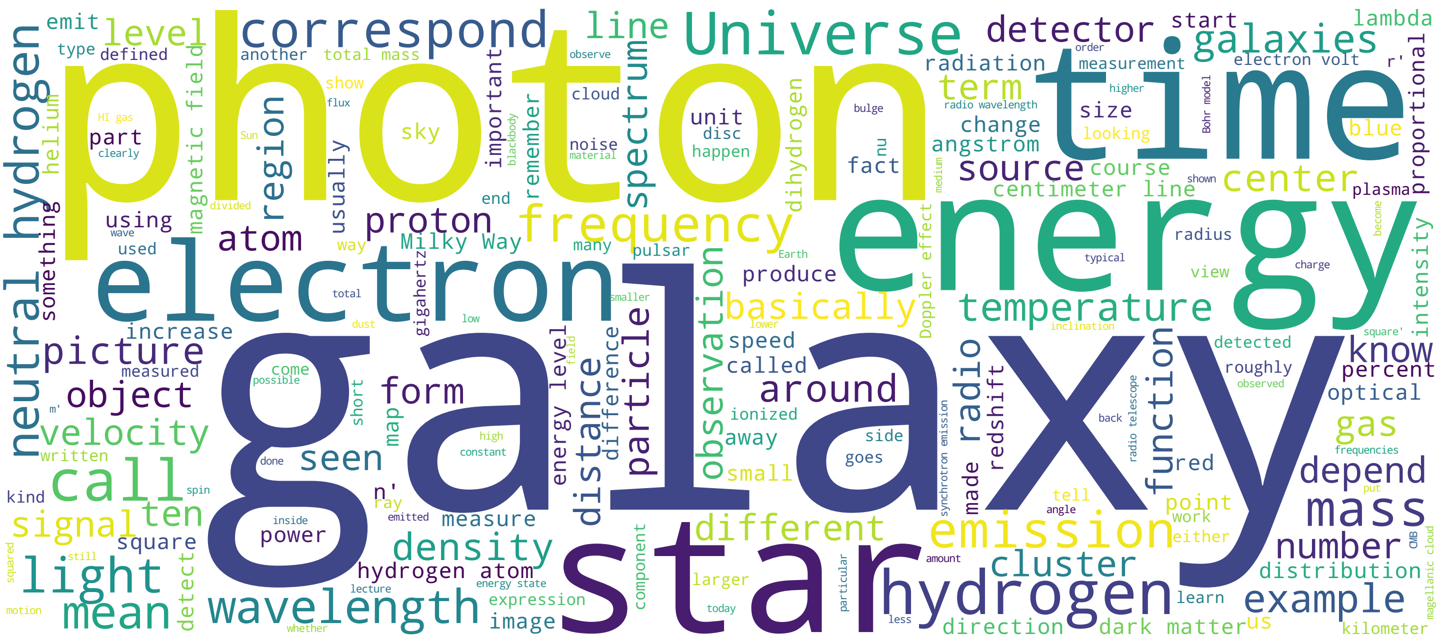
EPFL

Hydrogen in Galaxies

The Universe At Radio Wavelengths

Jean-Paul Kneib



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Video

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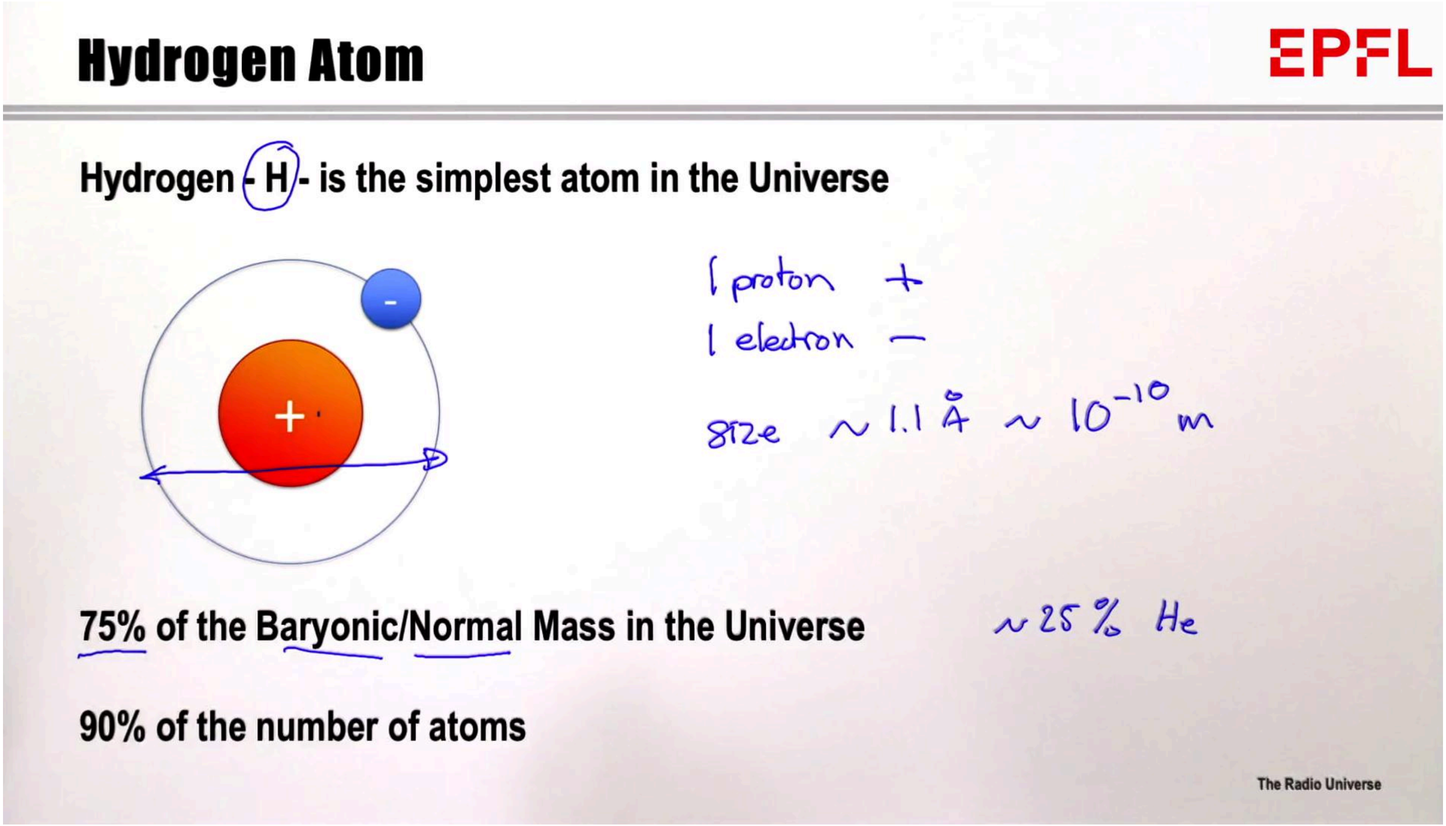
Hydrogen is the most common atom in the Universe. Hydrogen is also the fuel of stars that transform hydrogen into helium and produce a lot of energy and the light that is essential to our life on Earth. But the focus of this lecture is to look at the hydrogen in, between star and around galaxies. We can find hydrogen in different forms. It can be neutral, it can be ionized or it can be combined in a molecule. Depending on the form of hydrogen, we will map it using different ways. The 20 centimeter line of neutral hydrogen is the efficient way to chart hydrogen in the galaxy and around. In particular, neutral hydrogen can be detected at ridges a few times larger than the stellar light allowing to probe the dark matter around these galaxies. Moreover, neutral hydrogen is an excellent tool to learn more on the mass assembly of galaxies. In short, hydrogen can reveal us some of the dark side of galaxies.

Notes

Summary

0m 05s

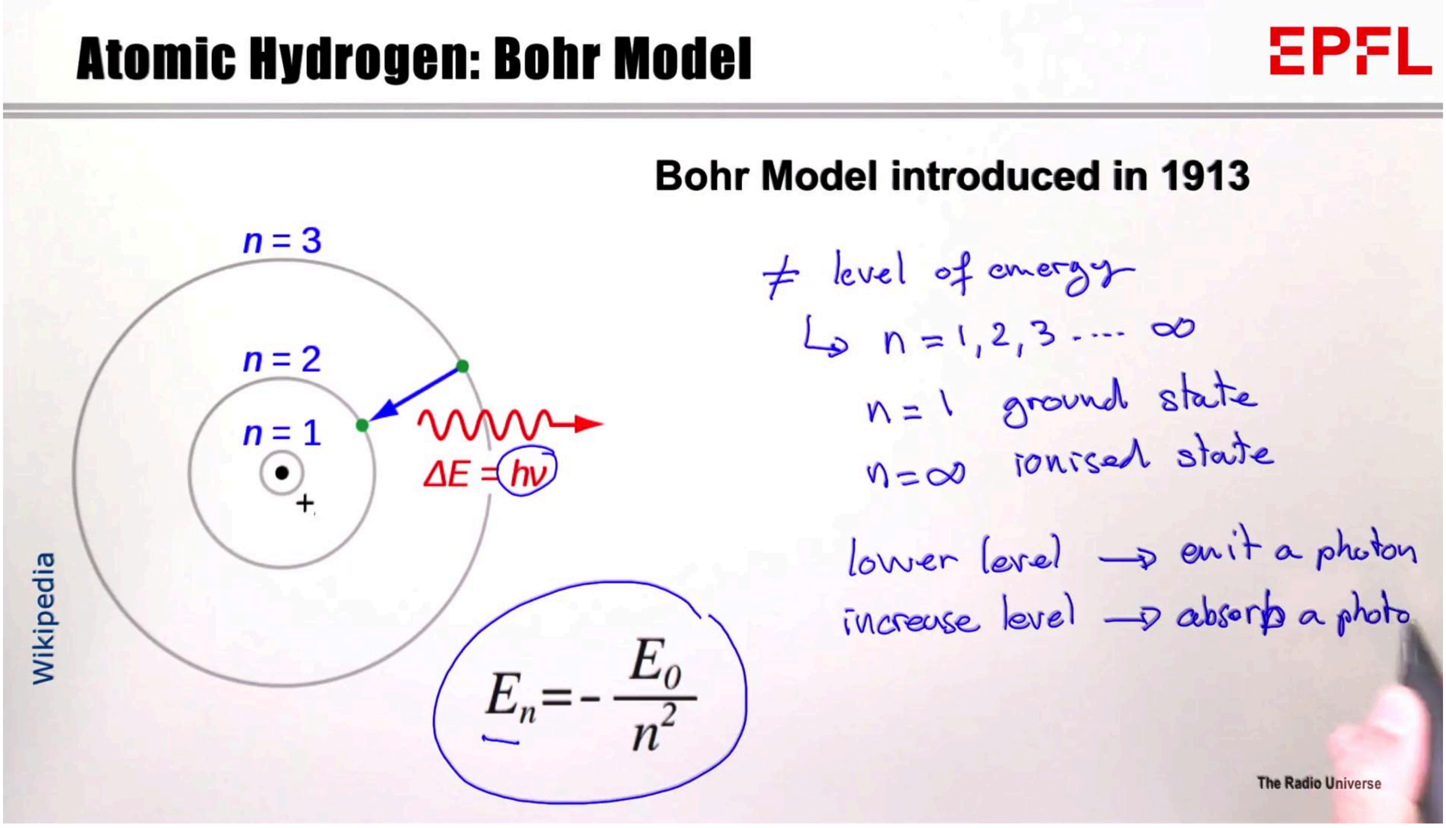


To start this session we're gonna talk about the hydrogen atom. And let's start by quick recap about the hydrogen atom first. The hydrogen atom is noted 'H' is the simplest atom in the Universe. This is a very simple picture of the hydrogen atom. It is made in red by one proton which is positively charged and also one electron which is negatively charged. This very simple model is what we call the Bohr model. We can define a typical size of the atom and the size of the atom is about 1.1 angstrom which correspond to ten to the minus ten meter. Hydrogen is the most common atom in the Universe. In fact, it represent 75 percent of the baryonic or normal mass in the Universe so that is the mass which is made of particles that we know well like these atoms. So we have 35 percent of hydrogen and, in fact, we have about almost 25 percent of helium. So in total about 90 percent of the atoms are hydrogen. Why? It's because hydrogen is the lightest element, helium having more mass, there will be a less atom of helium in the Universe. Okay. So 75 percent in mass and 90 percent in number.

