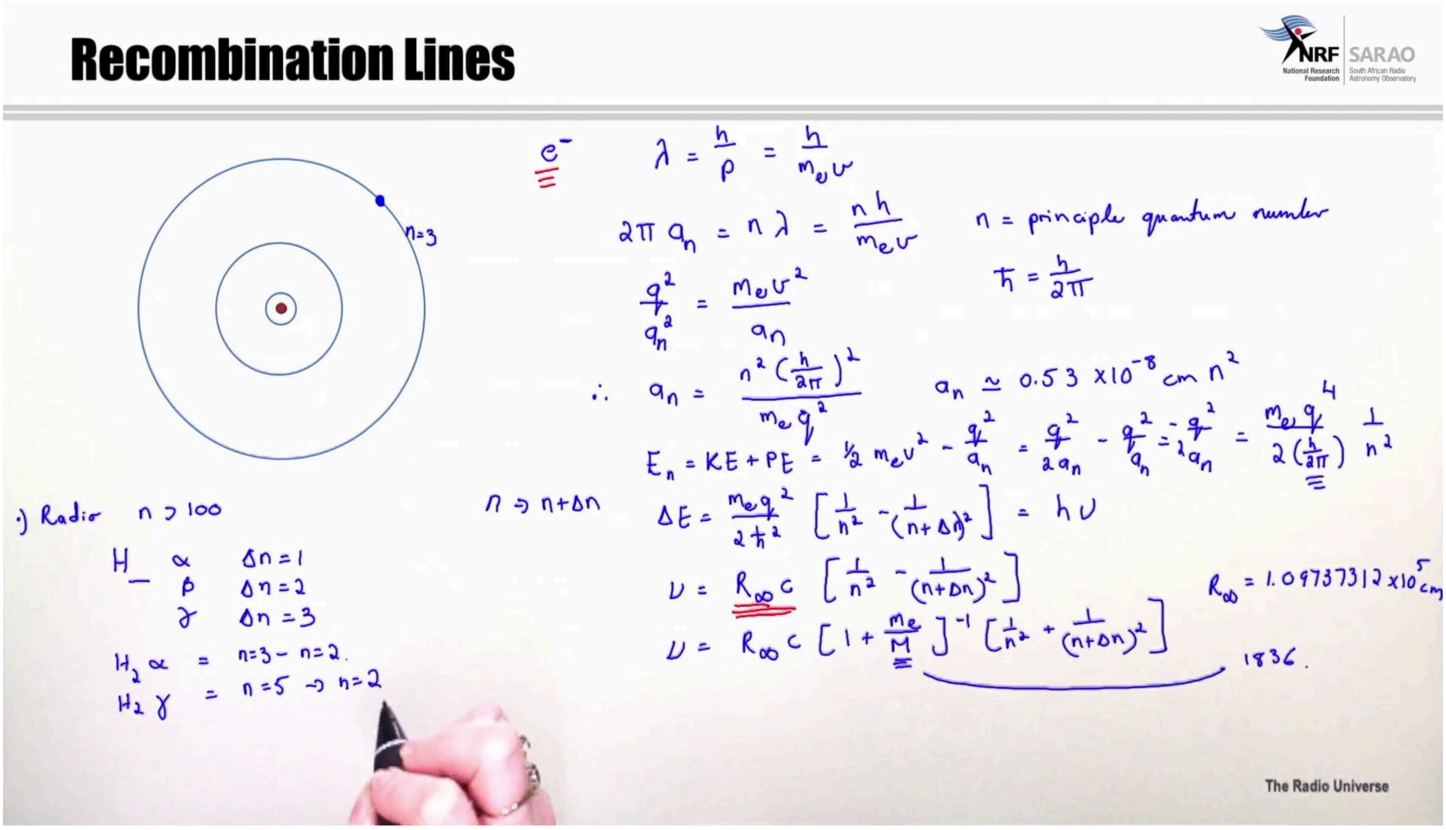


The infinite endless score here emphasizes that this is for the case where the proton has infinite mass but in fact, the proton's mass isn't completely infinite and so if you were to re-derive this entire equation by considering that these two are orbiting around the center of by considering the center of mass of this system then you would re-derive this equation to one that looks very similar such that nu is equal to the Rydberg constant times ‘c’ over one plus the mass of the electron over the mass of the nucleus here times one over 'n' squared plus one over 'n' plus delta 'n' squared. The Rydberg constant is given as a value of being... So from this we can calculate the frequency of any of any transition for the hydrogen atom. You simply need to know the mass of the electron divided by the mass of the nucleus which here will be the mass of the proton. So for a hydrogen atom this ratio is roughly equal to one eight three six. For higher more massive for more massive atoms, we’ll have a very similar situation for singly ionized versions of the more massive atom because if you have an atom here with six protons and it's only singly ionized so you have five electrons in the orbiting around those six protons then the recaptured electron over here still only sees the potential of one proton in terms of its electrostatic interaction.

