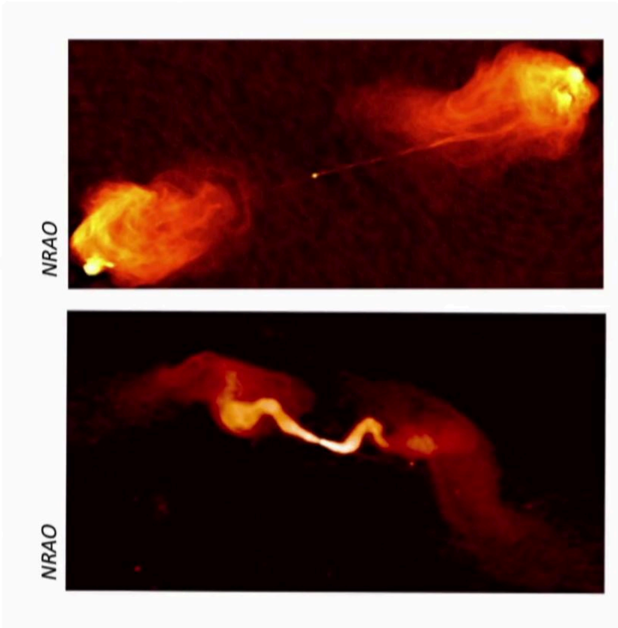
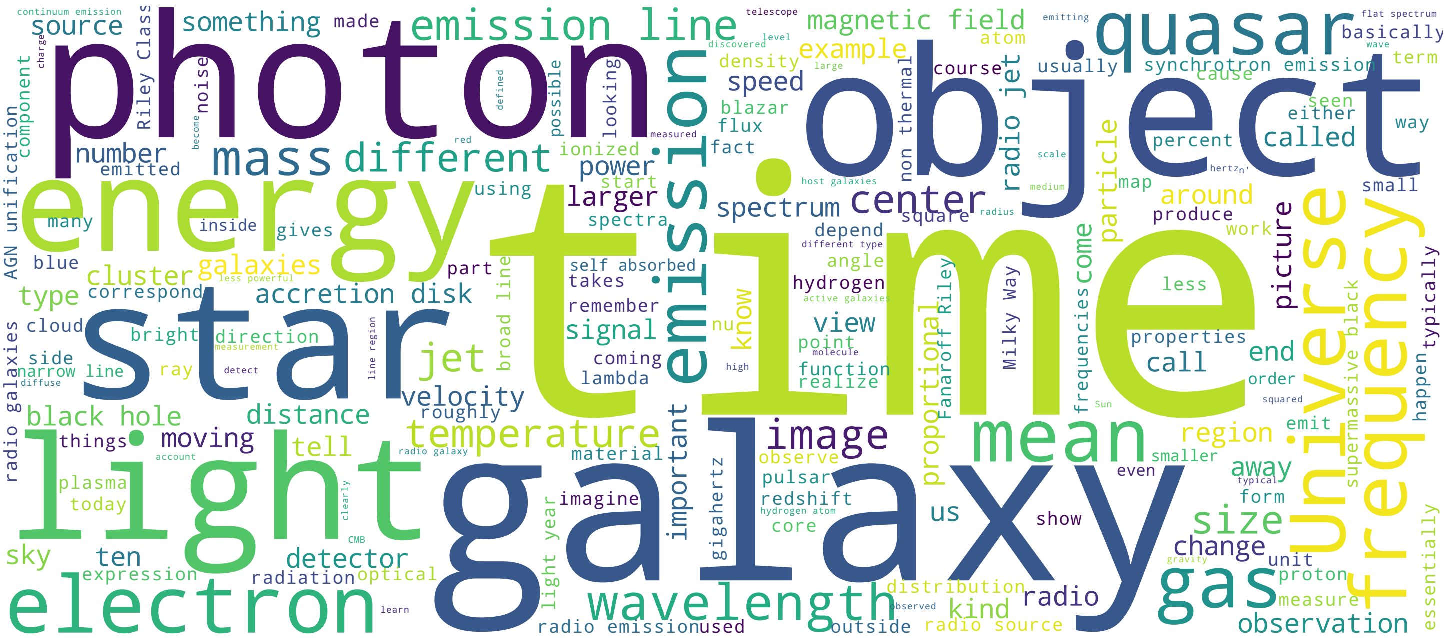
Galactic Nuclei

Kim McAlpine

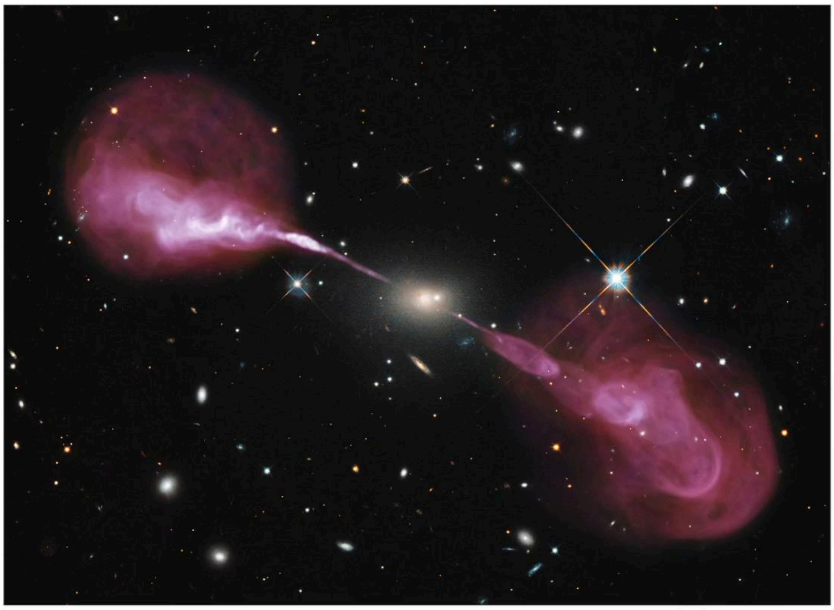




Search MOOC

Video

Introduction



Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

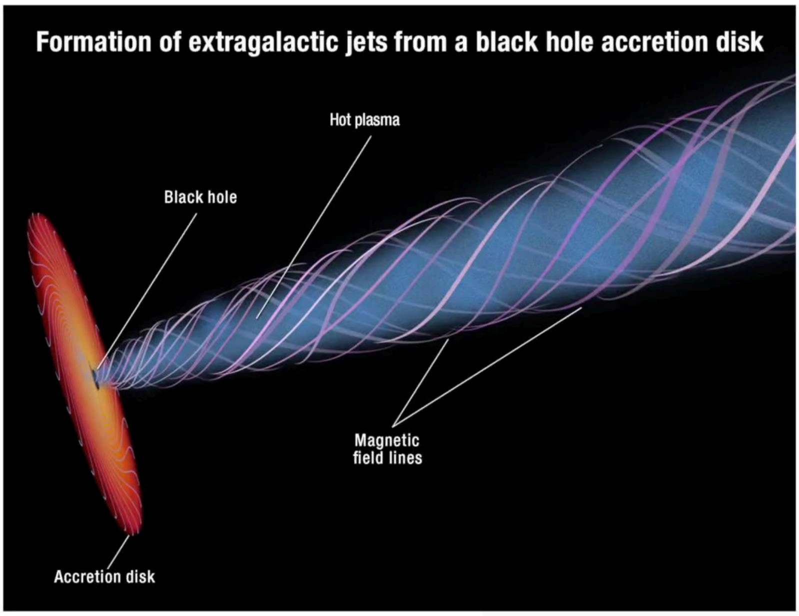
Welcome to today's lecture where we'll be continuing our theme of learning about different astronomical objects which produce radio emission. Today we're going to learn about Active Galactic Nuclei which are the brightest objects in the radio sky. Most of us are already familiar with the sky at optical wavelengths. You probably already know that if you look outside the Milky Way with a large optical telescope, what you'll see are other galaxies, similar to our own but very far away from us. Behind me are some images of typical galaxies. They come in a variety of types but they are all just a collection of stars bound together by gravity. The light we see at optical wavelength is, therefore, mostly produced by stars. It may be somewhat surprising then to realize that if you were to point a radio telescope at the same patch of sky, it would be very difficult to see any of these types of objects. Instead, the things that would immediately jump out at you would be very different and much more exotic than just ordinary stars. Most bright radio sources like this one are made up of twin high-speed jets that shoot out from a central galaxy.

Notes

Summary

0m 05s

Introduction



Credit: NASA, ESA, and A. Feild (STScl)

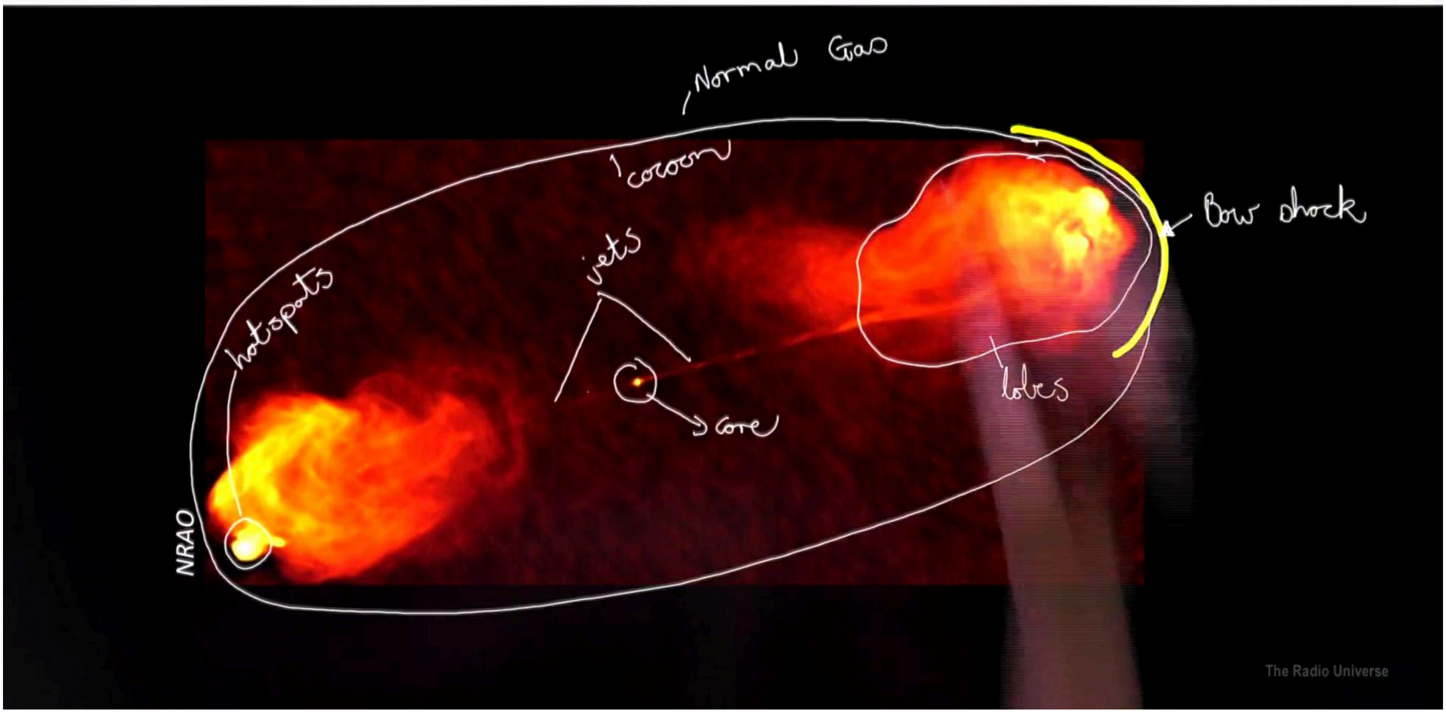
In the image behind me, the galaxy, the host galaxy is shown in white while the radio jets are colored purple. These jets light up in the radio because they are made of plasma which is moving at nearly the speed of light. The relativistic free electrons in this plasma are interacting with magnetic fields inside the jets producing synchrotron emission. These radio jets are the largest objects in the Universe. They can be up to a million light years in size and very much larger than the galaxy they originate from. They can also be incredibly bright and the brightest ones can be detected up to redshifts as high as seven or eight, up to the end of the Epoch of Reionization and the edge of the observable Universe. They can also have very large angular sizes on the sky. Centaurus A, for example, is nearly 200 times brighter than the full moon in the night sky. As we will learn in today's lecture, the jets are propelled by an actively growing supermassive black hole. As the black hole grows, material falling into it compresses down into a very thin rotating disk. This rotating disk creates a kind of funnel effect which then propels the jets outwards.

