ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Spiral galaxy NGC 2683

Image: NASA/ESA, Hubble heritage

Galaxies

Introduction to Astrophysics; Chapter 6.1

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Video

EPFL

In this lecture we will have a look at larger scales and explore the world of galaxies. Here is one of the most beautiful illustration of the diversity of galaxies - the Hubble Ultra Deep Field. that we already saw before. It reveals all sorts of galaxies up to faint (large) magnitudes so it shows very distant galaxies that emit little light. It is possible to see galaxies up to a magnitude of 29. The image consists of about 10 000 galaxies within an area of about one hundredth of the surface of the Full Moon. Each of those galaxies contains from about 100 millions to 100 billions of stars. We live in one of some 80 billions of galaxies that populate the Universe: the Milky Way. In this video we will look at the various types of galaxies, how to study them, and how to understand their formation process.

Notes

Summary

0m 06s

Hubble Sequence

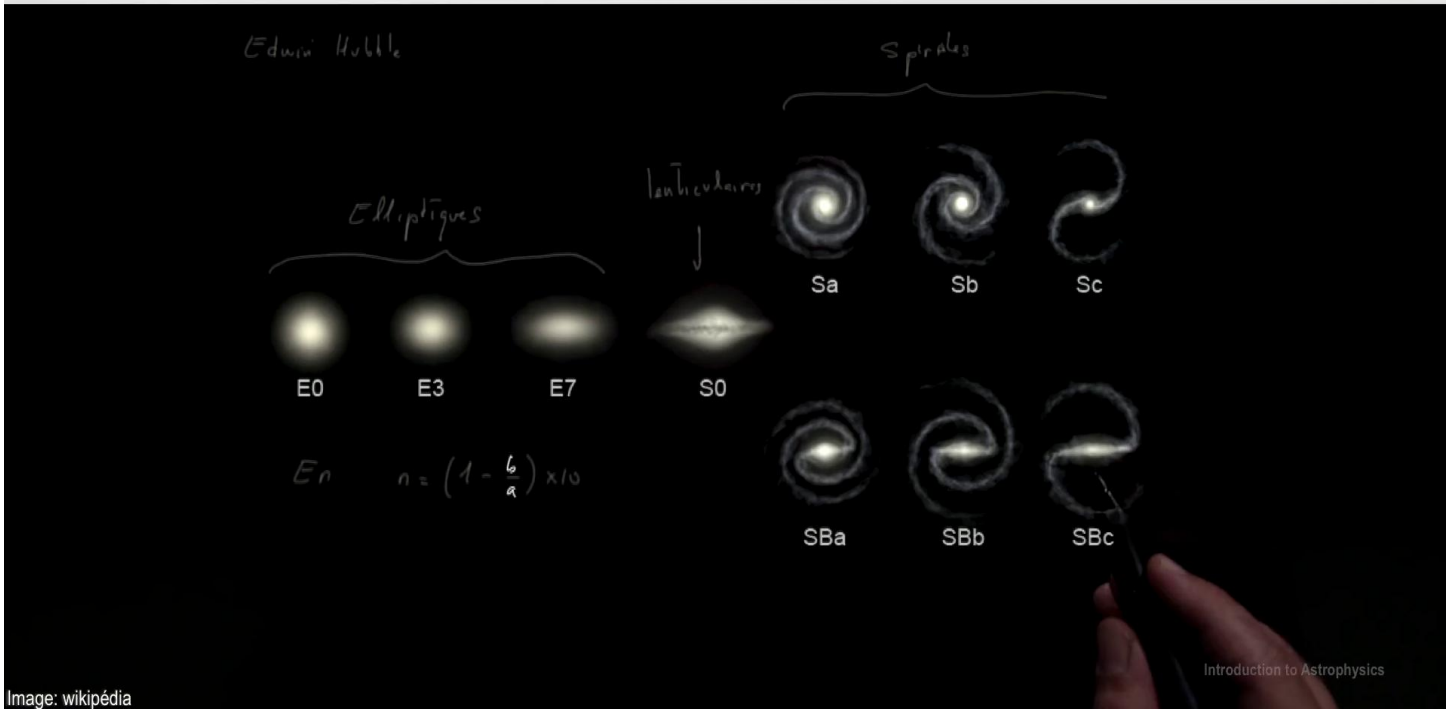

Image: wikipédia

Let's see how galaxies are characterised through the Hubble sequence. This is a sequence proposed by the American astronomer Edwin Hubble at the beginning of the 20th century. The Hubble Space Telescope and the Hubble law were named after the same astronomer. So Hubble established the evolutionary sequence which in fact, as it will be shown later, is not evolutionary. This is just a morphological sequence describing the galaxies. There are essentially two types of galaxies: elliptical and spiral galaxies. In between, there is an intermediate type - the lenticular galaxies. What is going on in this sequence? The elliptical galaxies, as the name indicates, have an elliptical form and they generally consist of old stars with random orbits around a common gravity centre. "E" stands for elliptical, then there are 7 possibilities for the ellipticity. The type of an elliptical galaxy can be written as E with an index n that is equal to (1 - A/B) * 10, where A/B is the ratio of the semi-major axis and the semi-minor axis. The ellipticity 0 indicates a circular galaxy while 7 inclides the most elliptical galaxies. The spiral galaxies form large spiral arms. Those galaxies are seen face-on.