Notes

Summary

9m 49s

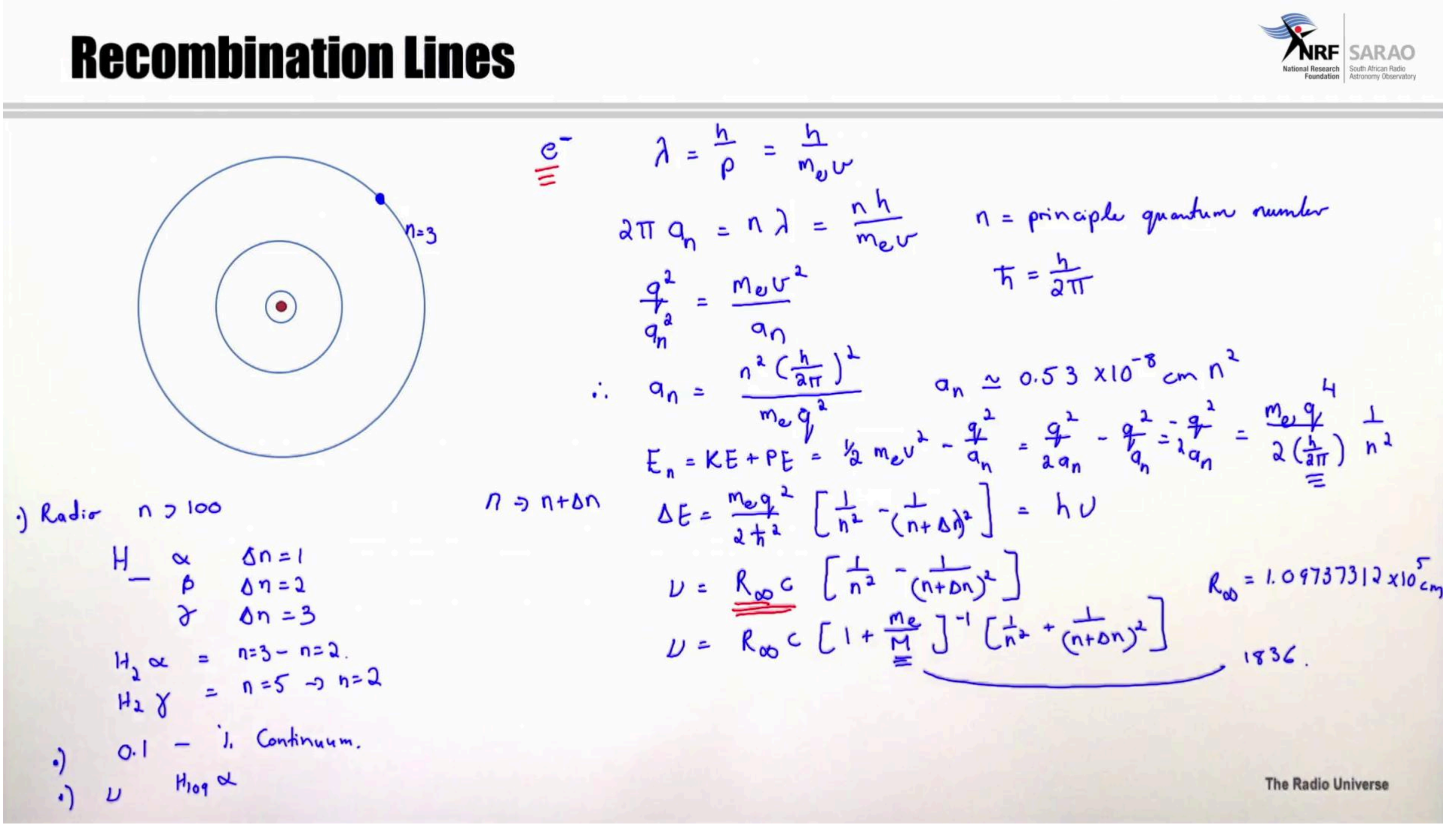


So in that case, you can more or less reuse this formula but with the only change being here that the mass of the nucleus will be larger for heavier elements. You will see if you were to plug in the numbers here that most of these lower orbital energy transitions actually fall in the optical regime and you only get radio recombination lines for very large numbers of 'n' so 'n' usually greater than about a hundred. Recombination lines in astronomy are usually indicated by the following notation where you'd say 'H' and here you would then give a subscript which indicates the final energy level so the final energy level where it's ended and then you give a Greek letter which indicates how many changes in energy level have taken place. So alpha, for instance, would say that delta ‘n’ is equal to one, beta tells you that delta ‘n’ is equal to two and gamma says that delta ‘n’ is equal to three. So, for instance, if you were to write the 'H' two alpha line that tells you that you've changed from 'n' is equal to three to 'n' is equal to two. Similarly, if you were to write the ‘H’ two gamma line then it would say you've traveled from ‘n’ is equal to five to ‘n’ is equal to two.