Notes

Summary

1m 30s

Radio Galaxies

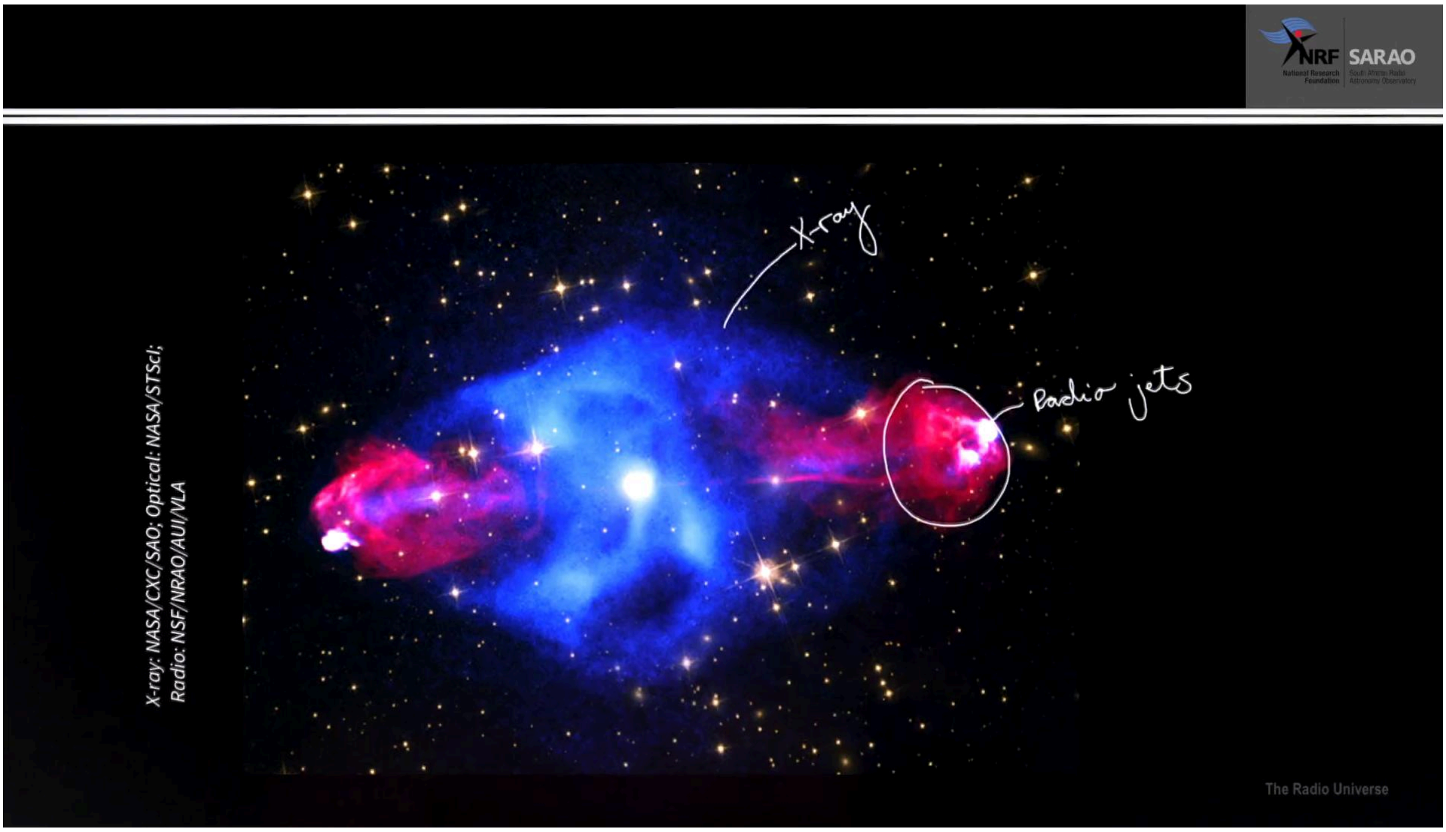


This is an image of a typical radio galaxy and I'll highlight some of its important features here. They usually have a core or a bright core that coincides with its host galaxy. It has twin radio jets which are shooting out in either direction. It has these large bright fluffy lobes and these bright points at the end which are called hotspots. In a typical model of how these radio galaxies work, you imagine that material is flowing out along the jets and collides with the intergalactic medium, the gas that is between galaxies in outer space. As it collides with this intergalactic medium, it forms a large shockwave or a bow shock at this interface. This causes the material to back-flow from this point and creates these large fluffy lobes of material that is flowing back towards the center of the galaxy. Inside the region where this is taking place there is a cocoon of shocked gas which has been cleared away from the central galaxy. Outside of this is just normal intergalactic gas.

Notes

Summary

2m 57s

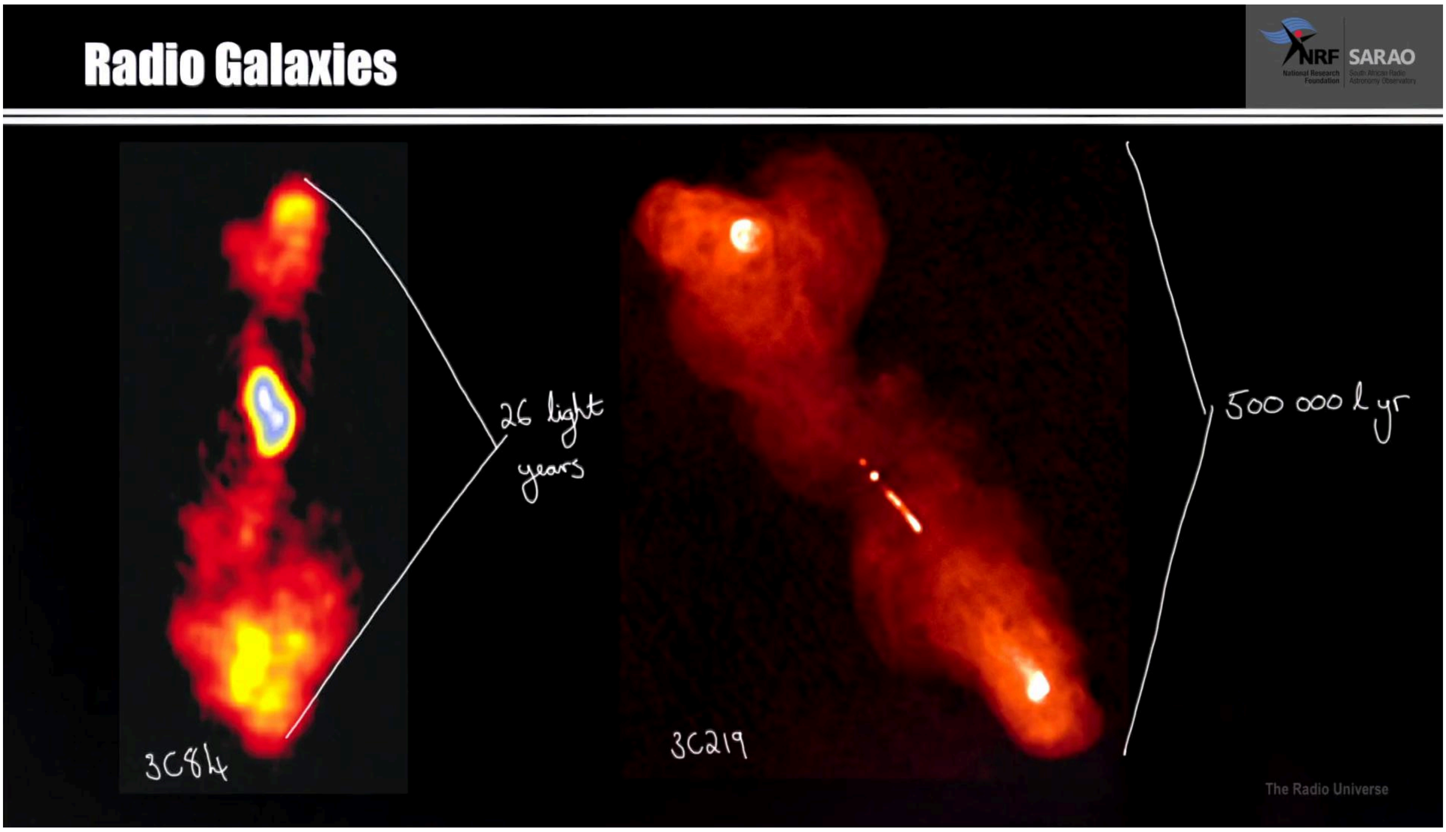


This is illustrated in this next slide more clearly where once again we have an image of the same object. Here in the purple are the radio jets and in the blue, we see the X-ray and what's happening inside this object is that inside the blue here is the evacuated empty chamber where the gas has been cleared away and on the outside you have this clear shock region which is emitting in the X-rays. So this is a kind of rugby ball-shaped object in the blue which indicates that empty cocoon of shocked gas.

Notes

Summary

4m 19s



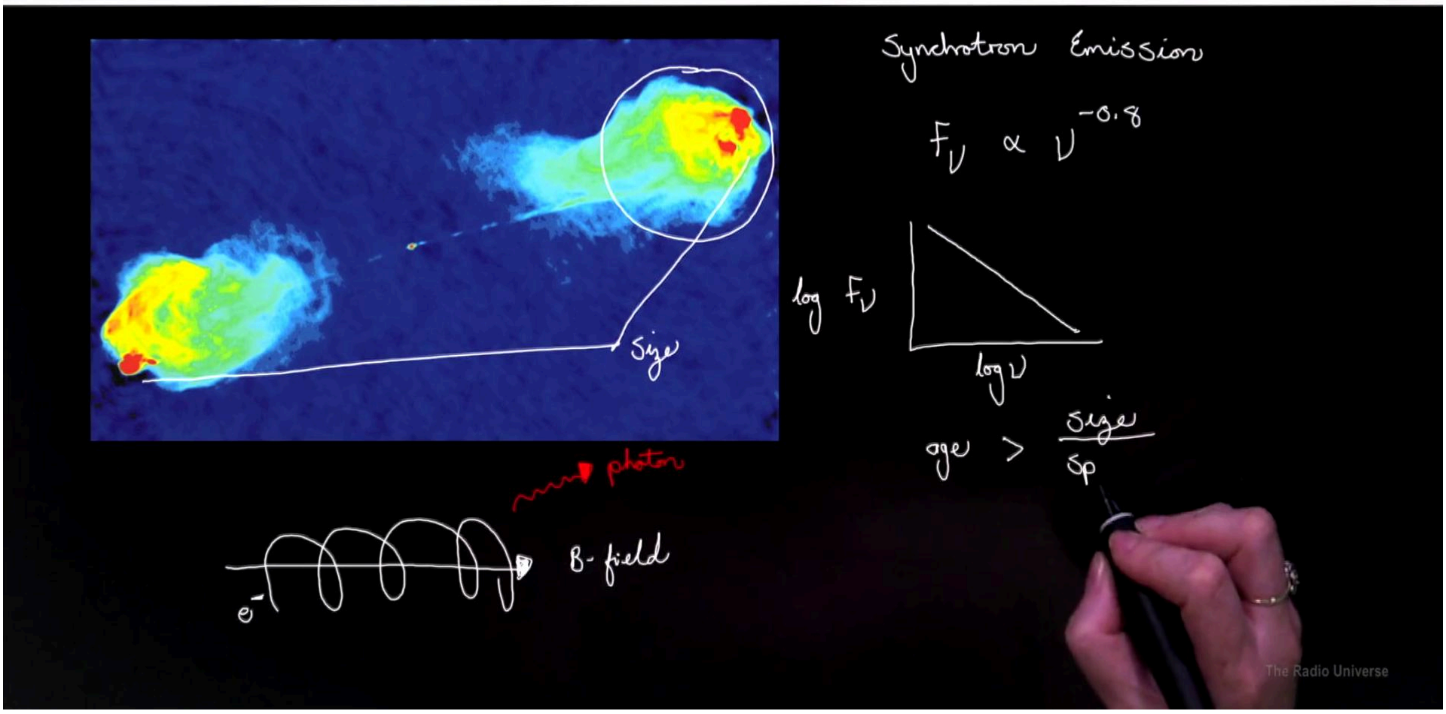
This basic structure for radio galaxies is the same regardless of size. On the left here we have a very small example of a radio galaxy. This is 3C84 and here it's being observed with a VLBI antenna. This is only 26 light years in size whereas on this side we have 3C291. This is a much larger object and it's nearly 500,000 light years in size and that you can clearly see that the objects have very similar structures.