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0m 56s

Hubble Sequence

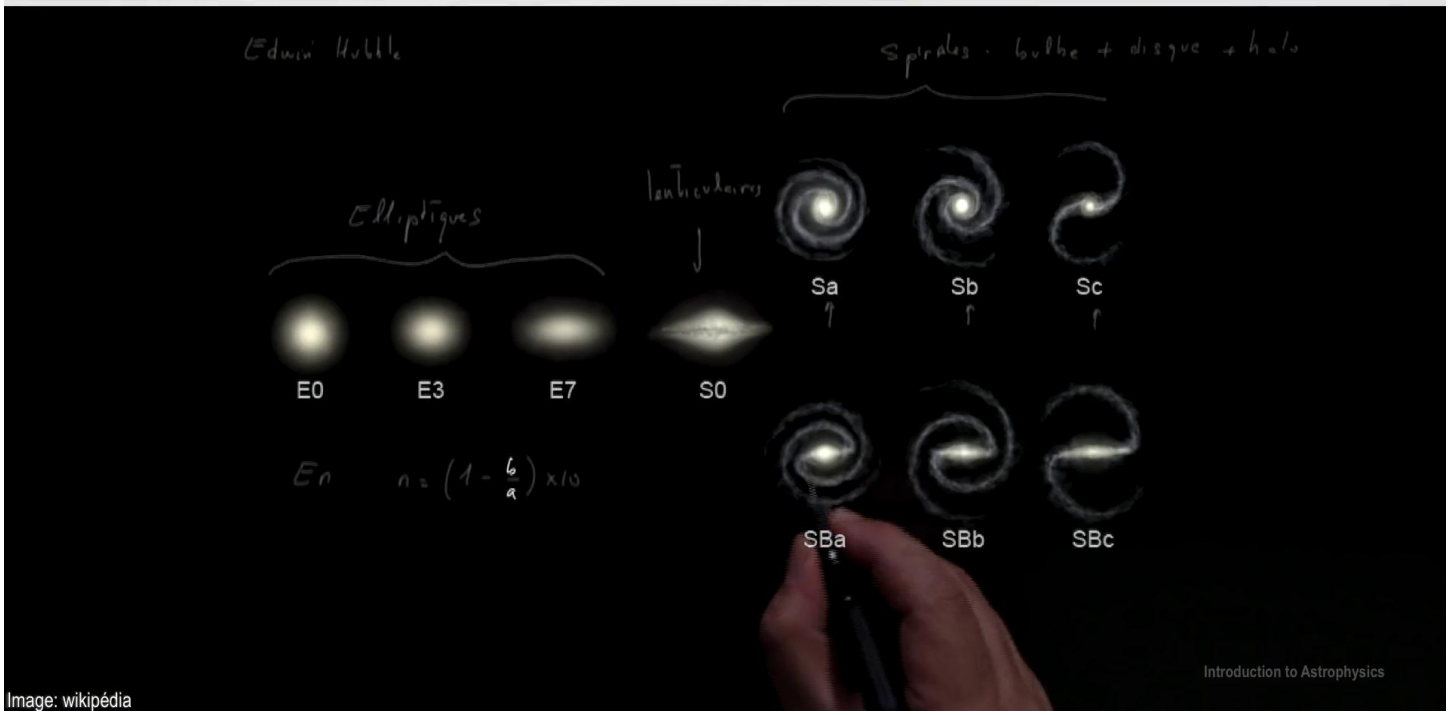

Image: wikipédia

Seen edge-on they would show a disk component. Some examples will be shown in a moment. There are two groups of spiral galaxies. In general, S stands for spiral, then the indices a, b and c depend on the importance of the bulge compared to the spiral arms of the galaxy and the opening of the spiral structure. Going form a to c there are less spiral arms and they are less wrapped around each other. Spiral galaxies, as was said before, have a bulge that can be seen in the centre. They also have a disk. It is in the flat disk, seen face on here, that the spiral arms form. There is also a dark matter halo. The elliptical galaxies as well have a halo which by definition cannot be seen as it is formed of dark matter. The halo will be discussed in the next videos. The lenticular galaxies were also mentioned. One can say that those are elliptical galaxies but possesing a disk through which one can even see dust. Those galaxies can be compared to the spiral galaxies with a large bulge that has the size of an elliptical galaxy. As it was said before, the Hubble sequence is not evolutionary. Hubble created this sequence assuming that galaxies form as elliptical galaxies, then they evolve progressively toward galaxies with spiral arms either wrapped around each other or wrapped around a bar.