Notes

Summary

1m 23s



So now let's have another recap of the Bohr model. Okay. I'm sure you've already seen that before. So Bohr model was introduced in 1930 and the importance of the Bohr model, it's this picture where again we have the proton at the center positively charge and here in green we see the electron. Okay. And what is important is that the electron can be at different level of energy and this is represented by a number 'n'. The number is an integer and so it goes from 'n' equals one two three up to infinity. Okay. So 'n1' is what we call the ground state and 'n' infinity is what we call the ionized state. Right. And so we define the energy level in this way where we have the energy of level 'n' is equal to minus 'E-zero' over 'n-square'. Okay. So energy level one 'E-one' is equal to minus 'E-zero'. And if you have 'n' equals infinity then the energy level is equal to zero. So if we have our electron that goes from a high level to a lower level, it will lose energy and the energy loss will be the production of a photon with energy delta 'E' which will be also proportional to the frequency. Okay. So if we lower the level, we will lose energy so that will mean we will emit a photon. Okay. Now if we increase the level 'n' then we need to gain energy. So we will absorb a photon.

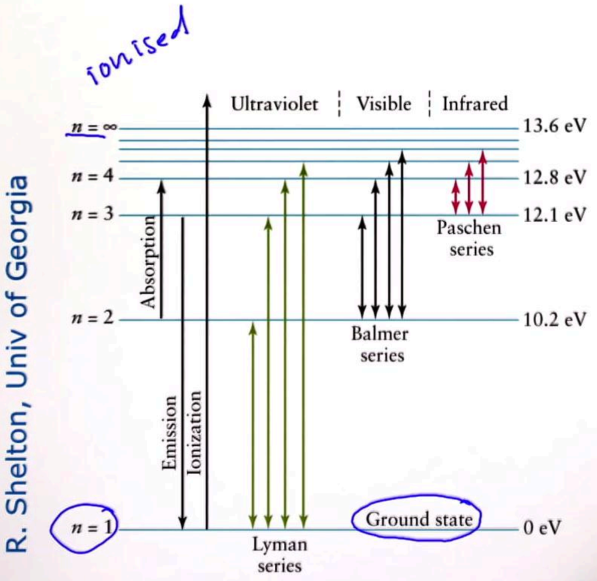
Notes

Summary

3m 24s

Atomic Hydrogen and photon interaction

EPFL



The Rydberg formula

$$\Delta E_{n,m} = E_0\left(\frac{1}{n^2} - \frac{1}{m^2}\right) \qquad n<m$$

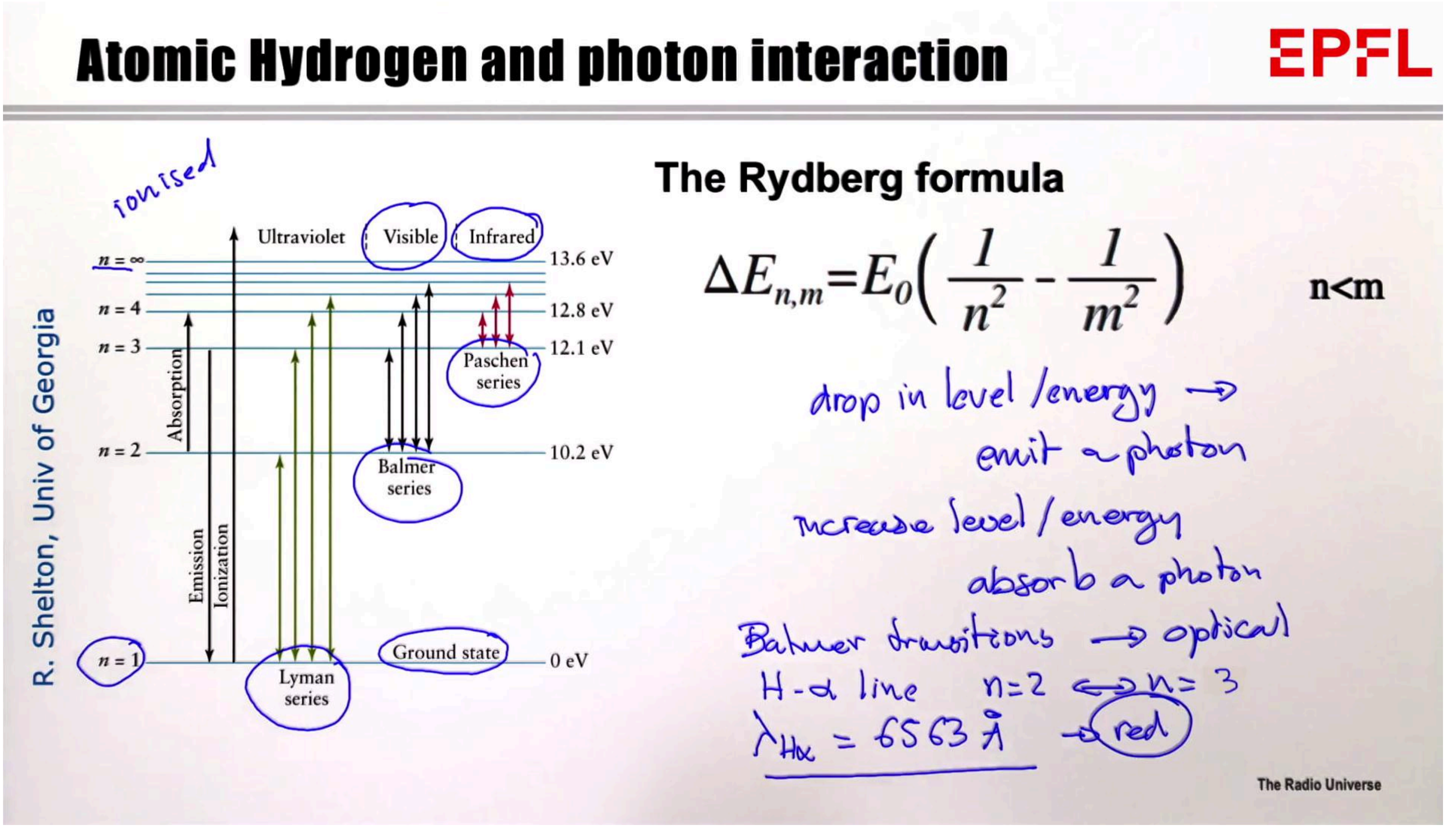
The Radio Universe

So let's have a closer look at the atomic hydrogen and the photon interaction. This can be summarized in what we call the Rydberg formula where it gives you the delta energy between level 'n' and 'm', where 'n' is smaller than 'm' and it can be written as 'E-zero' one over 'n-square' minus one over 'm-square'. So to explain a little bit this formula we have to go back to this picture where we see the different levels of energy 'n' equal infinity. Again that's the ionized state and the 'n' equal ones level which correspond to the ground state. So to go from level one to level infinity, we have a delta in energy which is 13.6 electron volt. Of course, we can freely go to any level to any other level and that will depend on this delta of energy 'n' and 'm'. If you want to go from level 'n1' to another level, you will have to either absorb or emit photons and those photons will be quantified in terms of energy and thus in terms of their wavelengths depending on the gap in energy. Okay. So if you go from, say, level three to level one then you will emit a photon and the photon will have an energy of 12.1 electron volt. Okay.