Notes

Summary

4m 56s

Radio Galaxies

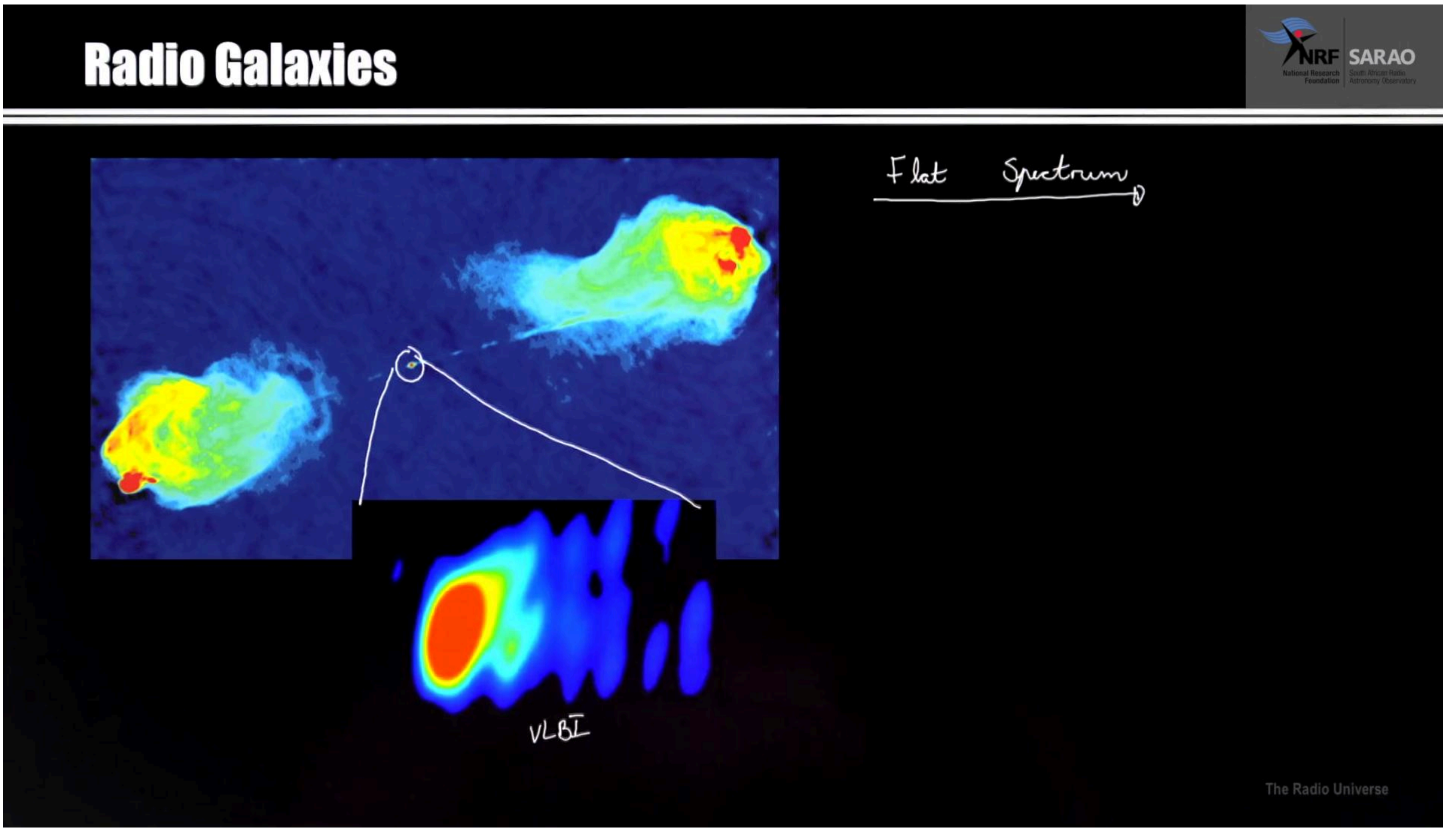


The lobes in these images have a steep spectrum which indicate that they are caused by synchrotron emission. If you remember, synchrotron emission is created by electrons interacting with the magnetic field. So if you have your magnetic field line here and you have, here you have an electron which is moving at relativistic speeds. This electron is spiraling around the magnetic field line and this causes it to emit a photon. This type of emission has a power law spectrum that means that the flux at any given frequency is proportional to the frequency to some power and in synchrotron emission this power is typically minus 0.8. So this means that as you go to lower frequencies, you have an increasing amount of flux observed. The size of the galaxy gives you an indication of how old the galaxy is or the minimum age of the galaxy. If you can imagine that the jets move at a specific finite speed then you can work out how long it would have taken them to expand at that speed to their current size. Bearing that in mind then you can get the minimum age is going to be larger than the size of the galaxy divided by the speed of the jet.

Notes

Summary

5m 42s



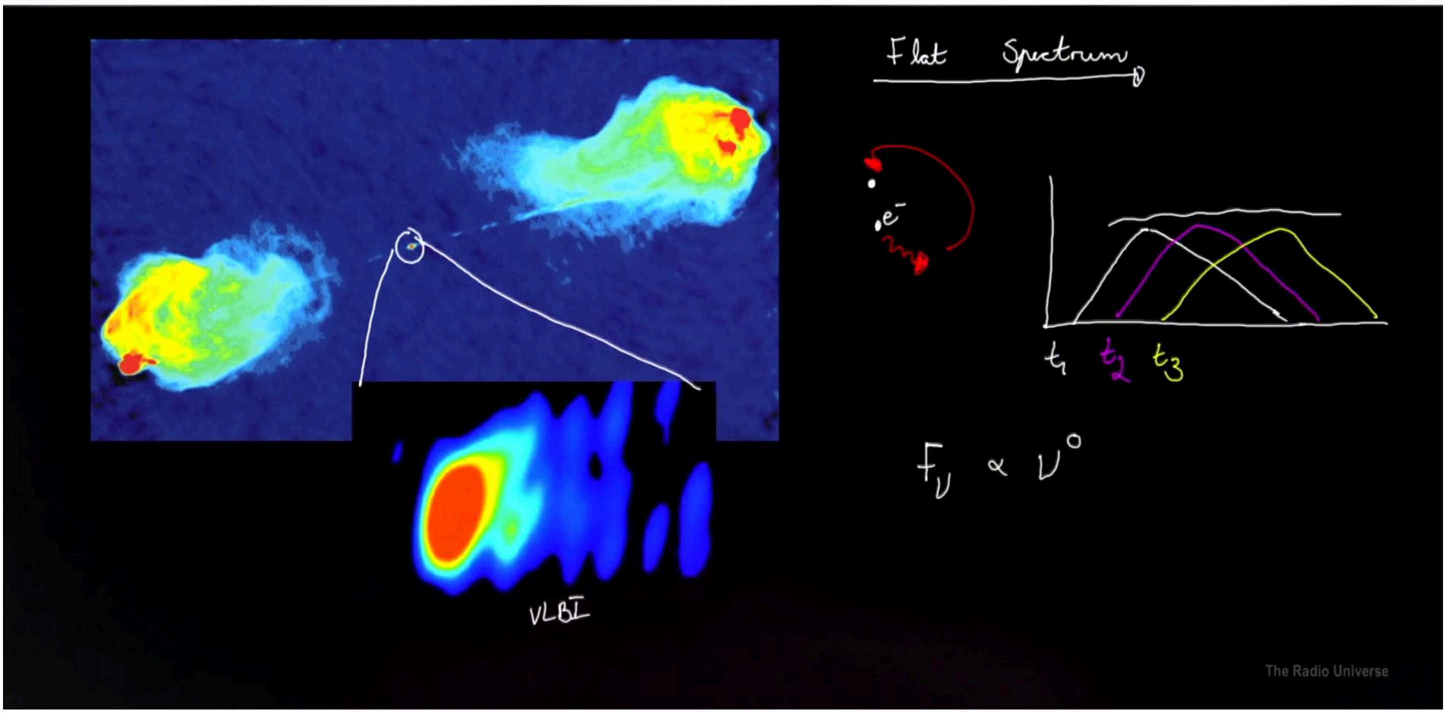
So for a typical radio galaxy you might say concretely that the size of the galaxy would be around 300,000 light years and it could have a near relativistic jet speed of around 0.3C which implies an age of roughly ten to the six years or a billion years. What's important about this is to realize that it will take some time for the electron to lose all of its energy via the synchrotron process. So this every electron has a typical lifetime before it's used up all of its energy. This is called the synchrotron cooling time and this synchrotron cooling time is typically very much less than the minimum ages of the source we're looking at which implies that this jet is not a one-time expulsion of very energetic material, that there is actually a continuous ejection of material over time into the lobes. The core of the radio galaxy is very very small and usually unresolved at even the highest resolutions. Here we have a VLBI image of this very tiny core. The core also has a flat spectrum. This means that it has approximately equal energy at all frequencies or wavelengths that you observe it at and this flat spectrum is interpreted as coming from synchrotron self-absorbed emission.

Notes

Summary

7m 36s

Radio Galaxies

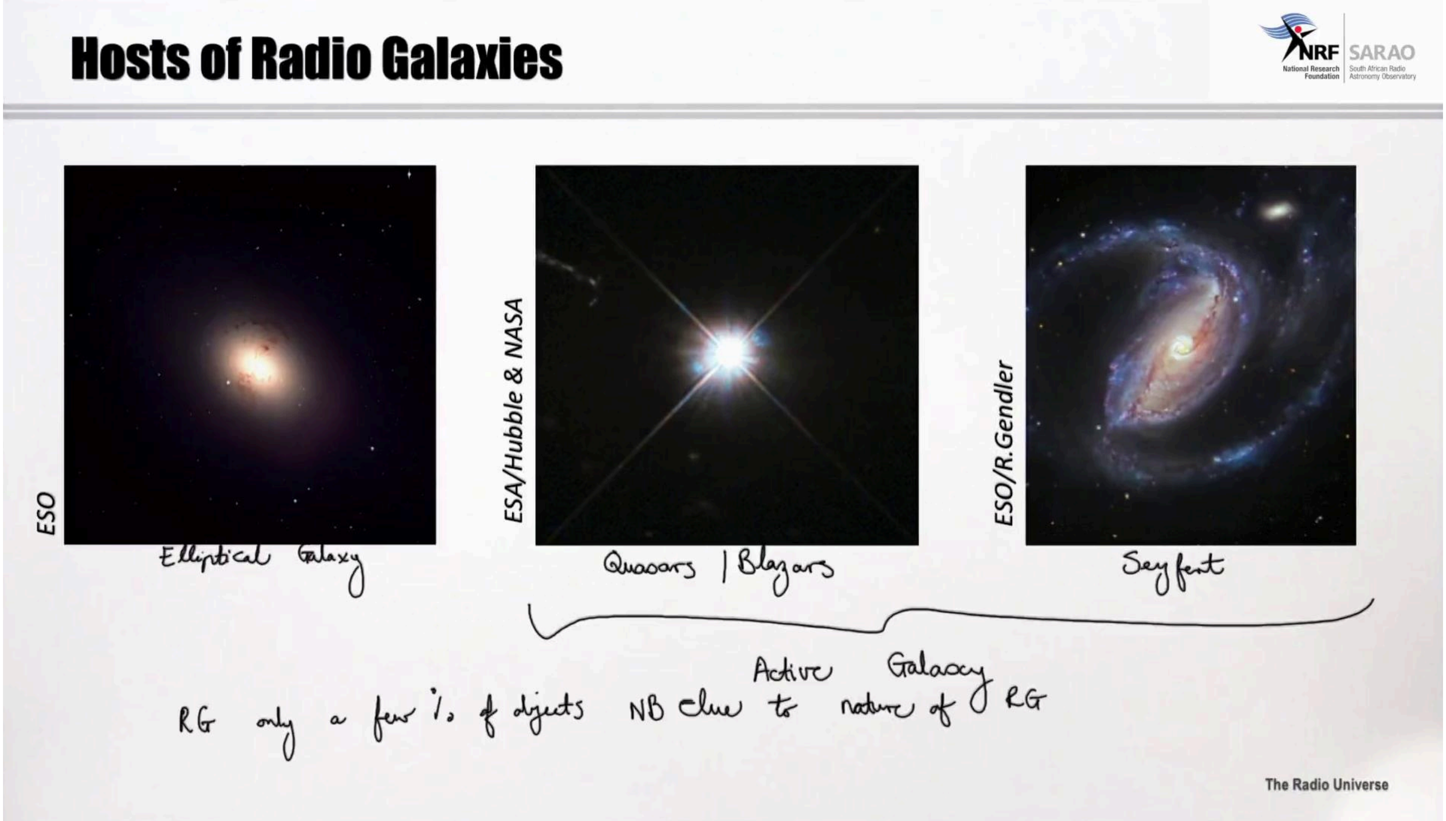


So if you remember from your previous discussions, if we have a very large number of very dense electrons then photons that are emitted by one electron can be reabsorbed by another electron. This causes the spectrum of your emission to have a specific shape. Instead of the emission continuing to increase indefinitely at lower frequencies, there is a turnover frequency where this absorption process starts to happen. So the flat spectrum is then interpreted as being a combination of these self-absorbed spectra. So if you imagine that you have one set of self-absorbed emission coming out at time one and then another another bit of self-absorbed emission coming out at a later time, time two and then again at a later time, time three. When you combine them what you'll end up with is approximately a flat spectrum. So this means that the flux at a given frequency is proportional to the frequency to the power of zero.