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2m 27s

Hubble Sequence

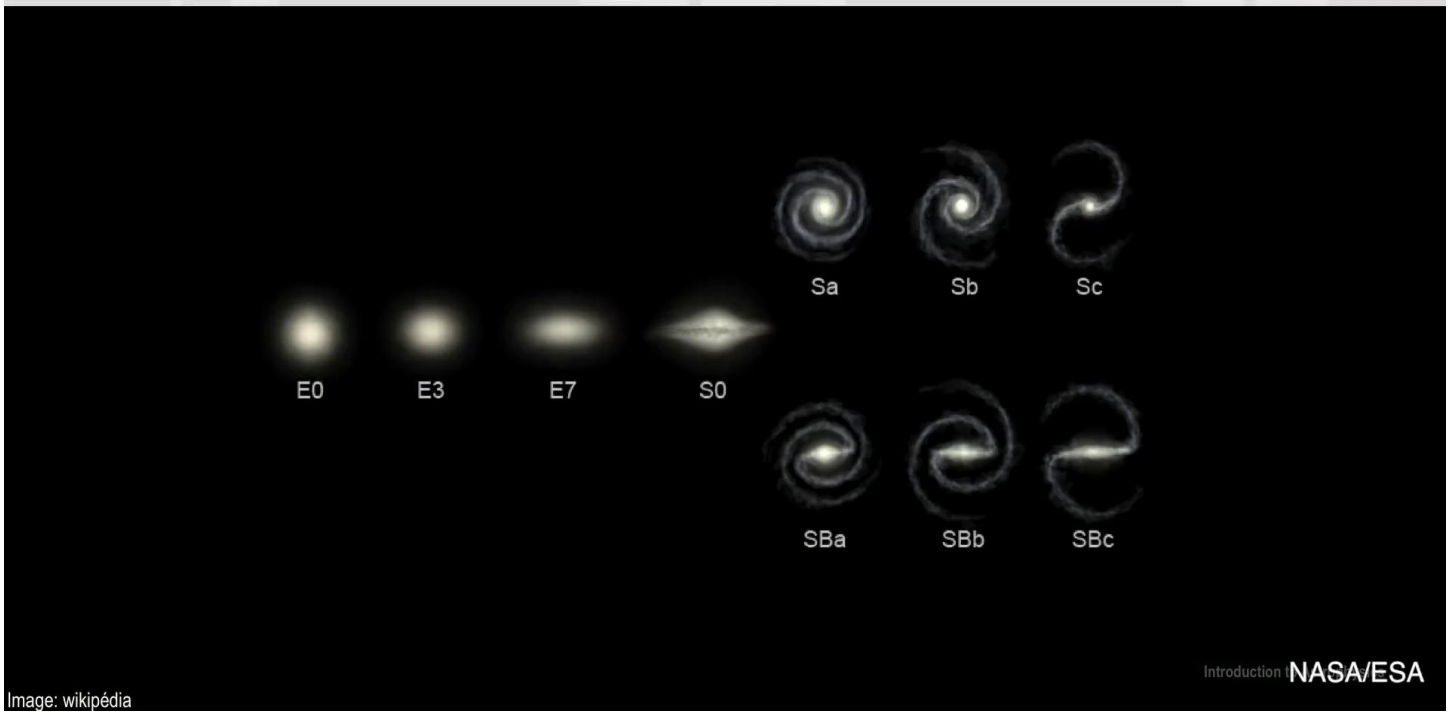

Image: wikipédia

Here we show barred spiral galaxies, they are named using a S for spiral, B for barred and then the index a, b or c which tells us how the spiral arms are wrapped around the bulge and the bar in this case. Back to the evolutionary sequence which is not evolutionary as the elliptical galaxies do not evolve into spiral galaxies, as it was thought by Hubble. This is a mere morphological sequence. Be careful here, the Hubble sequence is a morphological sequence.

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4m 17s

Here are some examples of various types of galaxies. Starting with an elliptical galaxy that is quite featureless surrounded by a group of other galaxies. This particular galaxy lies at the centre of a galaxy cluster in which the galaxies orbit about a centre of mass. Another example, this time a spiral galaxy, Messier 104 that is a magnificent example of a spiral galaxy Sa with a prominent bulge that extends almost over the entire galaxy, a disk is seen inclined in the line of sight and is materialized by the line of dust across the galaxy. As it was shown in the previous videos, dust absorbs the background light. This is the reason why one can see the stellar light that is absorbed by the dust in the galactic disk.

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4m 59s

Another fascinating spiral galaxy, Messier 101, seen face on, with large spiral arms expanding from the centre to the outer parts of the galaxy. One can clearly see the difference with Messier 104, the bulge that this time is much smaller as Messier 101 is a Sb type galaxy rather than Sa. Finally, a barred spiral galaxy NGC 1300, and as its name indicates it shows a bar that is placed in the plane of the galactic disk. Like the disks, bulges consists of stars, gas and dust.

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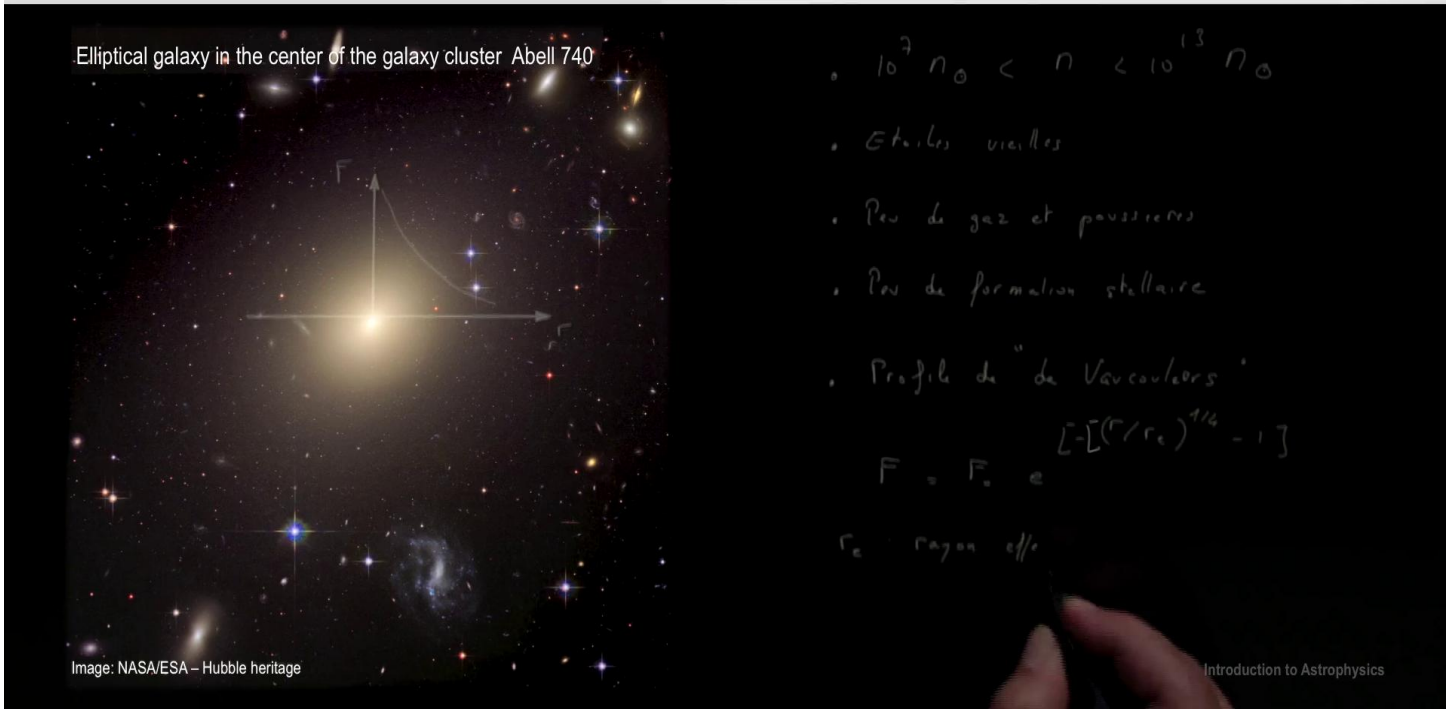
5m 51s