Notes

Summary

11m 38s

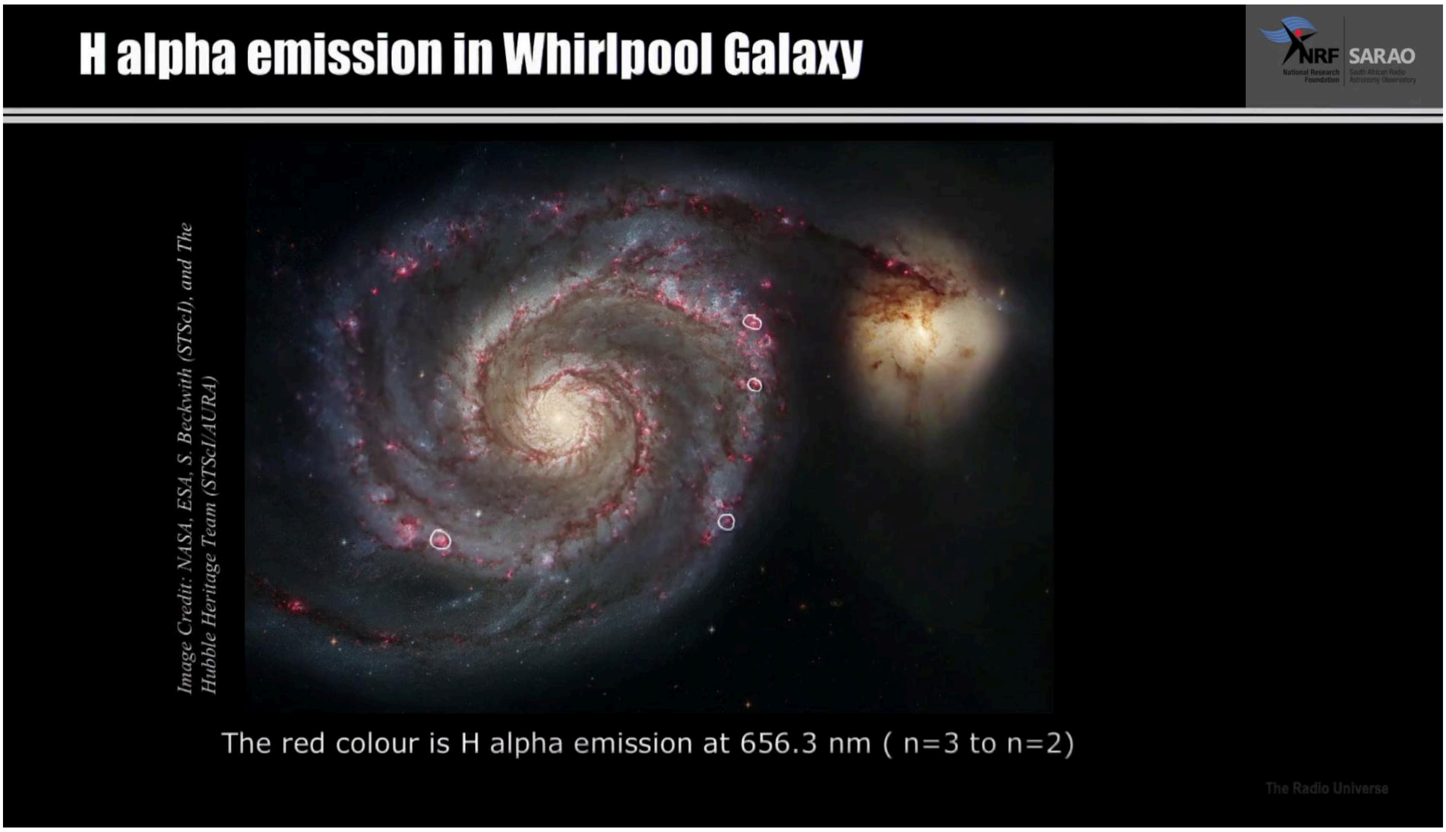


Radio recombination lines tend to be very weak and in fact, they're very hard to detect. They usually only have around say, 0.1 to 1 percent of the continuum flux and so they are not usually detected very much outside of our own galaxy. As an exercise for yourself, you can consider calculating what is the frequency for,for instance, the ‘H’ 109 alpha transition.

Notes

Summary

13m 10s



In this picture of the Whirlpool Galaxy what you can see is that these red regions that are, I'll highlight now by drawing little circles around them, all of these little discreet red blobs, those are all regions where you are getting recombination line emission from the 'n' is three to two line, and these are regions where hot young stars have ionized the hydrogen gas there and then that they are ions are being recaptured by the photons to emit these recombination lines.

Notes

Summary

13m 42s