Notes

Summary

9m 15s

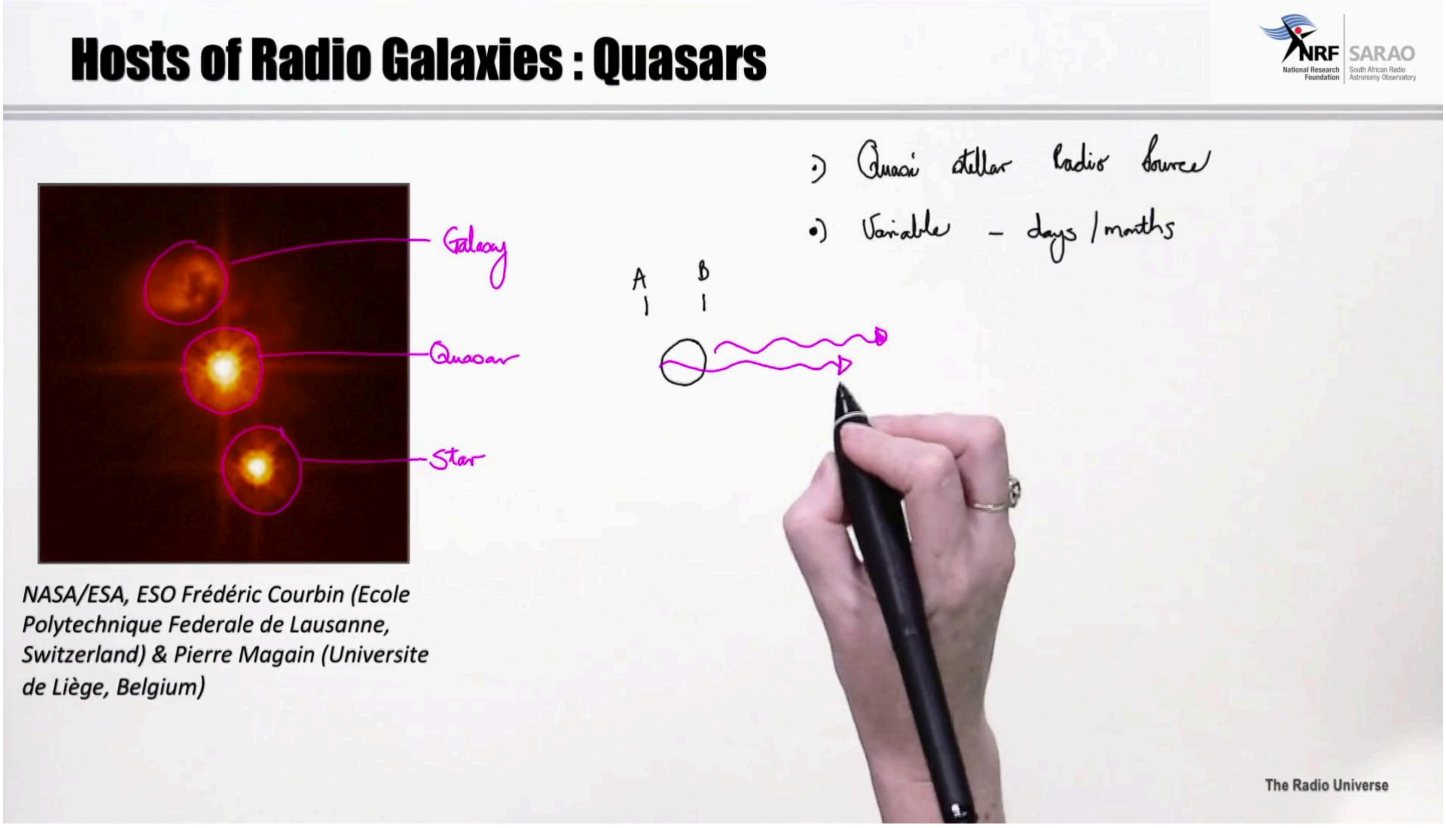


We now move on to the host galaxies of radio sources. Radio sources are hosted in a variety of different objects. They can come out of an elliptical galaxy so an ordinary elliptical galaxy or alternatively, it can come out of a class of galaxies called active galaxies. These active galaxies have a number of unusual properties which we will discuss in more detail in the next slides. There are different classes of active galaxies. They can be quasars, blazars or Seyfert galaxies. The properties of these active galaxies give us an important clue as to the nature of these radio galaxies and the cause of their radio emission. It is important to note at this point that radio galaxies are just a rare subclass of each of these kinds of objects. So not all elliptical galaxies are radio galaxies. Similarly with quasars and Seyferts. Only a small fraction of these are going to have radio jets.

Notes

Summary

10m 49s

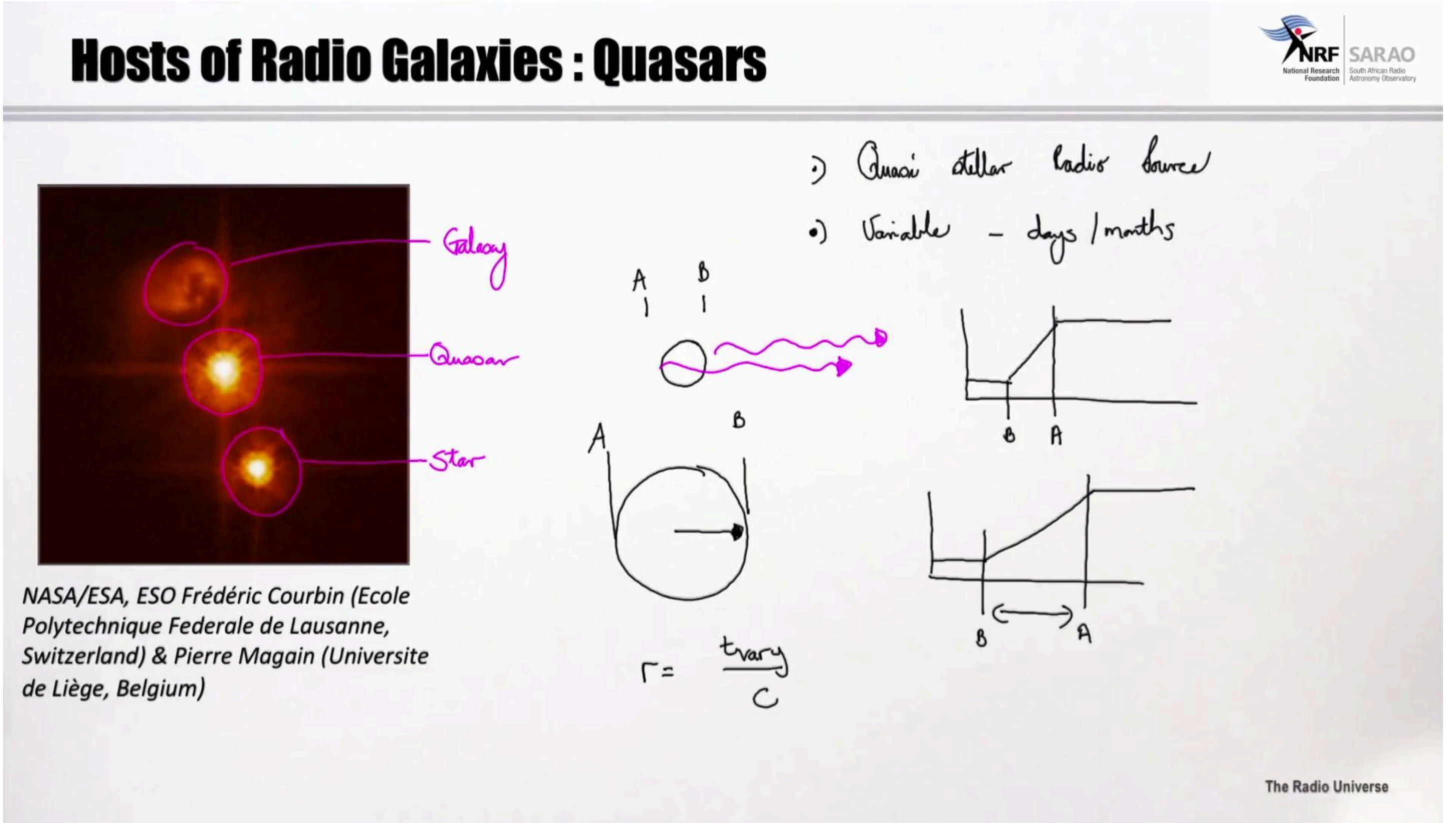


The word quasar comes from the acronym quasi-stellar radio source. This is because the earliest examples of this type of source were associated with radio sources and they're called quasi-stellar because they look very much like stars in images. Here is an example of an image of a quasar and here is an example of an image of a star. As you can see, the two objects look incredibly similar to each other. They're both bright unresolved point sources. In contrast, here we have an image of a galaxy which is much fuzzier and more spread out and not quite as point-like. The second hallmark of quasars is that they are incredibly variable. A variable over very short time scales from days to months and this is important because it has implications about the actual size of the region of the light that's coming from the object. It tells you something about the intrinsic size of the object that is varying. To illustrate this, consider that you have a small object like a star in space. This object has a finite size and light from the side that is closer to you will reach you at an earlier time than light that is traveling from the side that is further away from you.