Elliptical Galaxies



Let's look in detail at the various types of galaxies. Starting with the elliptical galaxies. One can be seen here, in the centre of a galaxy cluster. Quite often elliptical galaxies lie in the centre of a cluster, but not always. What is the mass range of the elliptical galaxies? Typically 10^7 solar masses for less massive, up to 10^13 solar masses for the most massive galaxies. The most massive elliptical galaxies often, but not always, lie in the centre of a galaxy cluster. They consist of old stellar populations, i.e of the age of about billions of years. There is little or no gas or dust, so the interstellar medium is quite poor. There is a little star formation, stars are old with random orbits around the centre of mass. Taking the cross section of a galaxy in such a way, one can define the light profile. y axis represents the flux F, x axis the radius of a galaxy. This is a typical light profile of an elliptical galaxy - de Vaucouleurs profile, after the astronomer that defined this profile. The flux as a function of radius is equal to a normalisation constant times exp - [(r / re)^1/4 -1]. This is a typical light profile of elliptical galaxies. re is the effective radius, i.e.

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6m 27s

Spiral Galaxies

the radius that contains half the total light of a galaxy. Let's take a look at the spiral galaxies. In spiral galaxies there is a disk and extending spiral arms. Here we have a Sab galaxy, a type intermediate between a and b, the galaxy Messier 101 seen face on. The mass range is different for spiral galaxies. The least massive spiral galaxies are more massive than the least massive elliptical galaxies. However, the most massive spiral galaxies are less massive than the most massive elliptical galaxies, 10^12 solar masses instead of 10^13 solar masses as it was for elliptical galaxies. The sizes are also valid for the elliptical galaxies, even if the elliptical galaxies are in general a little bit larger, i.e. about 40 kiloparsec in diameter. This limit is not quite precise as around the bulge and the spiral arms there is a dark matter halo that is not visible but the size of which can be estimated indirectly. In spiral galaxies there is a lot of gas and dust from which stars form. There are young stellar populations and a lot of star formation. In fact, there are two components of the stellar populations. The bulge consists of older, less massive stars, the reddish colour implies that the peak in the black body distribution is in the red part.

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8m 10s

Les galaxies spirales

Galaxie spirale Sab M101 (vue de face)

Image: NASA/ESA – Hubble Heritage

Galaxie spirale NGC 4565 (vue par la tranche)

Image: ESO

Introduction to Astrophysics

The spiral arms consist of young, more massive stars that radiate in the blue part of the spectrum. What is the light profile of spiral galaxies? Let's take the cross section as before and look at the luminosity profile starting from the centre. There would be two components. The disk component curve, so, the flux as a function of radius, is an exponential curve F = F0 e^(-R/h), where h is the characteristic height of the disk. This is the luminosity profile of the galactic disk. On this curve there will be superimposed the second component: the bulge. Its profile is obviously the de Vaucouleurs profile, the same that characterised elliptical galaxies as it was seen before. This is another spiral galaxy, this time seen edge on. If one takes a cross section through the disk, with the flux on the y axis and the radius on the x axis, one will find the curve of the same type, an exponential curve with h as a caracteristic height. Taking the cross section at this point, the resulting curve will be the sum of the de Vaucouleurs profile that is characteristic for a bulge or an elliptical galaxy, and a disk component. In this case, the measurements are affected by dust in the galactic plane. If our measurements were not affected by dust, the luminosity profile of a spiral galaxy taken either perpendicularly or along the disk would be an exponential function.

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9m 46s

Stellar Populations in Galaxies

What are the means that can be used to study those galaxies in details? There are two ways: through spectra or imaging. Starting with imaging. This is the bulge of a spiral galaxy Messier 83, Sab galaxy. This bulge is caracterised by the de Vaucouleurs luminosity profile. Then, there is also a disk component with a fraction of dust that is seen in absorption. This is a false colour image taken with three different filters. The first one is the H-alpha filter that shows the gas ionized by massive hot stars that are being formed. If one is interested in the zones of the star formation one should look at the red areas whose spectrum can be presented on a diagram of the flux as a function of the wavelength. Typical spectrum of those areas is the black body spectrum with the peak in the blue part as young, hot, massive stars emit most of the radiation in the blue; then, here we would observe the H-α emission line. This image was taken using three filters: blue, intermediate colour and the H-α filter that enables us to see these zones that are of the size of the Strömgren sphere which was presented in the lecture on the interstellar medium. It is interesting to take a closer look at the Hα emission of the gas ionized by young stars.