Notes

Summary

6m 02s

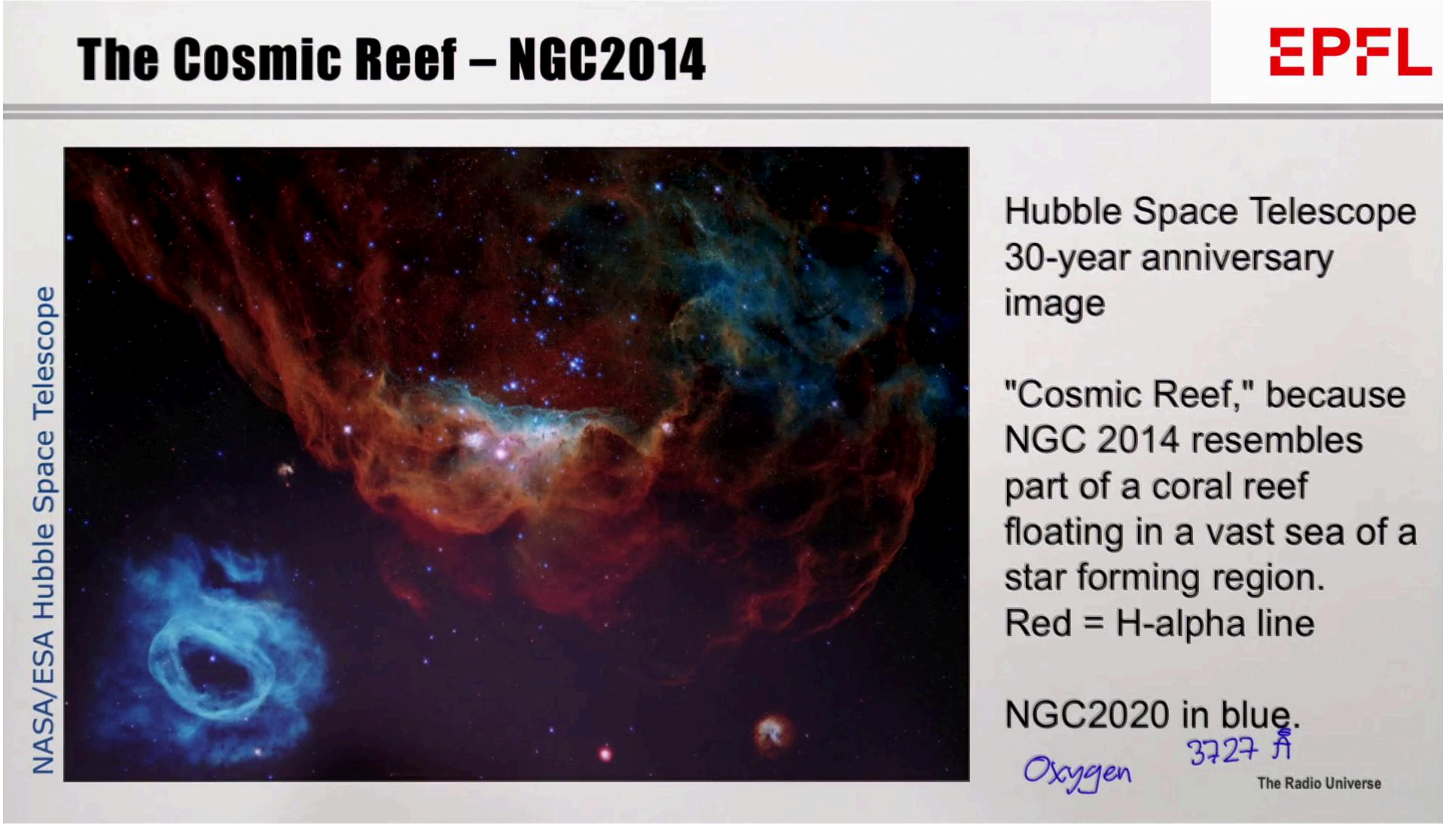


Or if you go from level 'n2' to level 'n4', you are gaining in energy so you have to gain a photon which is of energy 12.8 minus 10.2 which correspond to 2.6 electron volt and that's correspond to emission that you can see at visible wavelengths. Okay. So summarize that again. If I drop in level so drop in energy also, I will emit a photon and if I increase the level so increase in energy, I will absorb a photon. Okay and the photon energy is given by this Rydberg formula. So for level 'n2' those transition correspond to what we call the Balmer series. Okay. In ultraviolet that correspond to the 'n1' transition that's the Lyman series and for the level 'n3', it's the Paschen series and that's correspond to the infrared. Okay. So balmer transitions are seen in optical wavelengths. The most common and stronger transition is what we call the H-alpha line and that goes from 'n' equal two to 'n' equals three. Okay. So we can either see it as an emission or an absorption and the wavelength of H-alpha is at 6063 angstrom which correspond to the red part of the spectrum. So so you usually see represented in astronomy called image, the H-alpha line at 6563 angstrom in red color.

Notes

Summary

8m 00s

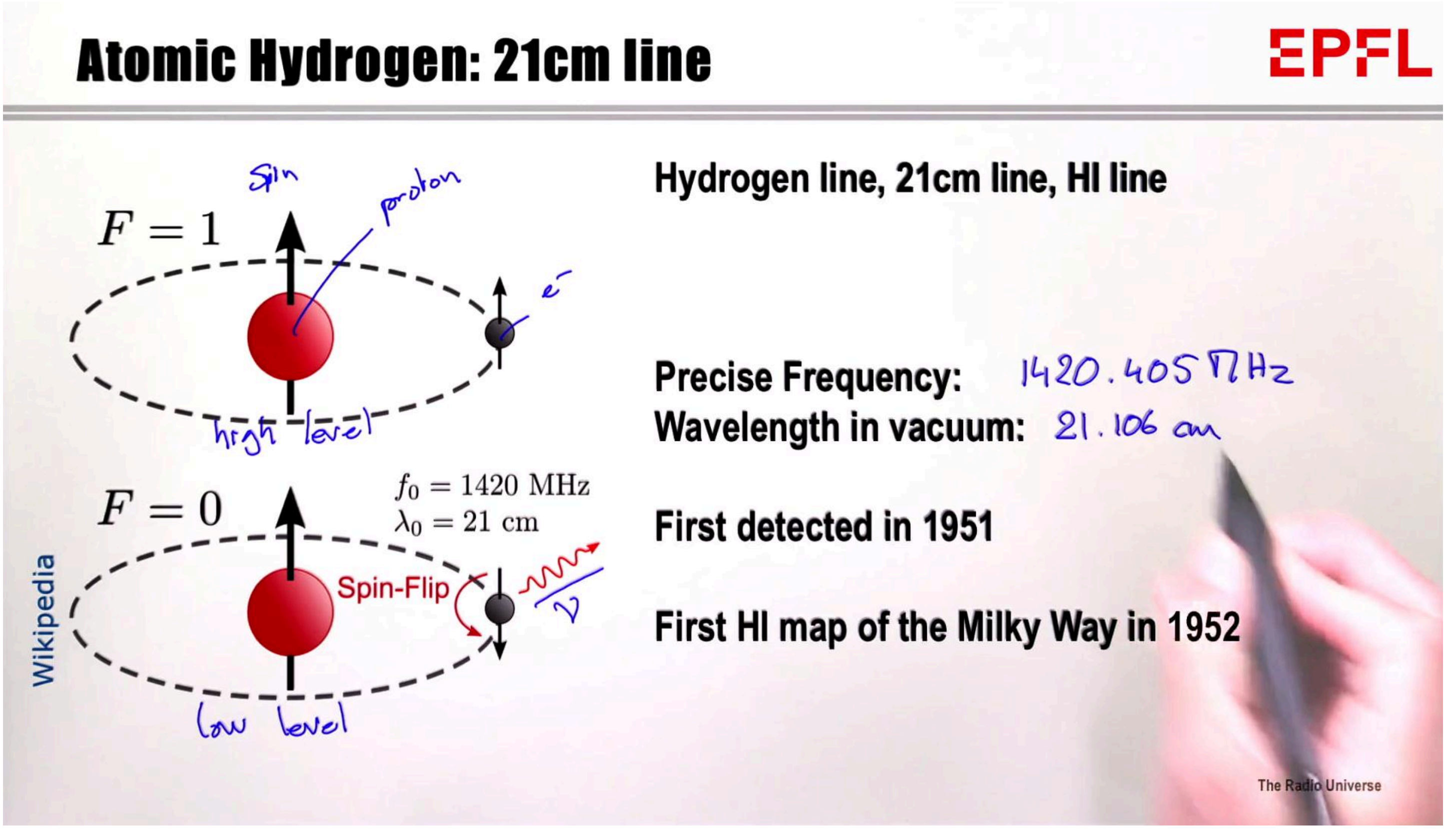


So that's just an example of the ionized hydrogen in a particular image which is the Hubble Space Telescope 30 years anniversary image. It pictured here the cosmic reef that is the nebula NGC 2014 and it resemble a part of a coral reef floating in a vast region of star forming. The red color we see here correspond to the H-alpha emission that has mentioned. Okay, which is the excitement state from level two to level three when you ionized the hydrogen. What we see here on the side is the nebula NGC 2020. It's shown in blue. It correspond to the oxygen atom which is ionized and for ionizing the oxygen you have a transition line which is at 3727 angstrom which is in the blue part of the spectrum. So in short, you see that when you see a picture of the Universe of this diffuse light, the color has some meaning. Red is hydrogen and blue is the oxygen.

Notes

Summary

10m 23s

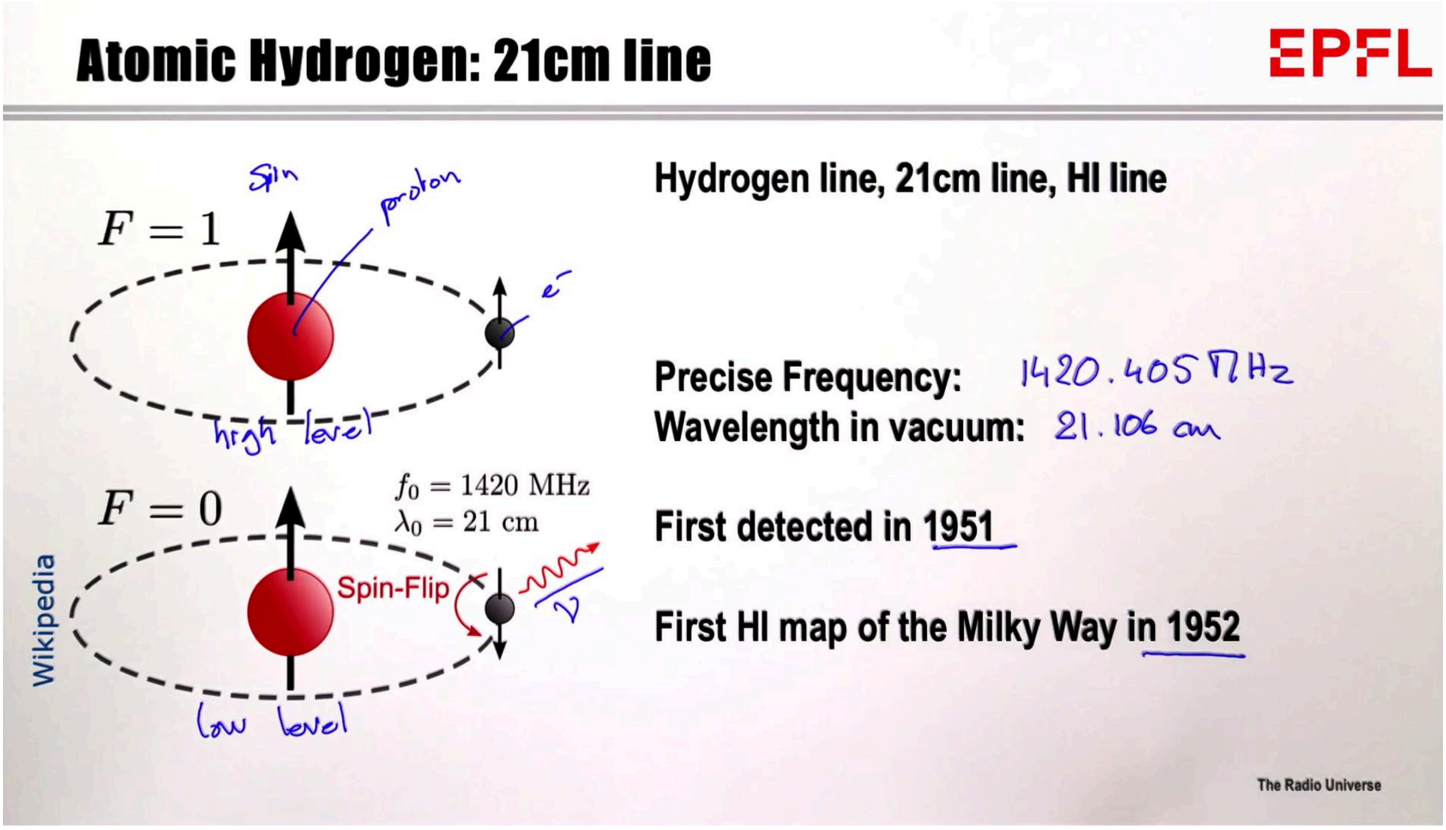


Right. So we have seen that we can detect the ionized atom and particle of the hydrogen but what about the neutral hydrogen or the atomic hydrogen? How can we observe it? Well, we have to go not in visible light but in radio light and in particular, we are going to have a look at what we call the 21 centimeter line. We call it 20 centimeter line, also hydrogen line or again 'HI' line in short. So what is the origin of the 20 centimeter line as a recap? Right. So here we have a picture again of two hydrogen atom. So again here we have the proton, here we have the electron and what is shown by the arrow here is the spin. Okay. Spin of the proton, spin of the electron. And we have two different levels of the atom. We have a high level of energy and the low level of energy and that depends on the direction of the spin of the electron whether it's up like the one of the proton or whether it's down opposite to the one of the proton. So if you do a spin flip from this high level energy state to this low level energy state, what you will produce is a photon with a frequency of 1420 and more precisely, the transition frequency is 1420 405 megahertz which correspond to a wavelength in vacuum to a precise 21.106 centimeter.