Notes

Summary

12m 07s

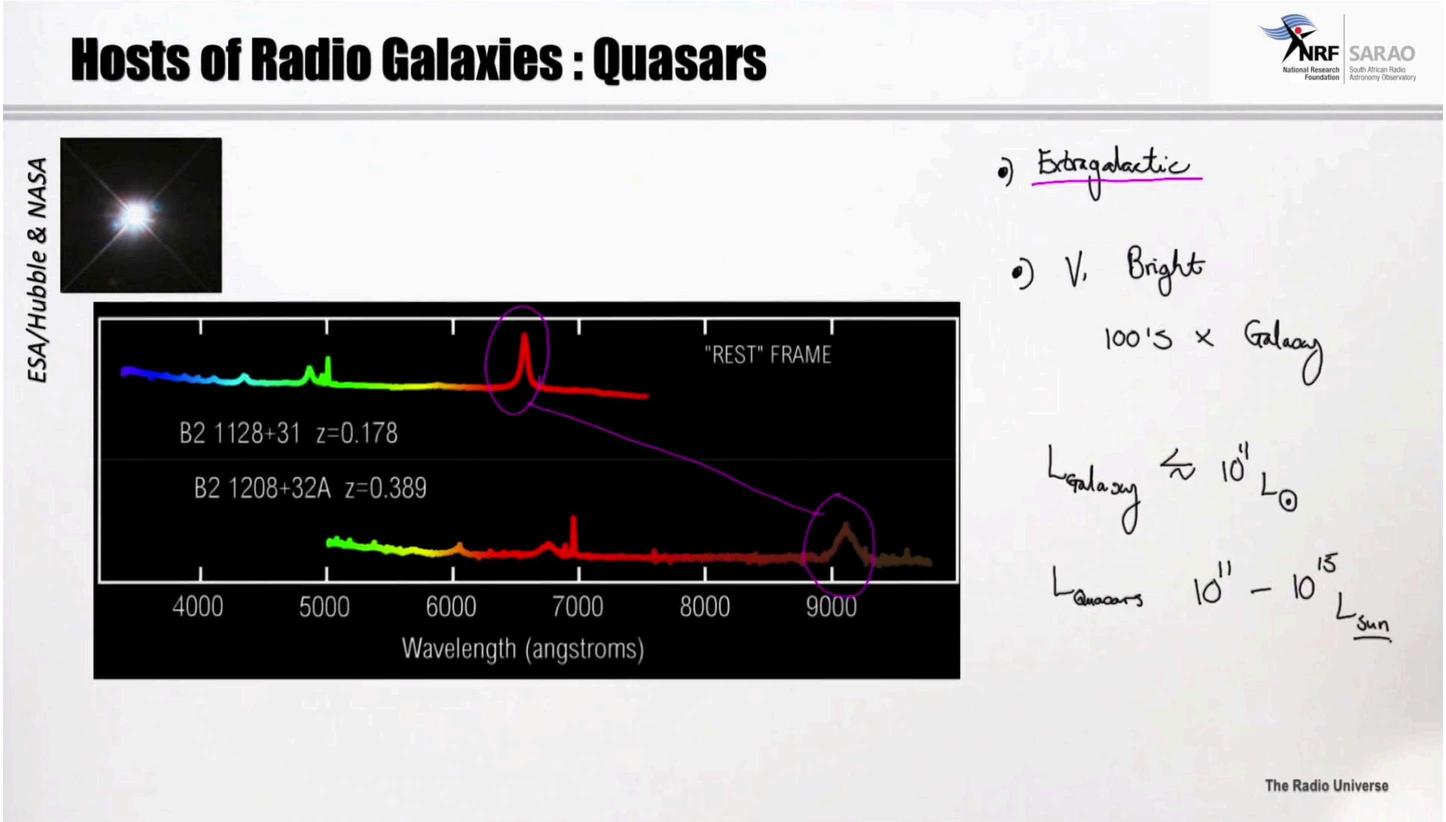


And what this inevitably means is that it takes a little bit of time for the object to reach its full maximum brightness. As the photons from side 'B' arrive here, the object starts to brighten but it's only when all the photons from side 'A' have arrived that the object reaches its full maximum brightness and so the larger the object, the longer it takes to vary. So what this tells you is that the radius here is equal to the time it takes to vary from its minimum brightness to its maximum brightness divided by the speed of light. The shorter the period it takes for the object to vary, the smaller the object that the light is coming from. And as quasars are variable on the scale of days to months, this tells you that the region that the emission is coming from is as small as several light days in size.

Notes

Summary

13m 49s

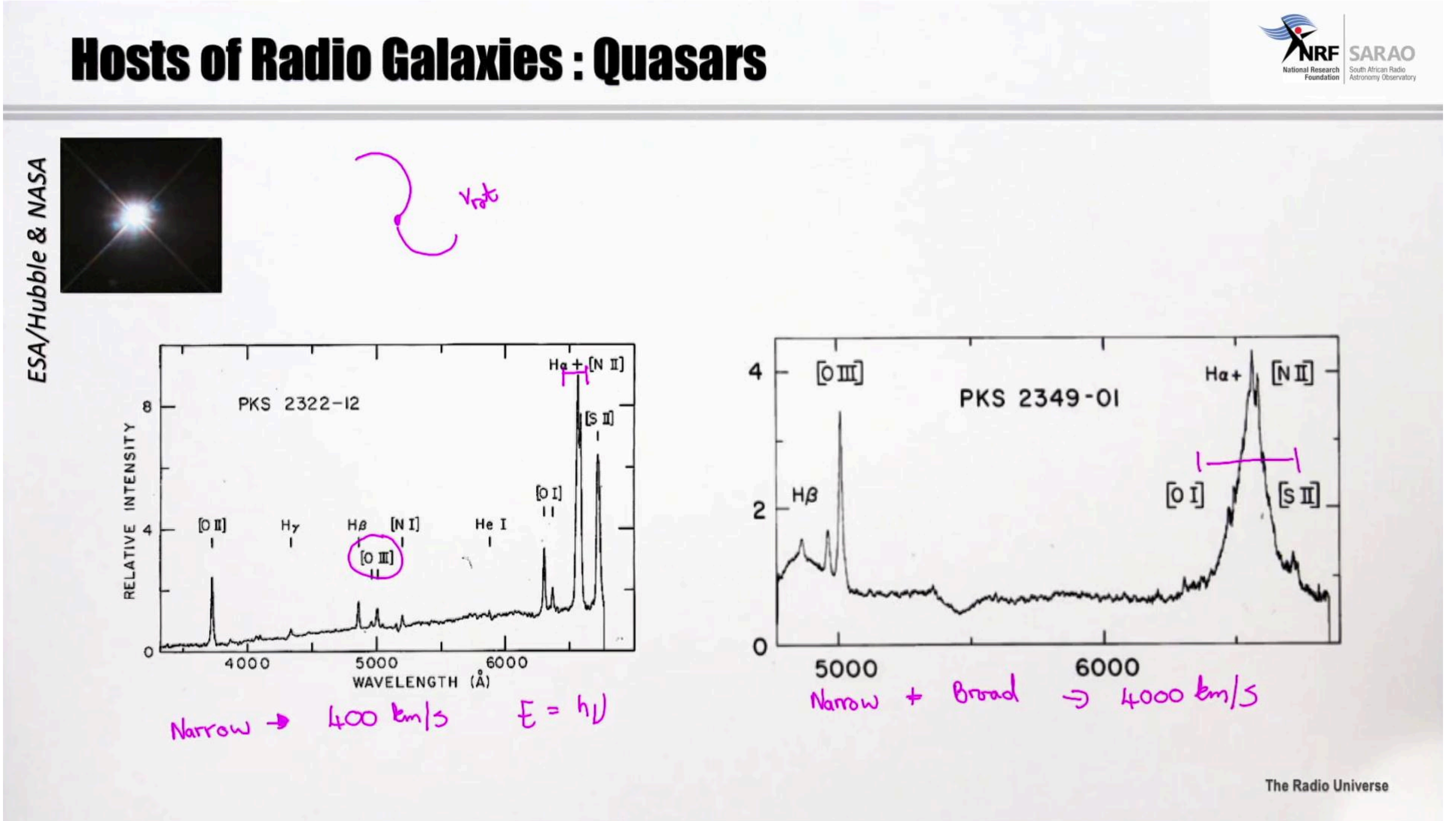


One of the most surprising things that was discovered about quasars when they were first discovered is that they are extragalactic. Because of their very bright nature it took a while for astronomers to realize that these objects were actually outside our galaxy and they realized this by taking spectra of the objects and seeing that the lines in there in the spectrum are redshifted to much higher wavelengths. Using Hubble's law from this you can infer that these things are outside of our galaxy and the distance from our galaxy can be inferred from Hubble's law. As they are extragalactic which means that they are very far away from us but they have a similar flux as bright as stars which are very close to us, you can conclude then that these objects are very very bright. They are, in fact, hundreds of times brighter than typical galaxies. Typical galaxies have luminosities that are around ten to the eleven solar luminosities or less than whereas quasars have typical luminosities of between ten to the eleven to ten to the fifteen solar luminosities. This is incredibly puzzling to early astronomers because what could be producing such incredibly bright radiation. Certainly not normal stars.

Notes

Summary

14m 59s

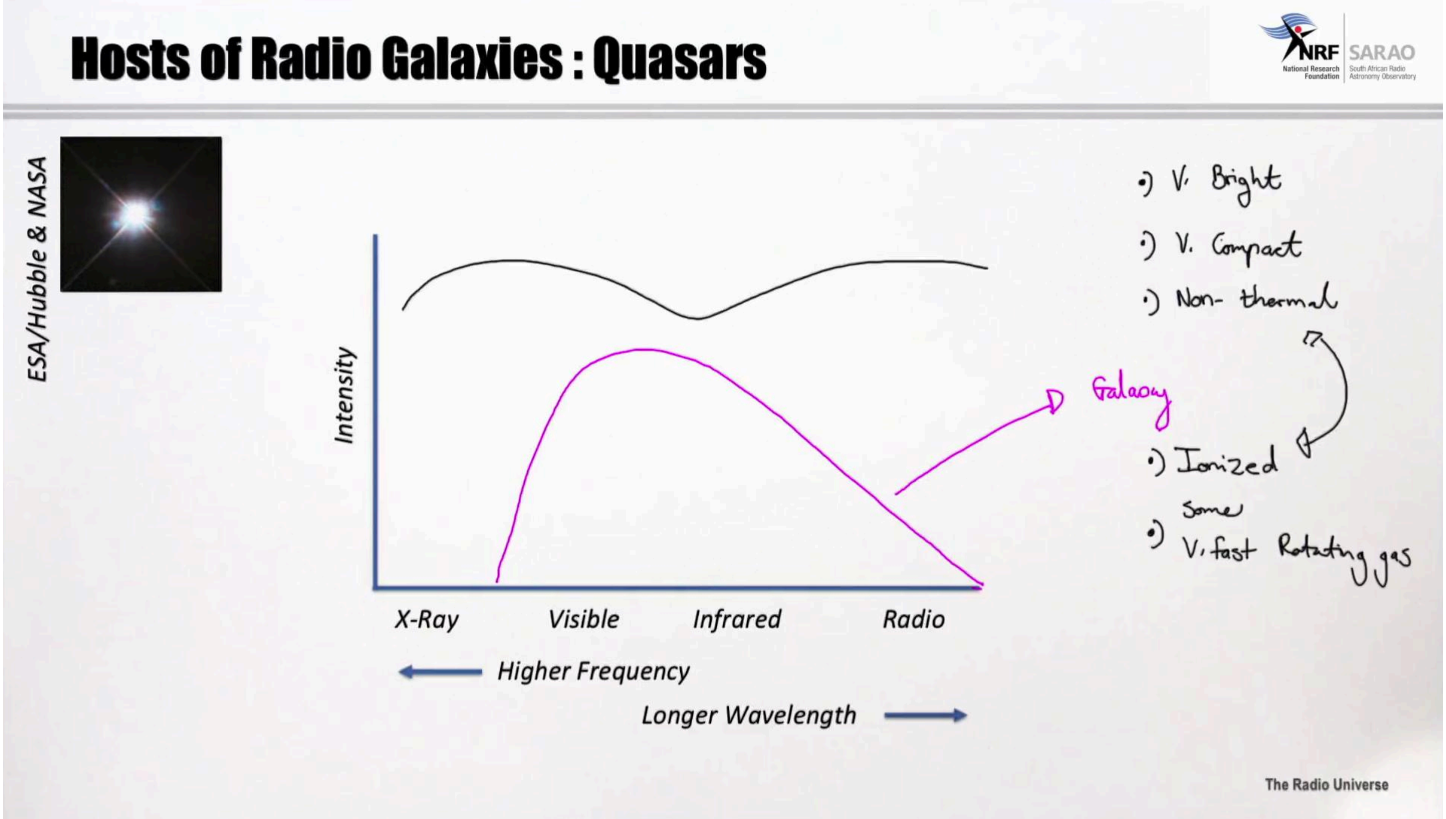


Another important feature about quasars is their spectra. They all show very bright emission lines and these emission lines are often from very highly excited multiple ionized species. So that means that they have been ionized by something that has enough energy to strip off multiple electrons from the atom. So remembering that energy is equal to 'h' times frequency, this tells you that these objects are being ionized by something that have very high energies and very high frequencies. So they are being ionized by something that is very energetic, much more energetic than a normal star. In some quasars, you only get narrow emission lines such as these. You can see that they're relatively narrow. Remember that the width of an emission line tells you something about the velocity of the gas that is emitting the emission line. As the, as the gas rotates, the emission lines broaden. Using the width of these emission lines you can show that the narrow emission line gas in these quasars has a rotation velocity of around 400 kilometers per second which is comparable to a typical or very fast rotating galaxy. However, some quasars in addition to these narrow lines also have very broad emission lines. And what this tells you is that the gas in these quasars is moving at much higher velocities than the gas in these quasars. They are moving at speeds of roughly 4000 kilometers per second.