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11m 45s

Stellar Populations in Galaxies

Previously, in the lecture concerning the colour-magnitude diagram it was shown that the stellar populations can be characterised by referring to the colour-magnitude diagram. This can be done in the different parts of a galaxy, for example in this area with some young stars. Such a colour-magnitude diagram can be created using very high resolution images taken by the Hubble telescope, for example. One places the flux and colour of all the stars from a chosen area on the colour-magnitude diagram. Then, the main sequence might be visible, maybe some other structure, but in any case there is a possibility of characterising the stellar populations that can be found in the marked area. Proceeding in the same way for different regions in the galaxy, it may be possible to trace back the history of galaxy formation, in any case the history of evolution of the stellar populations in the galaxy. All this thanks to some simple measurements of the flux and colour of stars in various regions of the galaxy. If the image is taken at lower resolution and the stars cannot be resolved in those small areas, it is no more possible to use this method.

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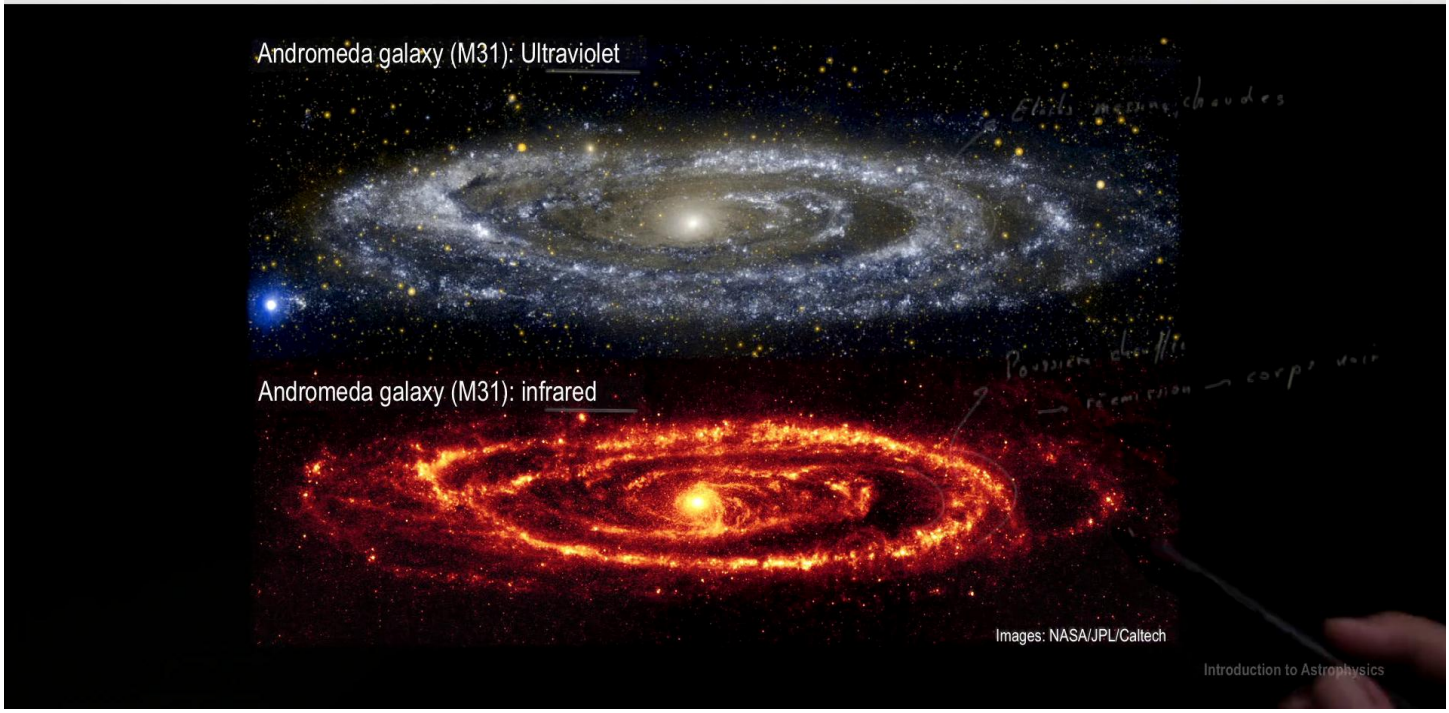
13m 30s

Multi-wavelength Studies



In the previous image, a spiral galaxy taken in three filters in the optical domain was shown. Obviously, the observations can be made at much wider range of wavelengths. This is Messier 31, the Andromeda galaxy in the ultraviolet and in the infrared light. One can see the spiral arms and a part of the bulge but it is more interesting to take a look at the spiral arms that are well marked by a great deal of bright points. In the ultraviolet we can see hot massive stars that ionize the surrounding gas and so a lot of points can be seen in the Hα emission, as it was shown before. Looking at the far infrared image, there is some dust and gas concentrated in the galactic disk of the spiral galaxy. Dust absorbs photons coming from hot stars and then emits a modified black body spectrum which peaks in the far infrared. One can easily notice that observing in the ultraviolet or infrared the same galaxy can give informations about various components. In the former case one observes young hot massive stars in the process of formation, in the latter case one can directly see the dust. Obviously, both images are alike as the stars heat the dust - physically both components are in the same place on the image.