Notes

Summary

12m 00s

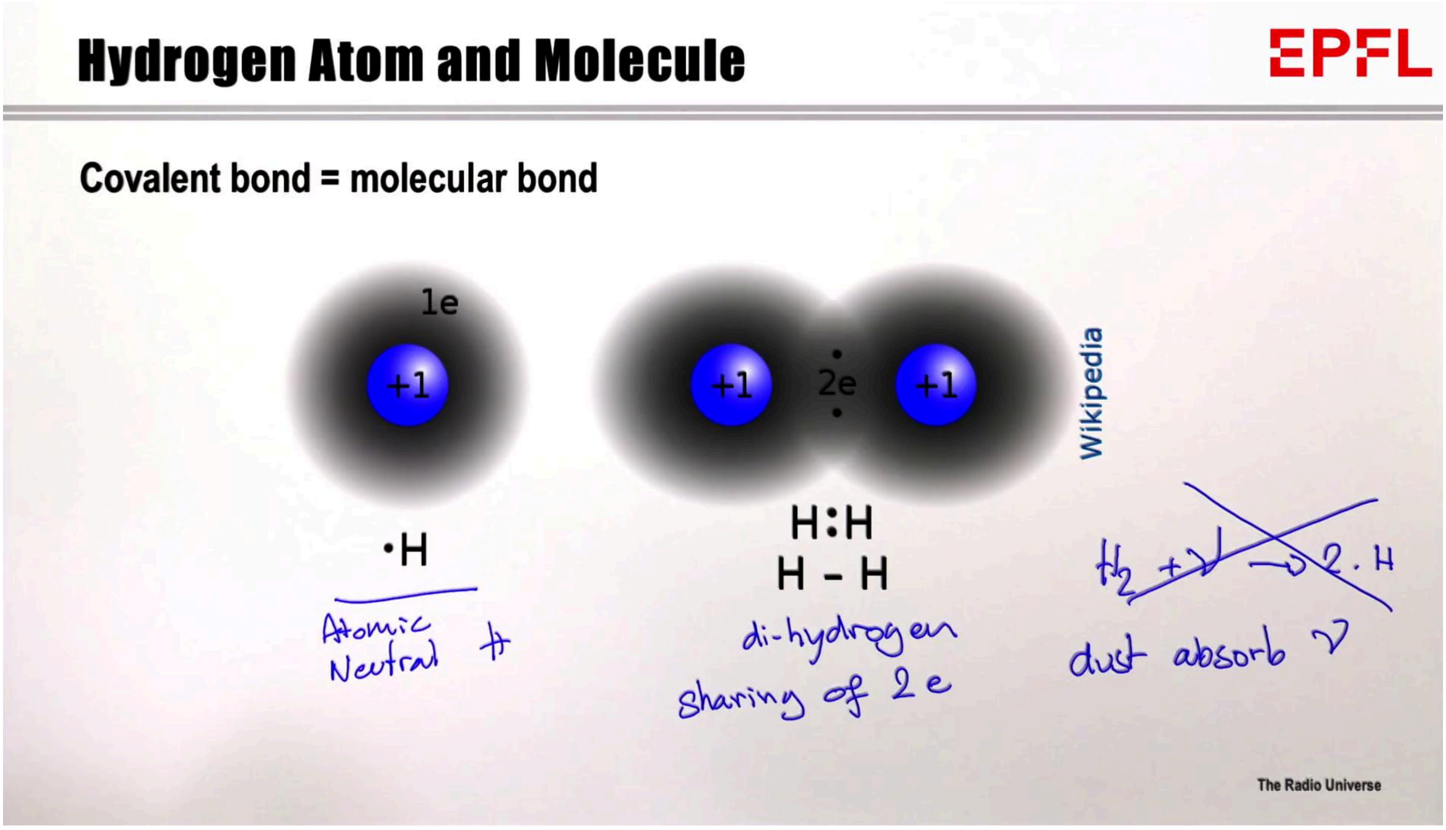


So this transition and the corresponding radio photon was first detected in 1951. And so soon after you detect this transition and when you have a radio telescope, you can map the Milky Way in 'HI' so the hydrogen the neutral hydrogen distribution in the Milky Way and this was done shortly after in 1952.

Notes

Summary

14m 10s

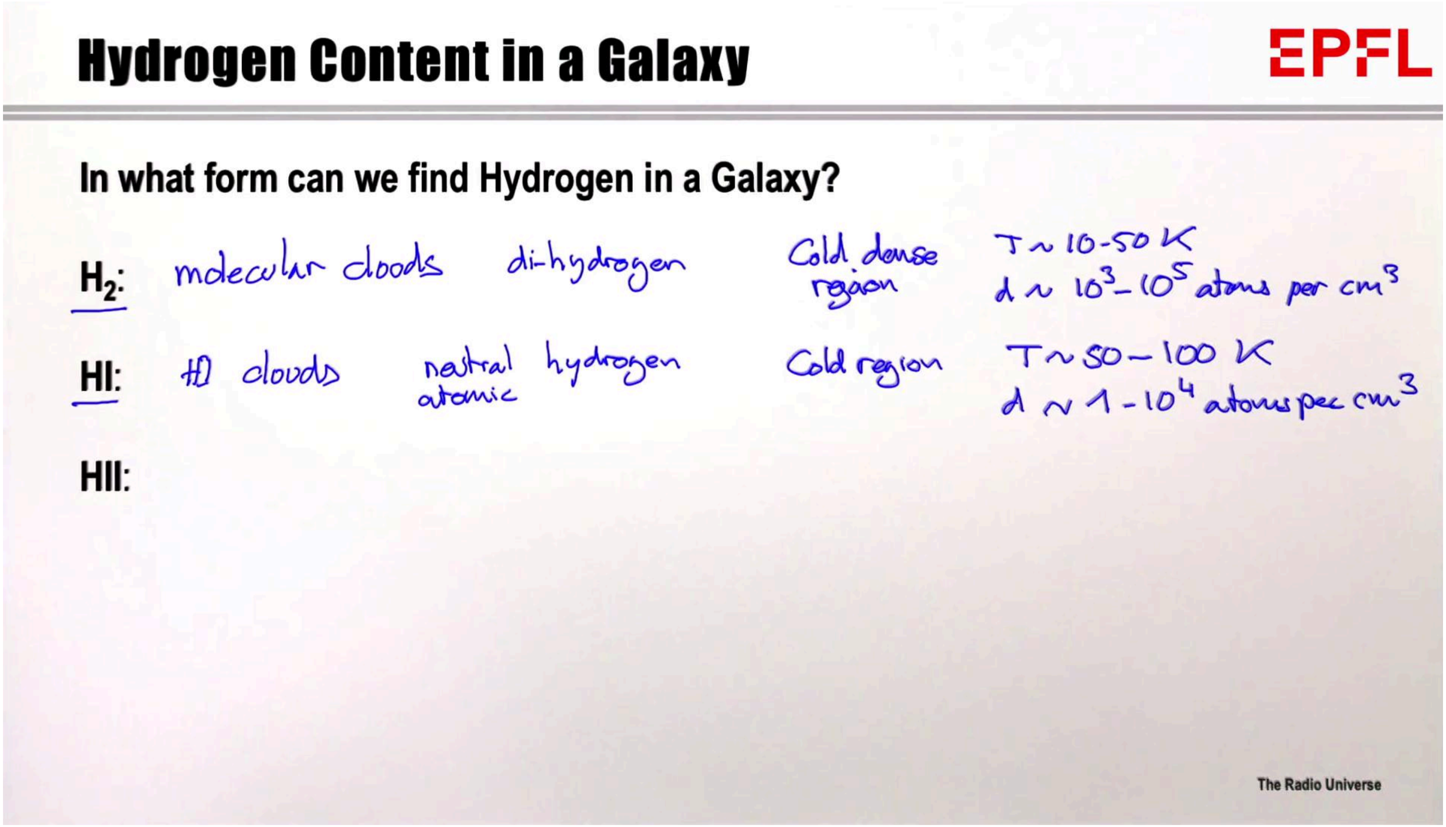


We have to look at the other possible form of hydrogen. It's the dihydrogen and so what is the difference? So here clearly you see a simple atom of hydrogen what we call the atomic or neutral hydrogen and here you see two hydrogen atom what we call the dihydrogen which is connected together. So the difference between the two is that in this case we have a sharing of the two electrons in between the two protons. So what is the relation between the two state? Well, again it's a question of energy. So if you have the dihydrogen and it and you eliminate it with a photon of a relatively high energy, say, UV typically UV light, the UV light can break the 'HII' atom and it will form two atomic atom of hydrogen. Okay. So if you have a lot of UV photon basically you will just destroy the 'HII' molecule but you still find in the Universe, you know, ‘H2’ molecule so what happened. Well, if you have dust particles that dust particles can basically absorb the photons and then basically you don't have this relation anymore. Okay. And then you ‘H2’ molecules can stay. Of course, it will depend on density and temperature but in short, when you have ‘H2’ molecules usually you have a lot of dust.

Notes

Summary

14m 40s



So now let's recap the hydrogen content in the galaxy. Okay and I guess the question is, in what form can we find hydrogen in the galaxy? Well, basically there's three form in which you can find hydrogen in the galaxy. Either in what we call molecular cloud. Okay. So here the hydrogen is in form of the molecule, the dihydrogen. So again that's two protons and two electrons. Okay. You can find that in what we find we call the cold and dense region. So what it means? Well, typically that means temperature which range from ten to fifty kelvin and in terms of densities, okay, it correspond to density of ten to the three to ten to the five atoms per centimeter cube. Okay. So that's for the molecular clouds ‘H2’. The other state is what we call the ‘H1’. Okay. We usually call that ‘H1’ cloud. Okay. That's correspond to neutral hydrogen, also called atomic hydrogen. And here again we have one proton and one electron so, you know, it's neutral. Again this is also usually in cold region typically cold but slightly warmer than for the molecule clouds so the temperature is more like 50 to 100 kelvin and the density is lower. So typically from one to one thousand ten to the four atoms per centimeter cube.