Notes

Summary

16m 42s

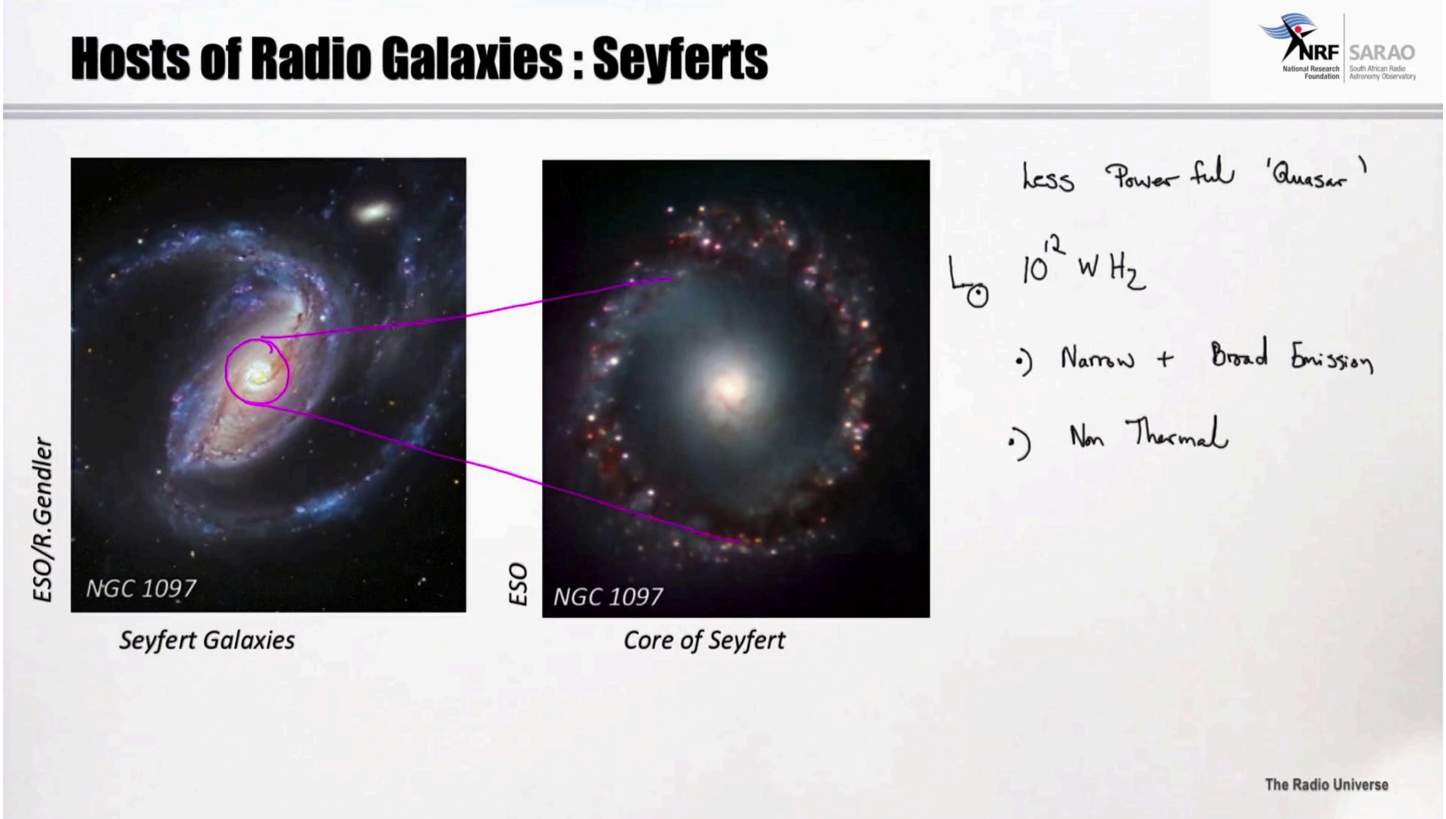


Next the final feature of quasars is that they have very unusual spectrum for the continuum emission that you observe from them. If you remember that blackbody radiation has a typical spectrum that looks something like this. In quasars so for a normal galaxy what you'd expect to see is a composite of different blackbody emission that you get from various stars inside the galaxy. But for an active galaxy, you really have a very different spectrum from this thermal signature. In fact, it looks something like this which is consistent with our picture that there should be a lot of short wavelength high energy radiation in order to produce the emission lines that we see in the spectra. So let's review some of the important points about quasars. They are very bright, the brightest objects in the Universe. They are very compact perhaps only a few light days in size or a few light months in size. They have a very non-thermal spectrum. Therefore, they have highly ionized material in the center. These two things are related and they also some of them, some have very fast rotating gas.

Notes

Summary

18m 43s

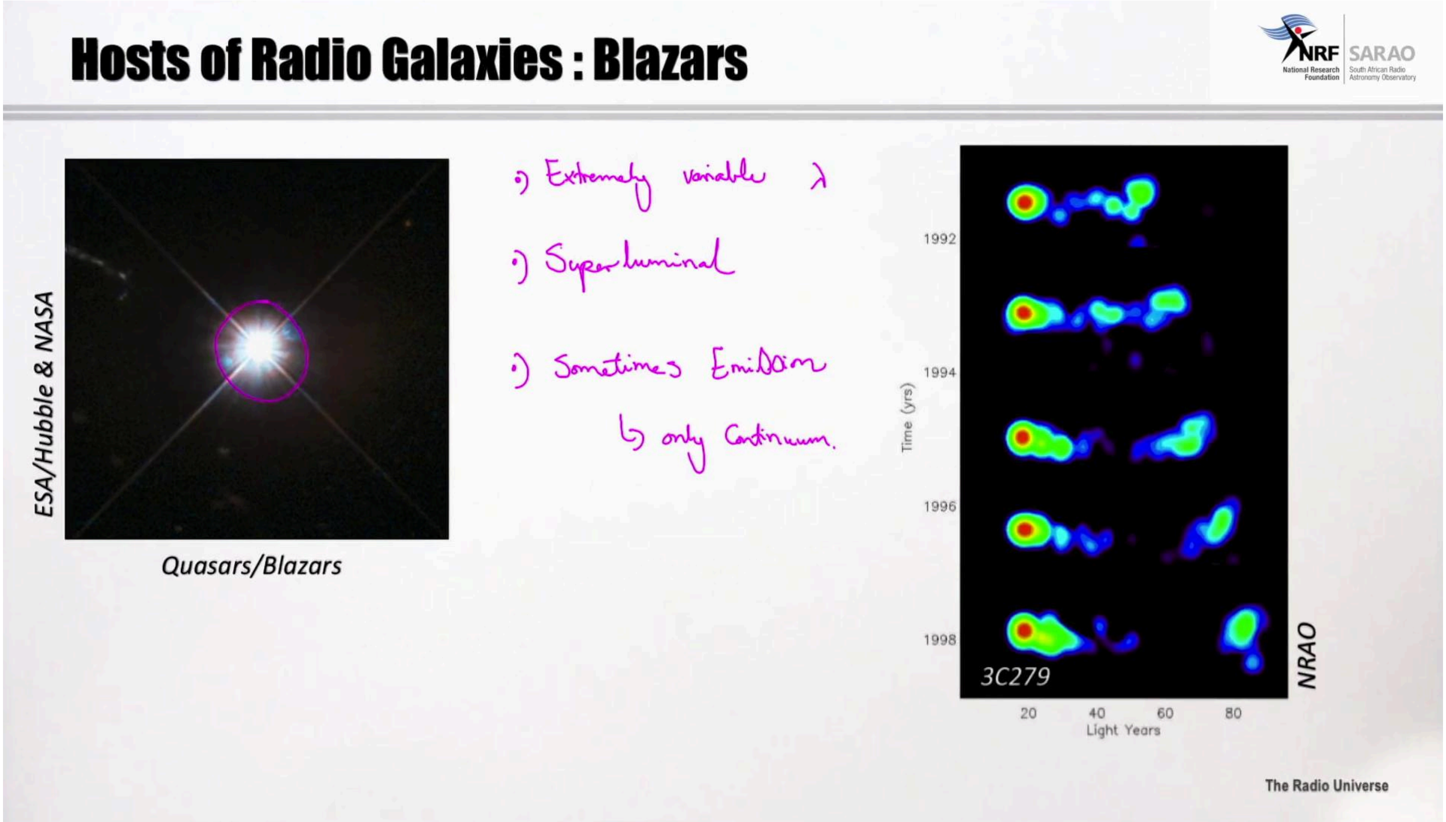


The second kinds of hosts of radio galaxies are Seyferts. Seyferts are essentially a less powerful cousin to the quasar. Seyferts look like normal galaxies everywhere except in the center where they have an incredibly bright region in the center of the galaxy. Here is a picture of a Seyfert galaxy NGC 1097 and here we have a zoom in of this very bright emission that comes from the center. It's important to realize that the emission from the center of the Seyfert galaxy can actually be brighter than the emission from the whole rest of this really large galaxy. So it can have luminosities of around ten to the twelve watts per hertz. They have many characteristics in common with quasars. They also have narrow and broad line emissions, broad emission lines and they also have unusual non-thermal emission but from the core only in this case. They're also very variable. So, in fact, Seyferts are just a less powerful version of a quasar and it has been shown that quasars do actually have a galaxy in the image around them. It's just that in most cases the quasar is so bright and so powerful that it really outshines the galaxy and you don't have enough dynamic range in your image to see both the quasar and the background galaxy in the same go.

Notes

Summary

20m 22s



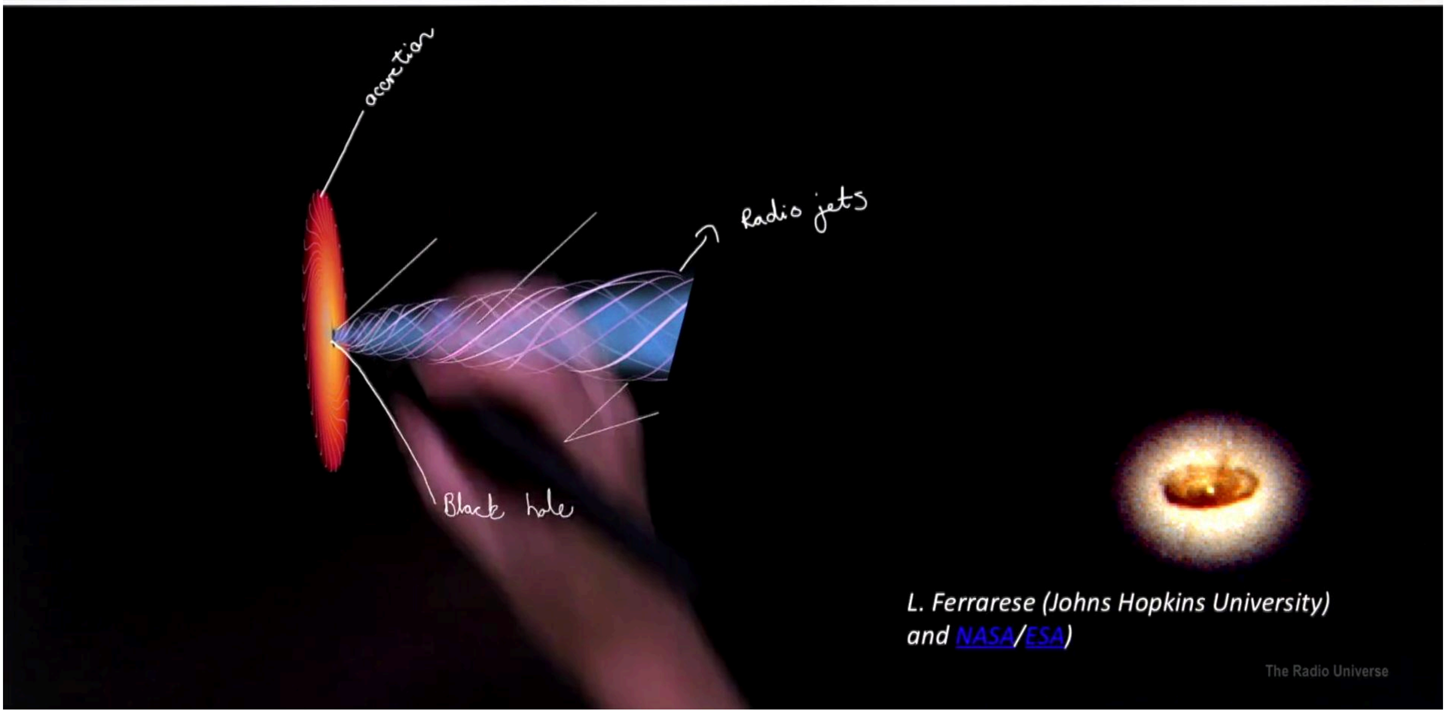
The final type of host galaxies you have for AGN are blazars. So blazars are also bright and resolved point sources and they look very very similar to quasars and images but they have a couple of important differences. They are extremely variable at all wavelengths and maps of the jets near them almost always show superluminal motion. That means motion that looks faster than the speed of light. In this VLBI map of the jet from 3C297, you can see the number of light years below and you can see this jet is expanding at much faster than the speed of light. Also unusually, sometimes you see emission lines in their spectra, but sometimes there are no emission lines. You only see continuum emission.