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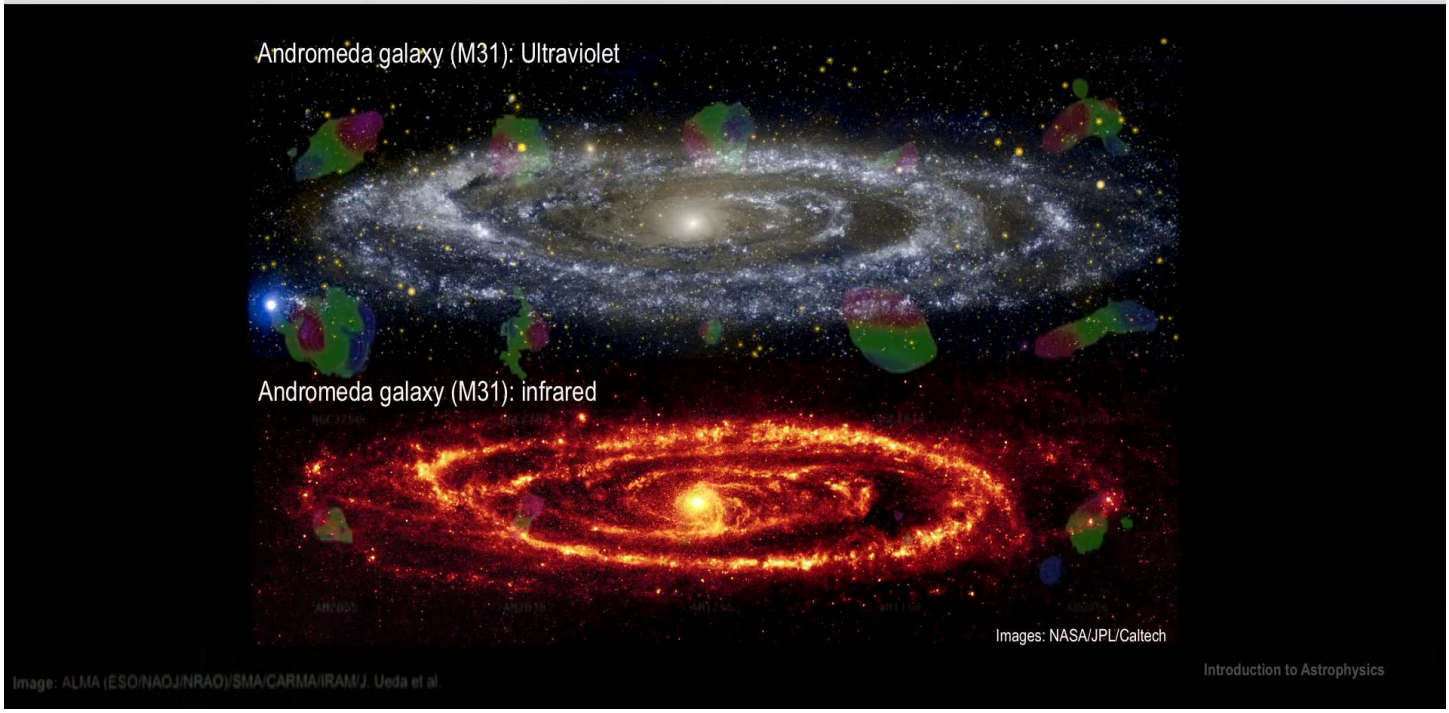
14m 41s

Multi-wavelength Studies



However, the physical processes that are observed are not the same. A multiwavelength study of celestial bodies, in particular the galaxies, enables us to characterise the stellar populations, the gas contents, and to learn how those two elements are linked.

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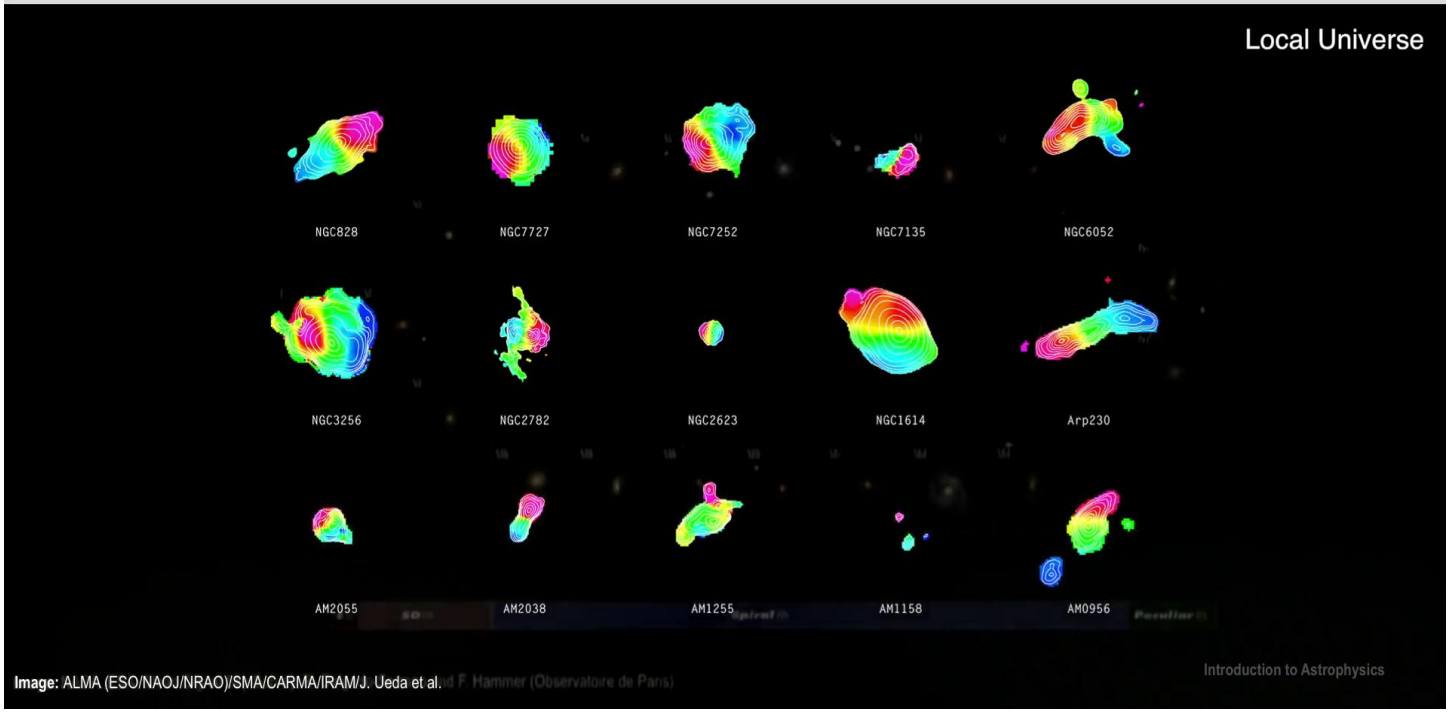
16m 36s