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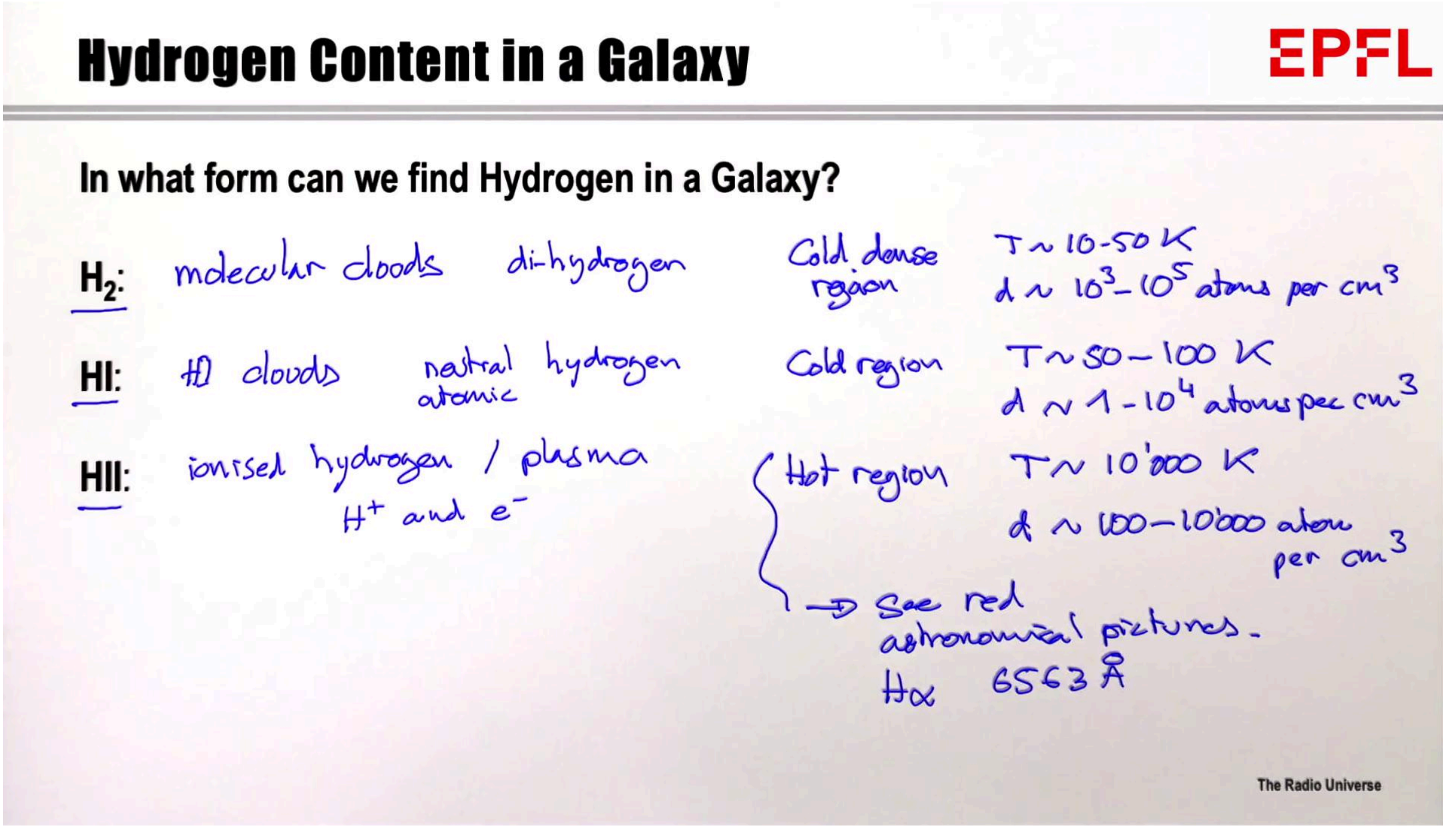
Summary

16m 52s

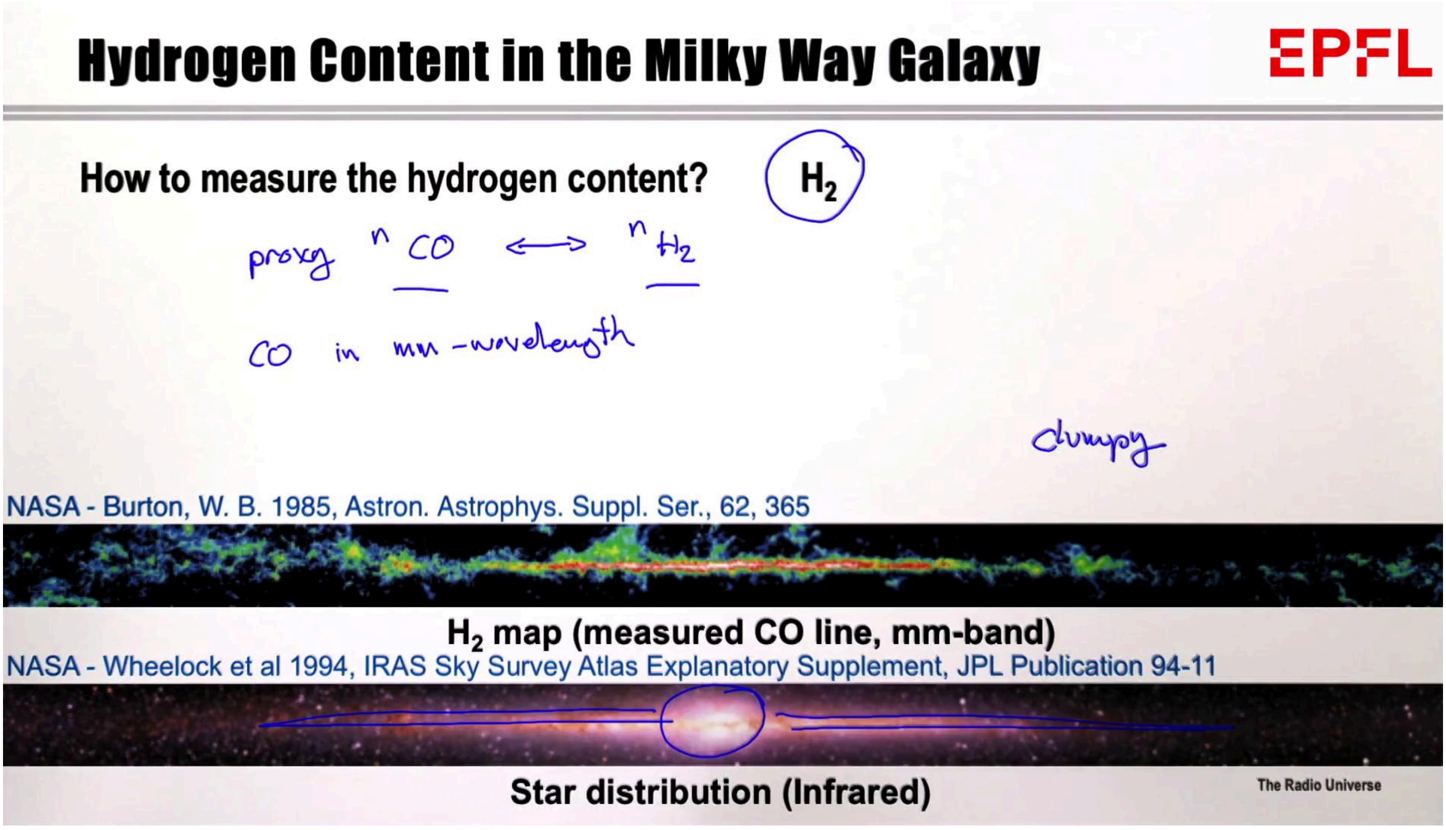


And the last form, the ‘H2’ form that's correspond to what we call the ionized hydrogen. Okay. Well, basically it's a plasma, okay, where we have a plasma of protons and electrons. To reach this plasma state, you need to have to be in a relatively hot region. Okay. And it's correspond to basically temperature of ten thousand kelvin. Okay. This is possible if you have lot of a bright star, blue star typically 'O' and 'B' type. And the density is then of the order of 100 to 10,000 atoms per centimeter cube. Okay. And those hot region is those one you see in red in astronomical picture. Okay because that's correspond to the H-alpha transition line which is at 6563 angstrom.