Notes

Summary

21m 55s

AGN Unification : Orientation is key

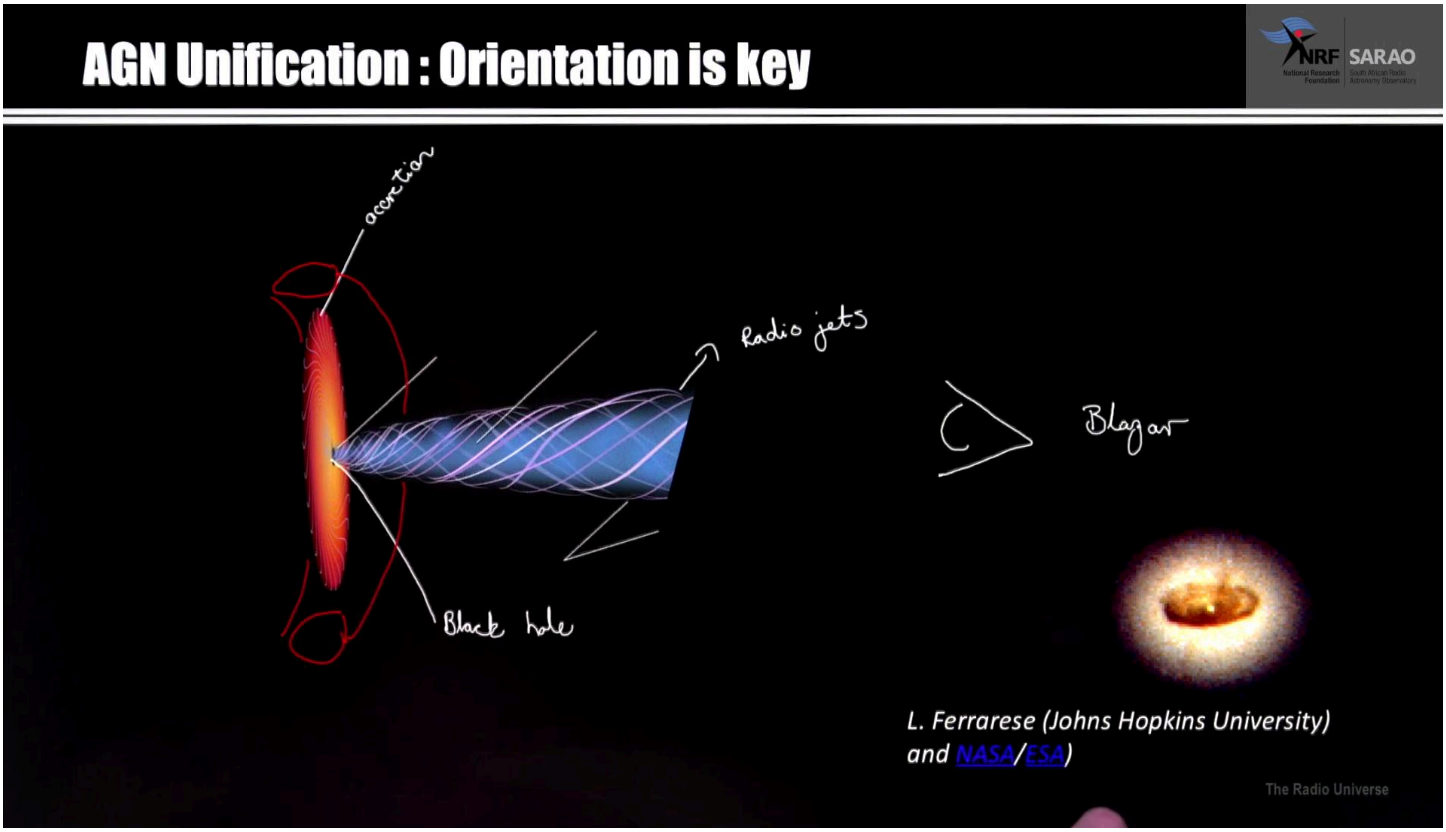


How are all these different types of host galaxies of radio jets connected? Why are all these seemingly diverse objects, all host radio jets? Well, the answer to that lies in something called AGN unification theory which says that all of these different types of objects are essentially fundamentally the same thing but simply viewed from a different angle. In AGN unification theory, it's postulated that there is a supermassive black hole in the center. This supermassive black hole is surrounded by a thin rotating accretion disk. Material falling onto the black hole falls onto this accretion disk and travels along it before it gets sucked into the black hole. This material will get superheated as it travels along the accretion disk and this is the source of the bright non-thermal continuum you see in certain quasars, you see in quasars. Magnetic fields from this rotating supermassive black hole funnel plasma which is being shot off it to form the radio jets. An essential component of AGN unification is a dusty torus so a kind of doughnut-shaped object, which surrounds the accretion disk and blocks our view of the light from the accretion disk at certain viewing angles.

Notes

Summary

23m 06s

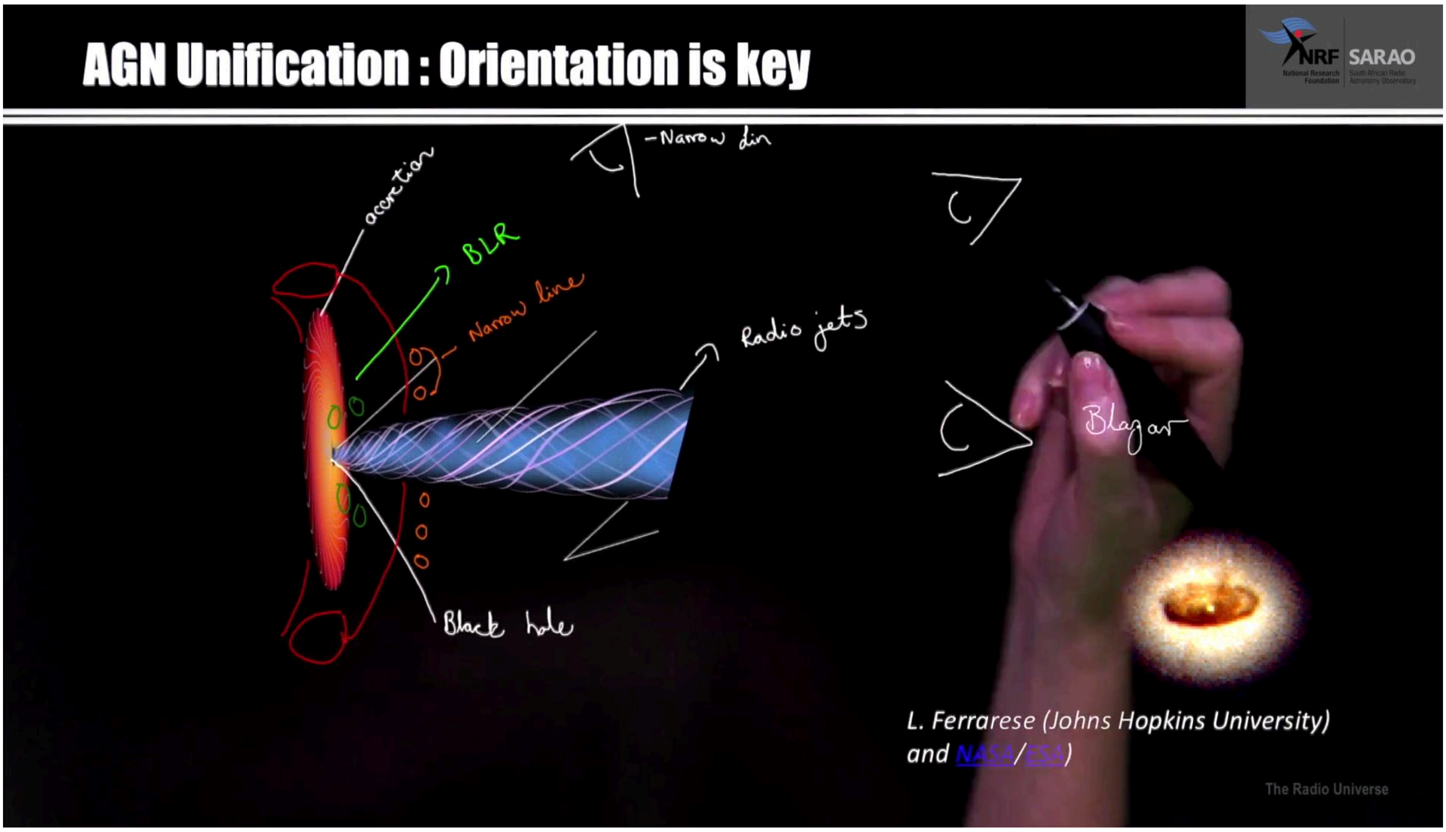


So if you imagine that you have a kind of doughnut-shaped object here which is surrounding this entire accretion disk. Dust is basically opaque to shorter wavelength emission because it absorbs this emission and then re-emits it at longer wavelength. In the AGN unification theory, what we say is that essentially that you have different viewing angles which then account for the different types of properties you see in these different host galaxies of radio AGN. If you look exactly head on down this jet then you will observe a blazar. The properties of the blazar are explained here because of the Doppler boosting of jets which are traveling at relativistic speeds. Basically, if you have a jet traveling towards you at very relativistic speeds, its brightness gets boosted immensely and this accounts for the extreme variability of blazars and also can account for the lack of emission lines because in certain instances the continuum gets boosted so much that it completely overwhelms all of the emission lines.