Rotation of Galaxies



Until now, we only studied the images, but there is also another important tool that can be used - the spectra. Those can be used to measure the Doppler effect. What can be seen here are the Dopper maps of some galaxies. Colours indicate a radial velocity of the stars as a function of the position in the galaxy. The red colour indicates the velocity that is directed away from us, the blue colour indicates the velocity directed toward us. Idem for this galaxy. What can be measured is the velocity of the galaxy as a function of the radius which in turn is used for the estimation of the galaxy's mass. This subject will be treated later. We can write the acceleration of the points along the rotation axis of a galaxy as a function of mass. We have $G*M(r)/r^2$, that is the gravitational acceleration is equal to v^2/r. This implies that v equals the square root of $GM(r)/r$. One can see that if the velocity at each point of the radius along the galaxy is measured it is possible to calculate the mass within this radius. Once more the Doppler effect turns out to be extremely useful, this time it gives us the estimation of the mass of galaxies, the mass of luminous matter as well as the mass of dark matter.

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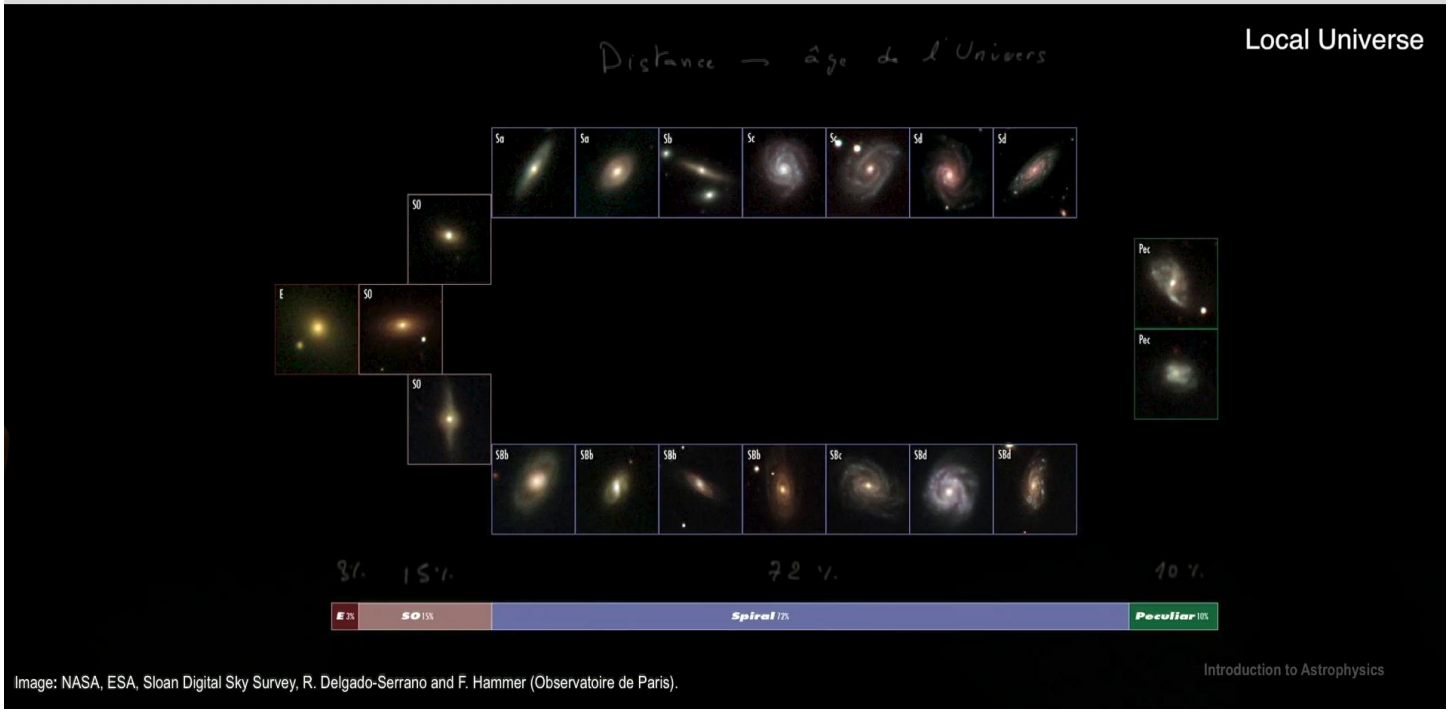
16m 54s

Morphological Type vs. Mass and Distance



We have discussed various diagnostics during this lecture: imaging, spectra and the morphological classification. This morphological classification is not just to classify the objects it is very useful to astrophysicists. The morphological classification changes with the distance. The distance is also the age of the Universe. The Universe was created during the Big Bang, it is expanding. Galaxies further away from us are closer to the Big Bang epoch, they are younger than the galaxies close to our own. If we establish a morphological classification as a function of the distance, in the same time we establish a morphological classification as a function of the age of the Universe. Observing at various distances, we observe different epochs of the Universe. Here we have a morphological classification giving the percentage of each type of galaxy in the local universe: 3% are elliptical galaxies, 15% are lenticular galaxies, 72% - spiral galaxies, the majority are spiral galaxies, and 10% corresponding to galaxies that we are not able to classify.