Notes

Summary

19m 05s

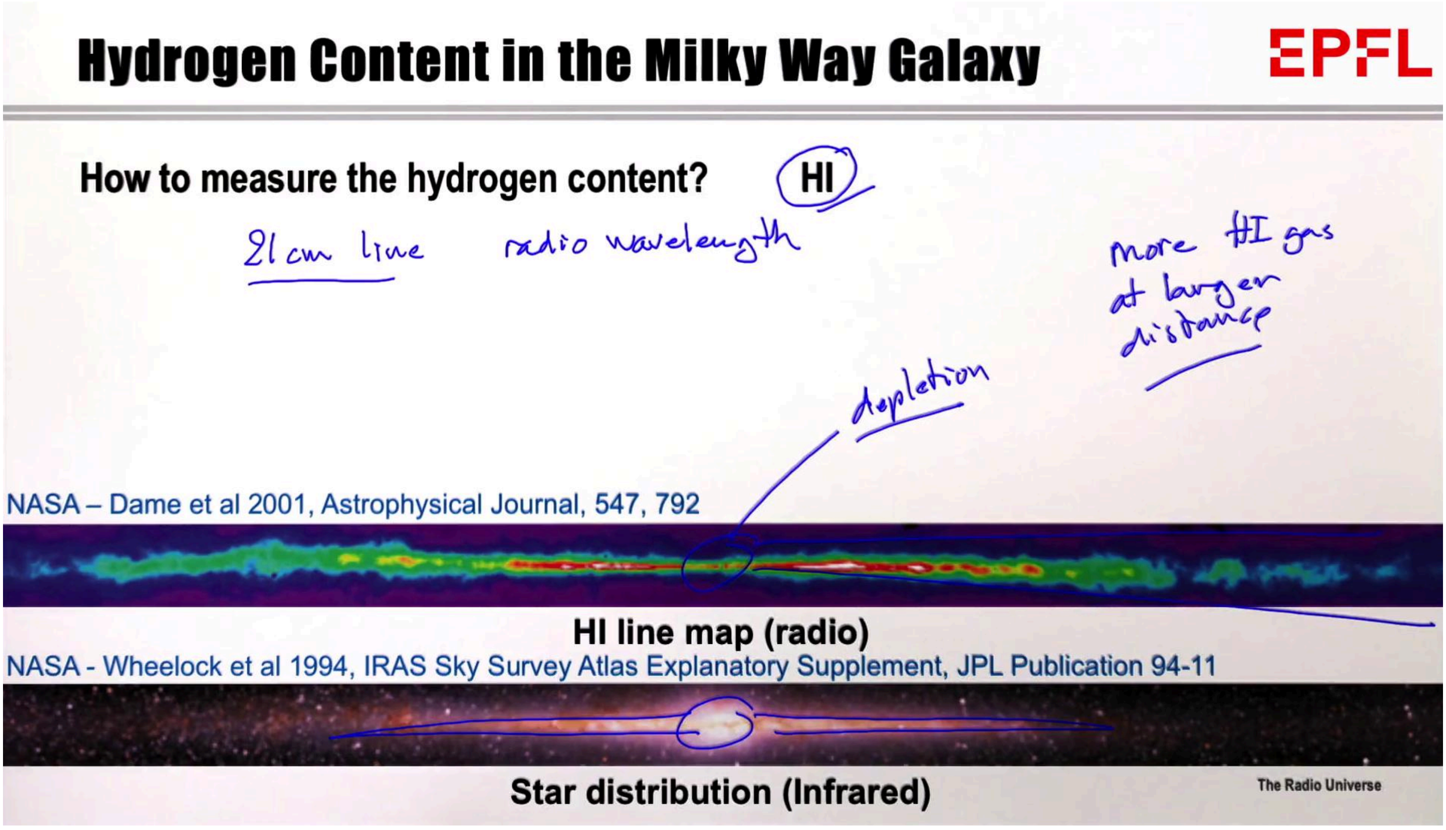


So what about the hydrogen in our Milky Way galaxy? Okay. And first we should question ourself how we measure the hydrogen content? Okay and it will depend on the form of the hydrogen. So let's start with the dihydrogen, the molecular cloud. So there's no direct way to measure ‘H2’ the molecule. So what we usually do is we're observing a proxy. Okay and the proxy would be another molecule molecule like 'CO'. And what we can show is that there's a link between a the number of ‘CO’ molecule and the number of the dihydrogen. Okay. So if we capable to measure 'CO', we're then capable to measure ‘H2’. Okay. So how to measure ‘CO’? Well, a good way is to measure 'CO' transition in millimeter wavelength. Okay. That's also in using radio telescope then we can map the ‘CO’ transition across the galaxy. So here we have two images, say, classical image of the star distribution in our galaxy. Here we see the galaxy center and we see the density of star which decrease as a function of radius. Okay. Our galaxy is very thin. Okay. So it's a disc. And we have the bulge at the center and we see clearly the disc here Okay. And we see that the distribution of the ‘H2’ dihydrogen is somewhat different. Okay. It's distributed again along the disc but it's very clumpy so we have a clumpy distribution of the dihydrogen so the molecular plots.

Notes

Summary

20m 26s

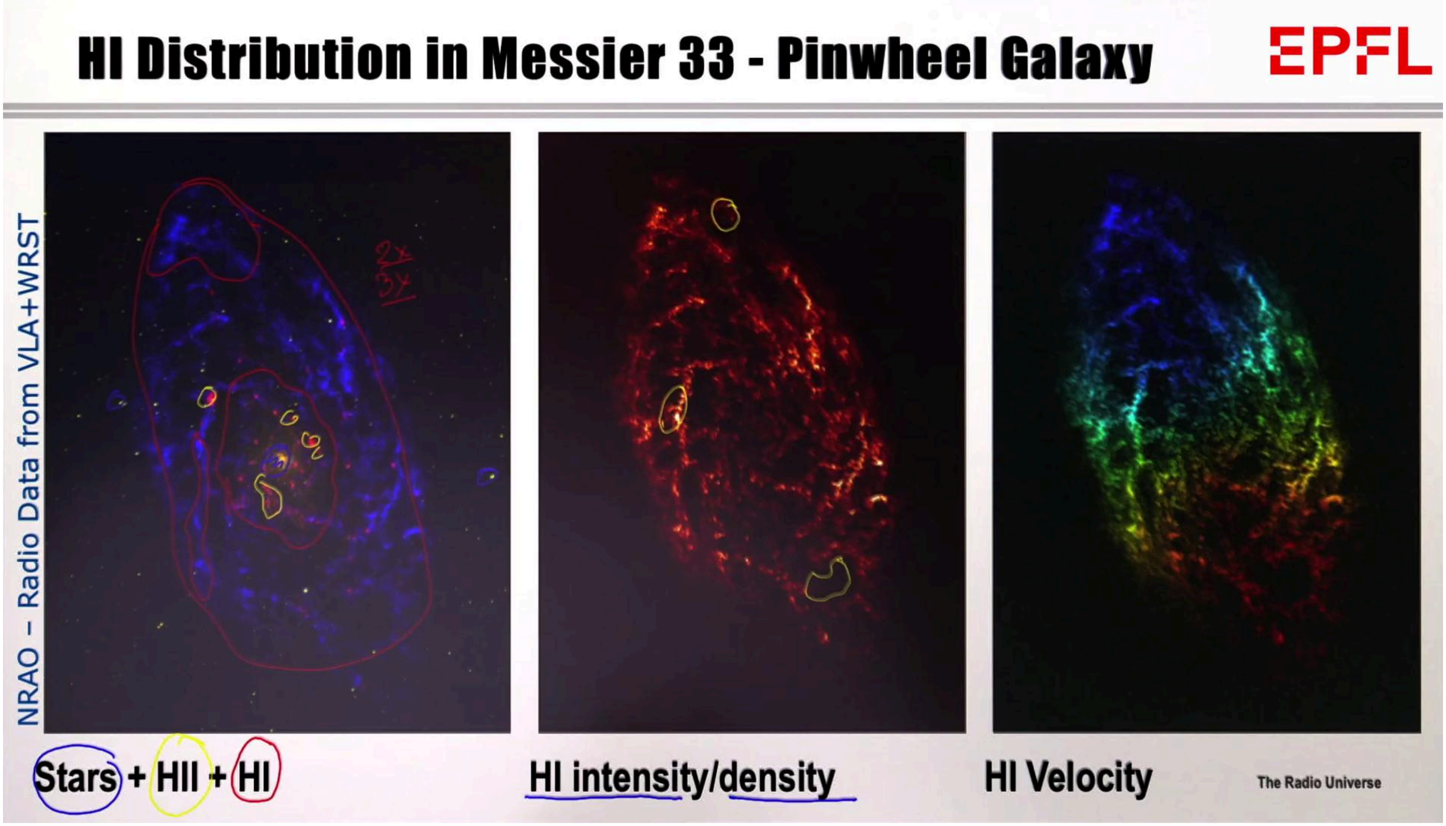


So what about the ‘H1’ gas, the neutral gas? Okay. Neutral gas is ‘H1’, neutral hydrogen. And as we've seen we can measure the neutral hydrogen using the 21 centimeter line. Okay. That's in radio wavelength and so we use radio telescope to observe this 21 centimeter line. And here again we have the star distribution as before. We have the bulge. We have the disc. And here we have the distribution of ‘H1’, okay, measured at radio wavelength. So what we see here there is a depletion. Okay. Compared to the picture of the stars, we have much less hydrogen neutral gas neutral hydrogen gas at the center but we have quite an extension at a large distance. Okay. So typically relatively compared to the star distribution, we have more ‘H1’ gas at larger distance. So can it be useful? Yes, it can be useful to determine the mass of the galaxy.

Notes

Summary

22m 38s

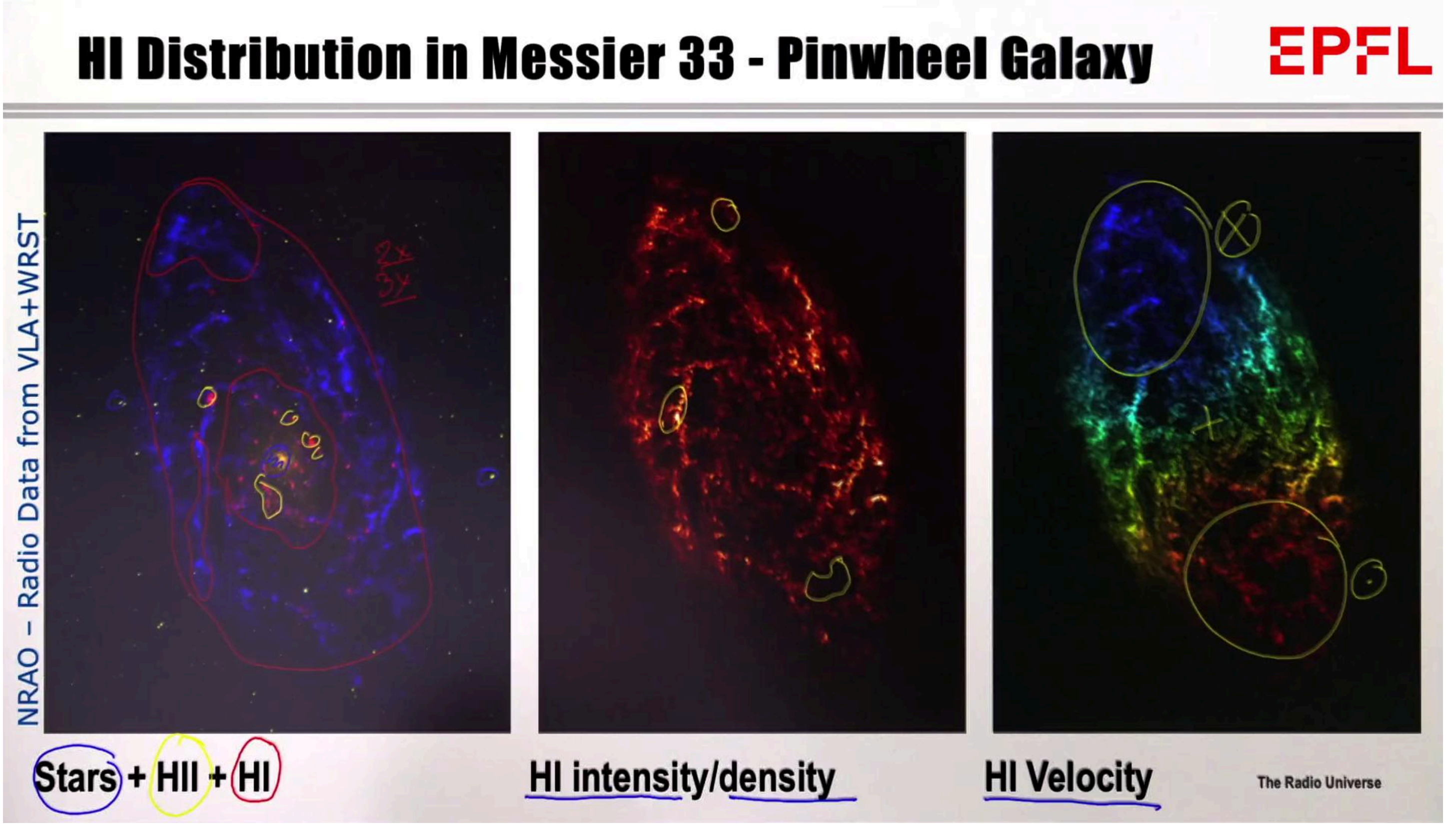


So this is a picture of the 'H1' distribution, neutral hydrogen distribution, in Messier 33, also called the Pinwheel Galaxy. We have three different maps. The first map show different things. It show the stars that are shown in yellow so this thing you see here are the stars over here at the center. Okay. We have this stellar light. What we see in red here, it's the 'H2' gas. Okay. So the ionized gas so that's the H-alpha emission. What we have in blue? Okay. That we see here, for example. Okay. Over here. Okay. All over here. That's the neutral hydrogen and you see that it go much beyond just the region of the stars distribution. So the neutral hydrogen has an extension which is two times to three times larger than the stellar disc. So what we see in the central part is what we call the 'HI' intensity so that's the amount of hydrogen luminosity we get by looking at the intensity of the 21 centimeter line and this is directly linked to the density of hydrogen. So, for example, in this region here we have much more hydrogen than, for example, in that region over here. Okay. So what we see also is that there's some region where there's basically no intensity which mean there's a low density of hydrogen.