Notes

Summary

24m 36s

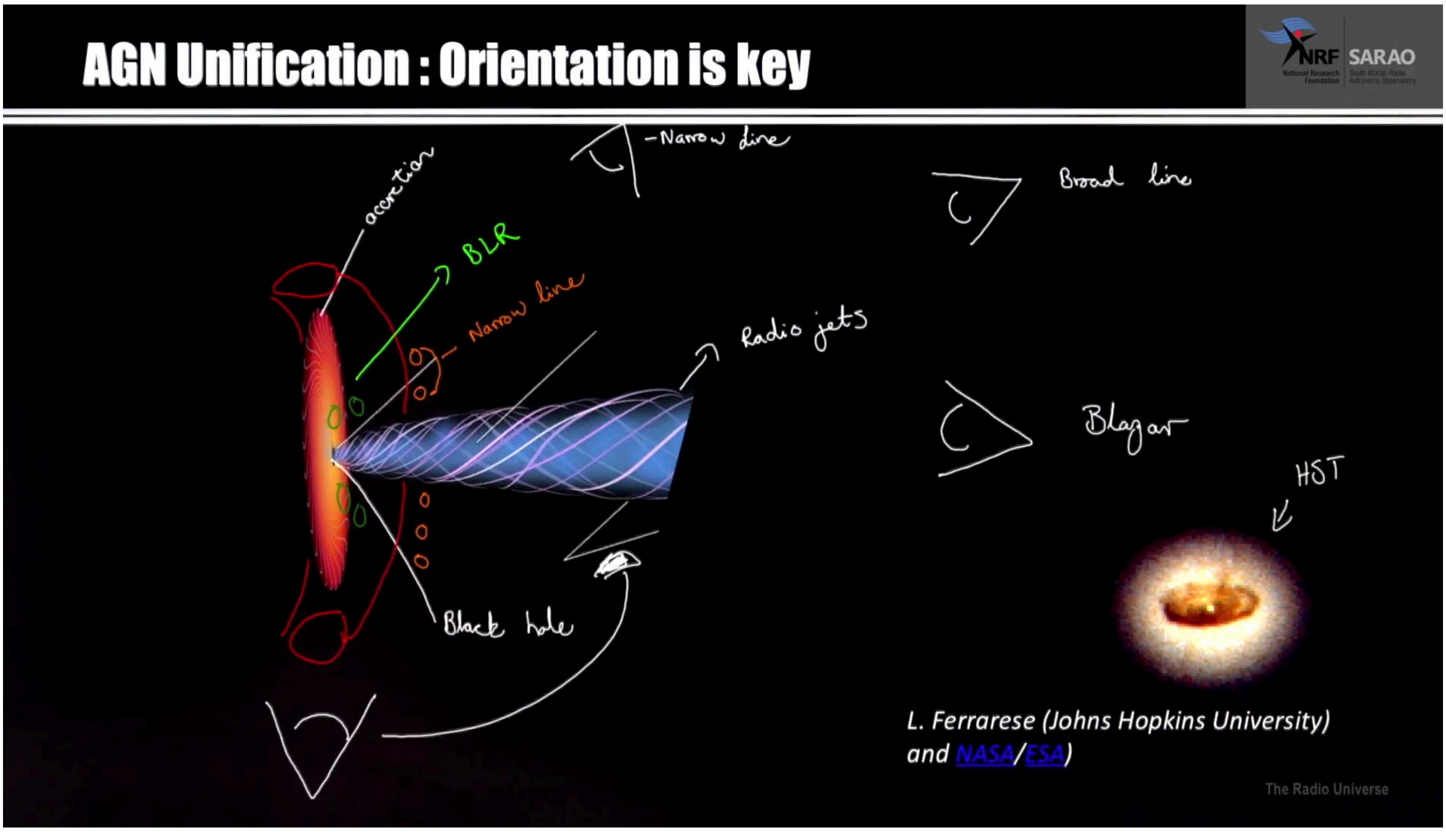


If you view this same object from a slightly different angle not exactly head on to the jet but at a few degrees away from the jet, what you will see is this bright ionizing radiation from the accretion disk and this ionizing radiation from the accretion disk is ionizing gas near the supermassive black hole and there are fundamentally two different kinds of gas. There is gas which is very near the accretion disk. This gas is near the accretion disk and is moving at very very high speeds and further out there is gas a little bit further away which is not being ionized as much. These gas clouds are moving at a much slower speed. If you view from this angle, you see this lower velocity gas which gives you the narrow line region and you also see this much higher velocity gas which gives you the broad line region or the broad lines in your spectra. If you view this object from an angle further away from the jet then much of the broad line region will be absorbed or obscured from your view by this dusty doughnut-shaped torus. So this gives you narrow-line AGN, narrow-line quasars and Seyferts.

Notes

Summary

26m 00s

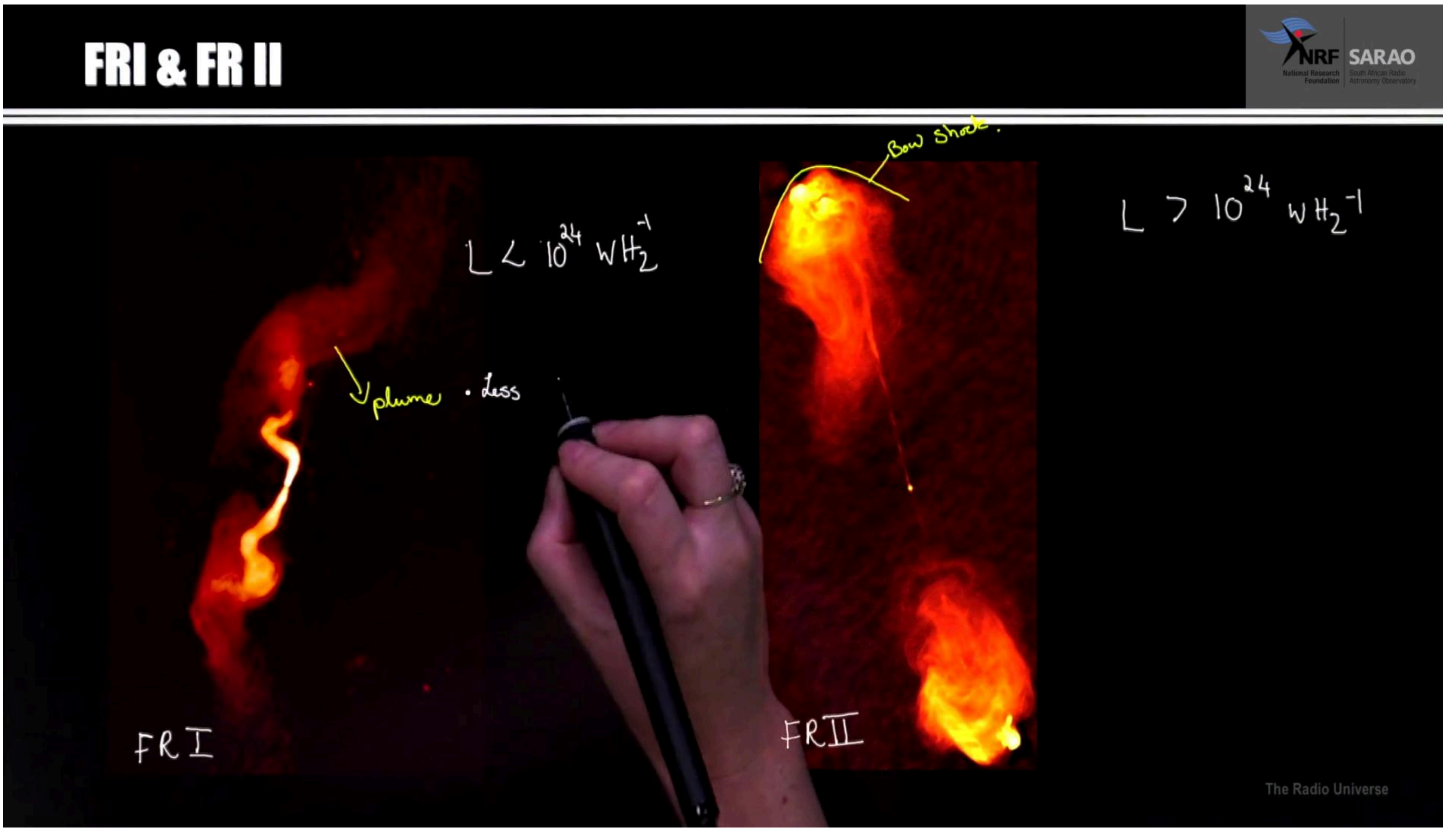


This gives you broad line quasars and Seyferts and finally, if you view directly into this dusty torus on the side then both the narrow and broad line regions will be obscured from view so you will not be able to see any of the hallmarks of a quasar. Also this bright continuum emission will be obscured from view and all you'll be able to see is the radio jet. This is an important thing to take note of because it means that radio is one of the best ways to find AGN that are orientated at this angle to our point of view. This model of AGN unification is supported by the fact that this image of HST has actually captured a tiny dusty accretion disk surrounding a supermassive black hole.

Notes

Summary

27m 30s

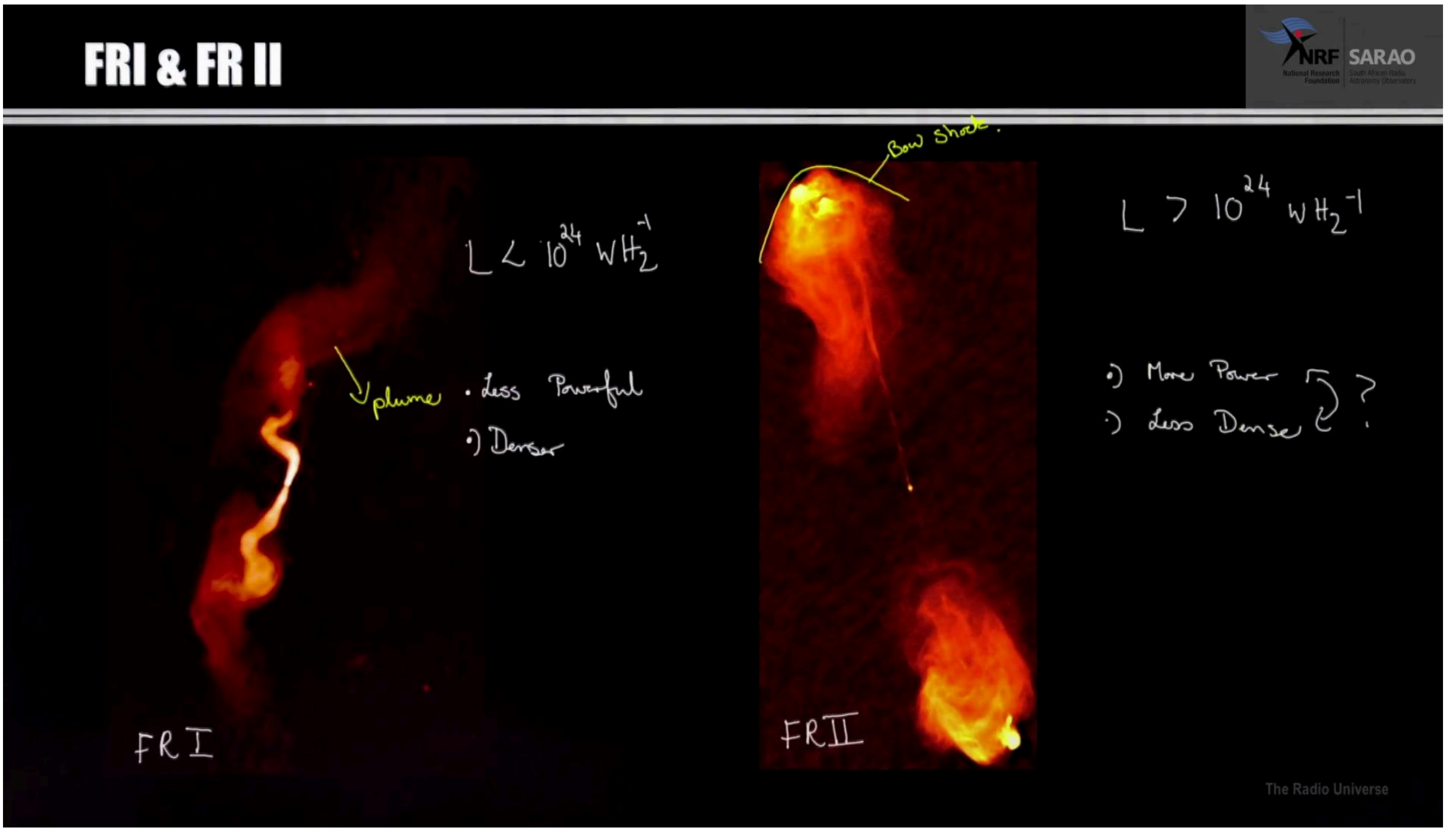


For our final slide, we just want to say that AGN come in essentially two flavors, radio AGN. They come in something called a Fanaroff-Riley Class I which are named after the people who first discovered this classification sequence and a Fanaroff-Riley Class II source. Fanaroff-Riley Class I sources tend to be lower luminosity. They tend to have luminosities of less than ten to the 24 watts per hertz whereas Fanaroff-Riley Class II sources tend to have higher luminosities, luminosities of greater than ten to the 24 watts per hertz. The main difference between these two objects is that in this instance you can see this classic picture of having a shock, a bow shock and two hotspots at the end. But in the Fanaroff-Riley Class I objects, you don't see this shock and hot spots at the end. Instead, what you have here is a kind of plume at the end of your radio source. Why are these two different classes of AGN? Why do they exist? Well, theories are bound. One is possibly that the jets are less powerful in FR I class sources or potentially that they may be in a much denser medium than FR II class sources or perhaps it's some combination. So they could be less powerful.

Notes

Summary

28m 21s



Which means that they lose power as they travel further away from their host galaxy and instead of generating this giant shockwave they just kind of dissipate out and end up in pressure balance with the surrounding intergalactic medium or they could also be in a much denser environment which makes it harder for them to retain their power as they travel out to further distances. Similarly, it's possible that FR II's are either more powerful in a less dense environment or it could potentially be a combination of these two factors. That's it for today.

Notes

Summary

29m 59s