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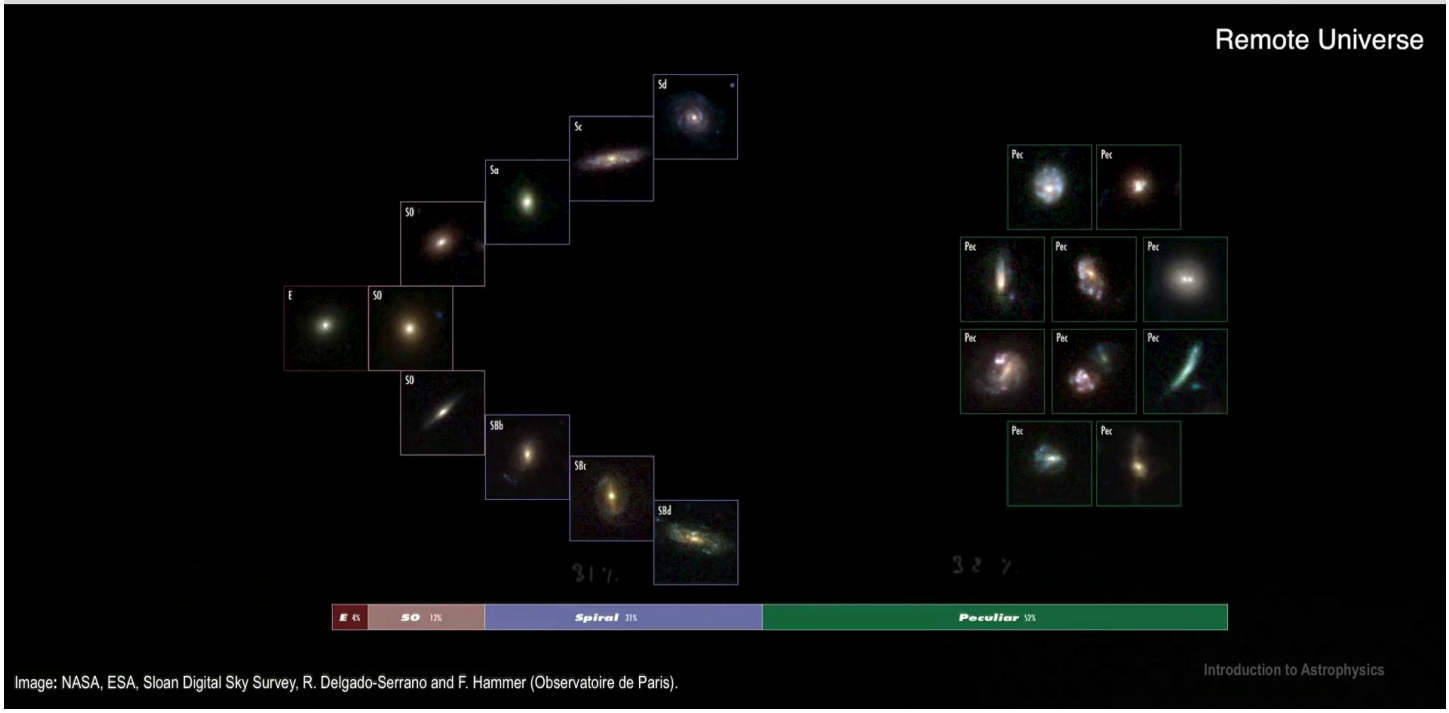
18m 35s

Morphological Type vs. Mass and Distance



This is one of the observational facts, another one tells us that if the same observations are obtained for galaxies further away the results are not the same. Previously there was 72% of the spiral galaxies now the spiral galaxies represent only 31%. The galaxies that are not classified represent 32% of the observed galaxies. These are the galaxies that are at a different evolutionary stage than in here. Those morphological classifications can be established as a function of distance regardless the theoretical tools at our disposal used to understand the observations. It is essential that those theoretical tools relate at the same time the morphological classification as a function of the distance, masses determined using the measures of the Doppler effect and the rotational velocities of galaxies. They also have to relate to the study of the stellar populations that uses for example the colour-magnitude diagrams of the resolved stars from various regions in galaxies also as a function of the distance.

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19m 57s

Currently, the studies of the formation and evolutions of galaxies make great progress from the theoretical as well as observational point of view. We have access to bigger and bigger telescopes that enable us to study galaxies which are further and further away, as the telescopes gather more and more light. It is possible to study galaxies with weaker and weaker intrinsic flux. And it is not all. In addition to large telescopes there are smaller ones that specialise in detailed cartography of large fraction of the Universe, maybe even the whole Universe. It is possible to study large samples of galaxies and with the obtained statistical properties, from the observational point of view, and with progress in the data processing and on the theoretical side as well, one can create simulations of entire "chunks" of Universe containing billions of particles that are subject to gravitational forces, pressure and even shock waves created by supernovae explosions in galaxies. It is now possible to confront theory and observations and to draw some conclusions about the validity of theoretical models.

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21m 01s