Notes

Summary

24m 09s

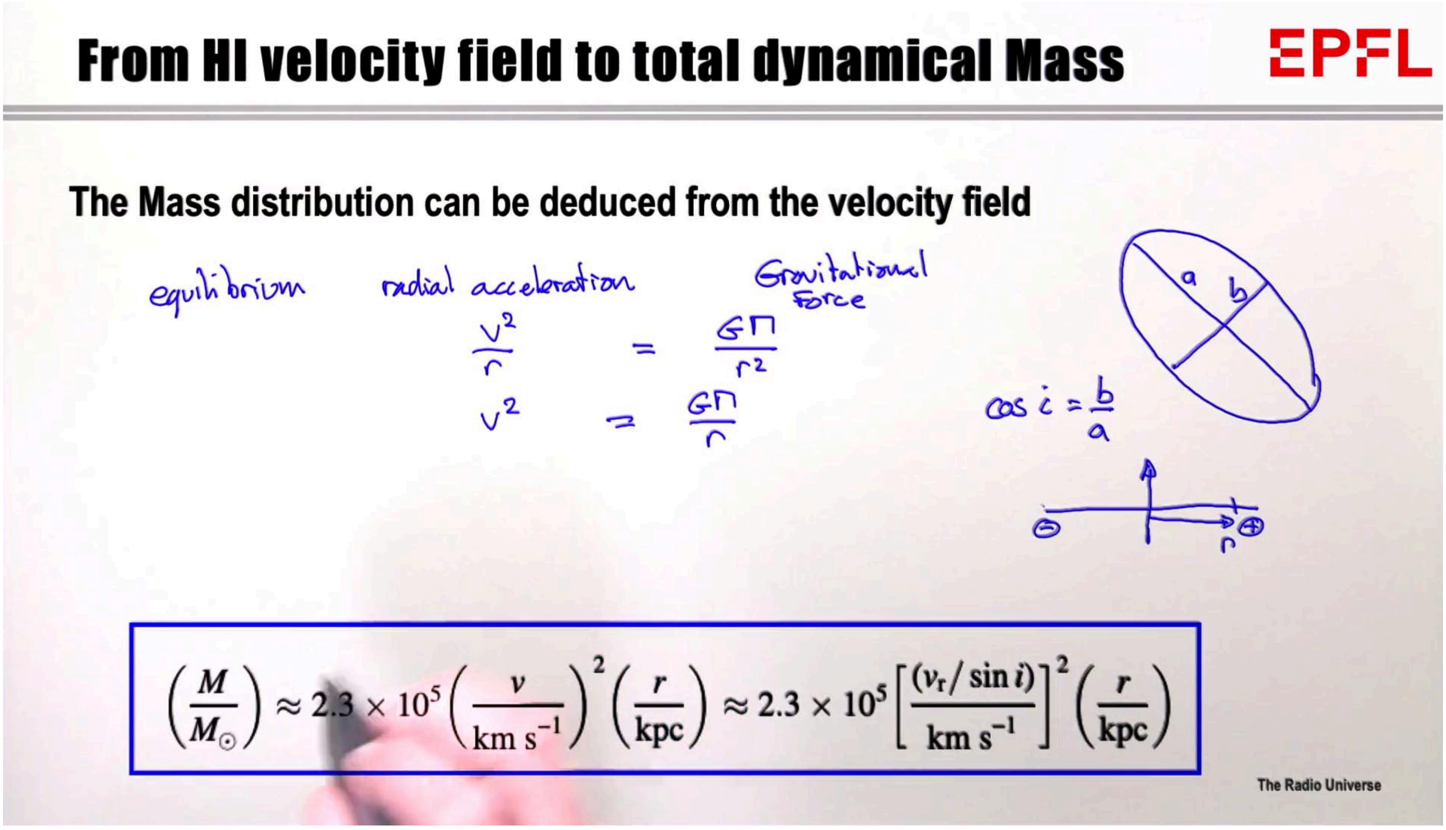


The final map is what we call the 'HI' velocity. It has different colors. So the blue color means the the velocity come toward us and the red color means the velocity go away from us. So relatively we have a positive velocity coming toward us and negative velocity going away from us. So that means this 'HI' gas is rotating around the center of the galaxy.

Notes

Summary

26m 28s

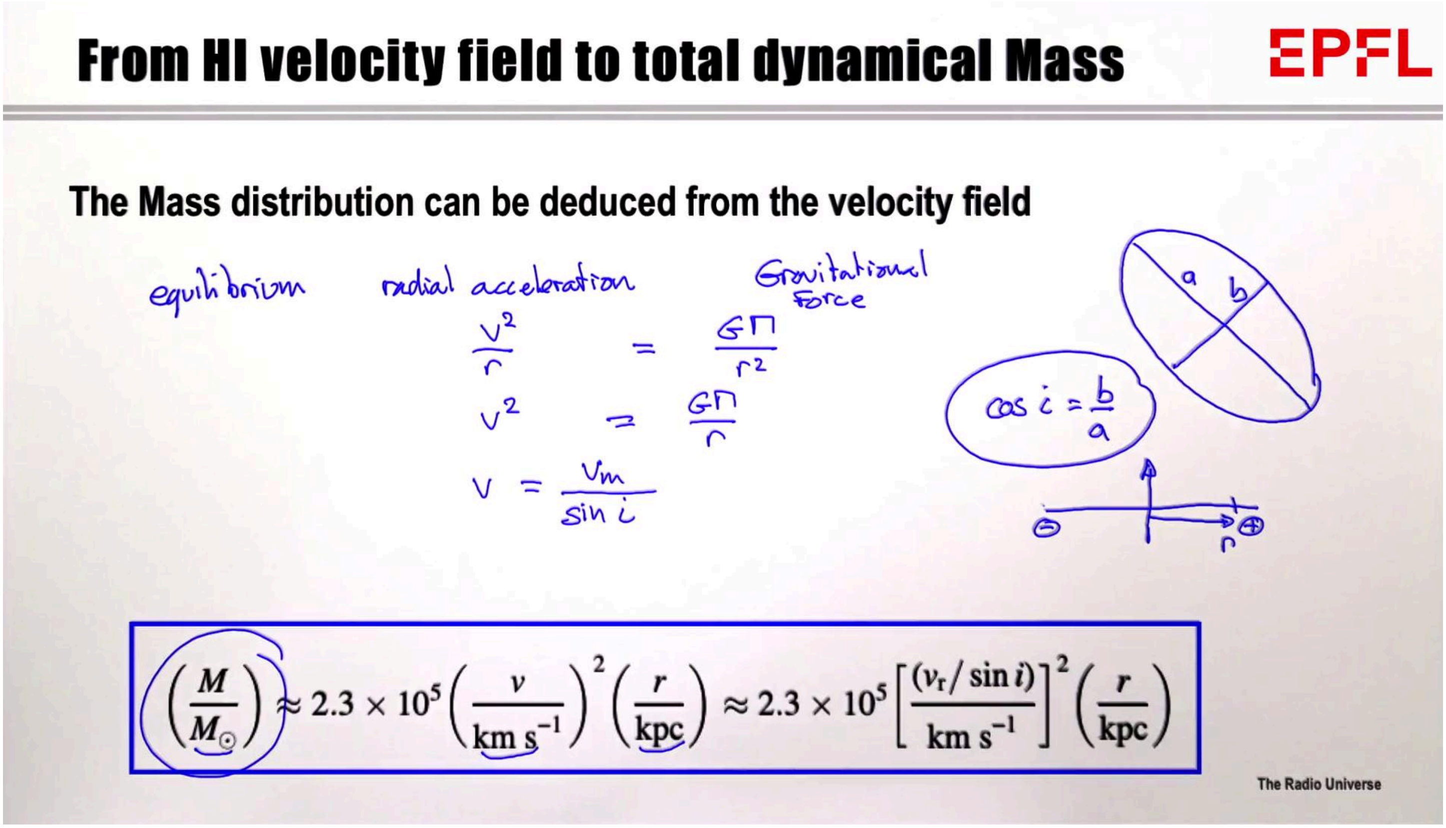


So how do we go from the ‘HI’ velocity field to the dynamical mass of the galaxy? So we have our galaxy here that I was just showing before. It has an elliptical shape so it means we don't see the galaxy face on. It's a bit inclined and the inclination can be calculated. Okay. Let's see this is the major axis 'a', 'b' the minor axis and so the inclination can be defined by cosine 'i' which is 'b' over 'a'. So that's just the geometry of our disc galaxy. What happened here? Okay. So we have a disc galaxy. Okay. That's rotating. Okay. So rotating like that, for example. Okay. This is, say, positive and this is velocity going negative. And so at a distance of radius of 'r', we have an equilibrium between the radio acceleration and the gravitational force. So assuming spherical symmetry and circular orbits the radial acceleration can be written as v-square over 'r' and this is to be balanced by the gravitational force which is 'GM' over r-square. So this can be rewritten. v-square equal 'GM' over 'r'. But okay when we are measuring the Doppler effect by looking at the velocity of our neutral hydrogen gas what we're gonna measure, it's the Doppler effect. It's not exactly the velocity ‘v’.

Notes

Summary

27m 18s

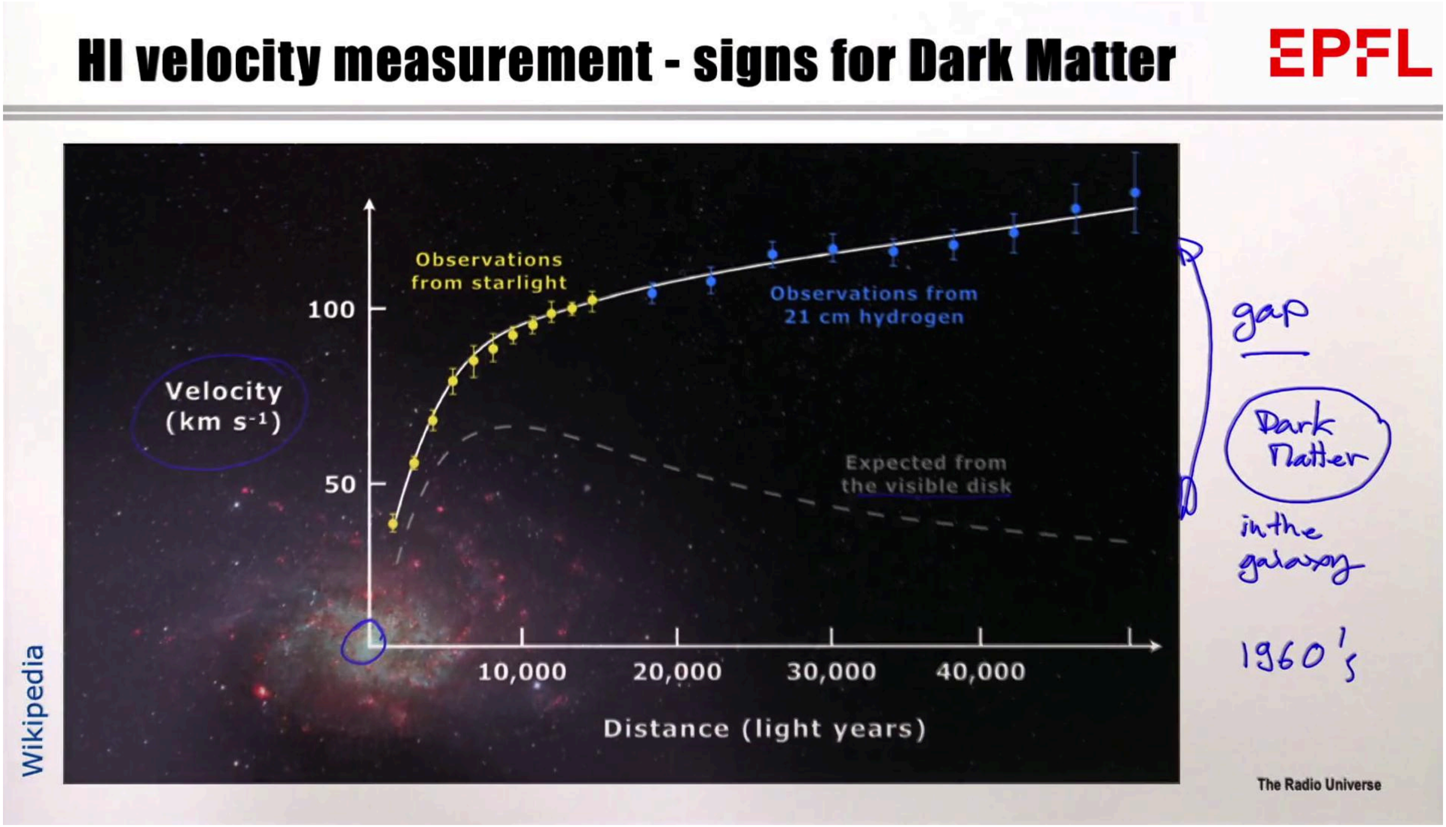


So we have to introduce the Doppler effect measurement see 'vm' because of the inclination of our galaxy. So we have the velocity which is equal to the velocity measured divided by sinus of 'i', the inclination. And remember we had defined cos 'i' to be 'b' divided by 'a'. So if you put that together and you introduce quantity like the mass expressed in solar mass, distance expressed in kilo parsec, velocity expressed in kilometer per second then you can show the total mass will be 2.3 ten to the five v-square times 'r', okay, where 'v' expressed in kilometer per second, 'r' expressed in kilo parsec. And that's give you a total mass expressed in solar mass. So by measuring the Doppler effect you can basically deduce the total mass of your galaxy, total dynamical mass.

Notes

Summary

29m 28s



Here is an example of the 'HI' velocity measurement and what it means in terms of the physics? Right. So again what we have here is the distance to the center so here we have the center of our galaxy and that's the distance expressed in light years. Here we have the measurement of the velocity expressed in kilometer per second and here we have data points which come from two different measurement. In yellow, we have the observation from the stars, the motion of the star rotating around the galaxy and in blue, we have the observation from the 21 centimeter hydrogen line. In dashed is what would be the expectation of the velocity as a function of distance if there was only the visible disc as terms of the mass. But what you see there's a big gap between what is observed and what is predicted if you put only stars in the galaxy. And this gap is basically what we call dark matter. So we need to reproduce the velocity curve as measured from the 21 centimeter line. We need to put dark matter in the galaxy in and around the galaxy to be able to have a model that match the observations. This type of measurement were first done in the 1960s. Okay. And they were one of the strongest confirmation at that time of the existence of the dark matter.

Notes

Summary

30m 43s

Magellanic stream around the Milky Way Galaxy

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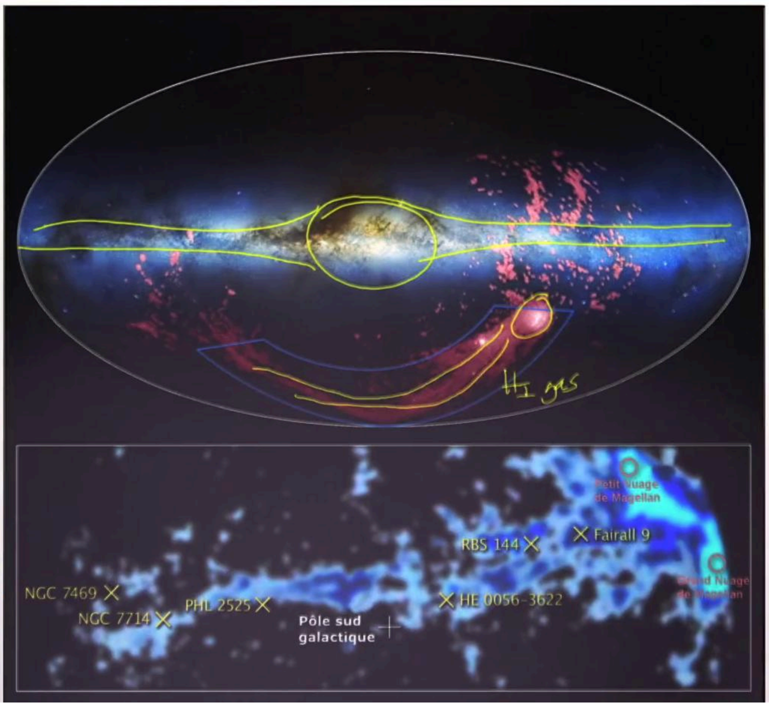

Wikipedia

Magellanic Stream

Discovered as a Neutral Hydrogen (HI) gas feature near the Magellanic Clouds by Wannier & Wrixon in 1972.

Trail of HI gas as the Magellanic Clouds are orbiting around the Milky Way.

The Radio Universe

Another use of the 'HI' mapping around the galaxy is to map stuff that are going around our galaxy. In particular, here in this picture we see what we call the magellanic stream. Here we have our galaxy with the bulge at the center, the disc. Okay. We see some dust in black and what we see over here is the magellanic cloud. And what we see behind the magellanic cloud are trail of 'HI' gas. So we can understand this picture by having 'HI' being stripped off by the motion of the magellanic cloud going around our galaxy. This was first detected in 1972 and as I say, this is a trail of 'HI' gas and we believe that it's orbiting around the Milky Way. Here we have some detail of this stream of gas which has different intensity with density, an intensity and density that is decreasing as a function of the distance of the magellanic clouds.

Notes

Summary

32m 46s

HI in Galaxy Group M81

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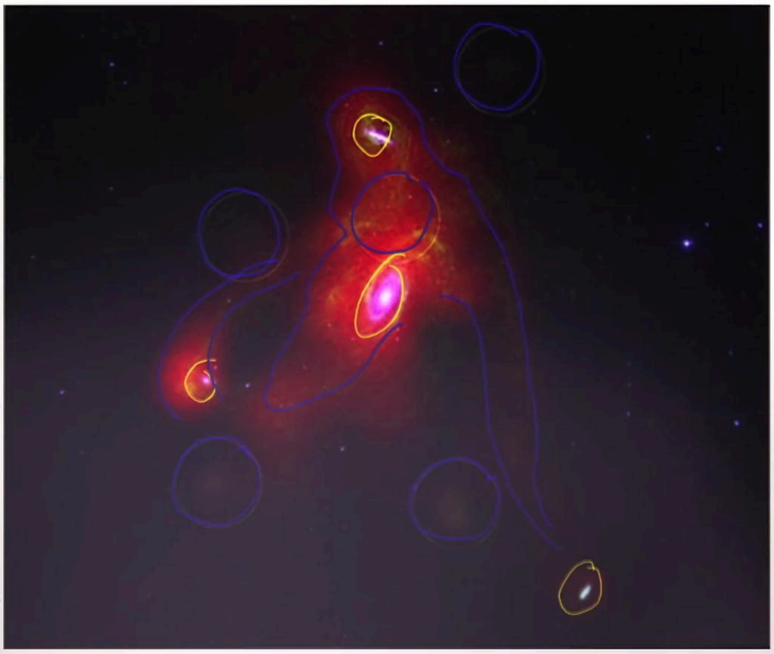

Chynoweth et al., NRAO/AUI/NSF, DSS.

M81 group of galaxies

11.8 million light-years away

At least 3 galaxies are interacting gravitationally with each other, as shown clearly by the **gas streaming** among them.

The Radio Universe

Here is the last example of the lecture is the ‘HI’ distribution in the galaxy group M81. So the galaxy group is likely made of at least three galaxy and probably four galaxy that we see and maybe here which is connected by stream of ‘HI’ gas that we see in red all over here and possibly also going over there. We do also see some ‘HI’ cloud that are not really linked to any bright galaxy at least. That are quite diffuse and maybe sometime early to be seen but that can be identified by looking clearly at the picture. So we have this gas streaming between the different galaxies, again you have these gas stream here, that are connecting the different galaxy and are showing possibly how this system this galaxy group is evolving with time. This is not too far from us. It's only 11.8 million years away and there's many of the system that you could study in the Universe.

Notes

Summary

34m 15s

The Universe is fascinating and full of hydrogen. In particular, mapping the neutral hydrogen is a good way to learn more about galaxies in our Universe. The spin flip transition of hydrogen seen at radio wavelengths is a unique way to map the neutral hydrogen in and around galaxies. We can learn about the distribution of dark matter as well as the formation history of galaxies. In the future, we will be able to map the hydrogen of billions of galaxy in the Universe. Stay tuned to discover more.

Notes

Summary

35m 37s