Radio Astronomy

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Introduction to Radio Astronomy

Hello everyone. Welcome to this course, the first lecture of this course Radio Astronomy. I am very happy that this course is running for the first time in NPTEL platform. As you know already from the intro video that this course will be taught by mostly by me, Abhirup Datta. I am a professor at Department of Astronomy, Astrophysics and Space Engineering here at IIT, Indore. And I will be assisted by my research scholar Mr. Harsha Avinash Tanti who will be acting as the TA for this course.

We are going to start today's lecture by introducing you to why we would like to learn about radio astronomy, why we are so excited about doing radio astronomy and what are the prospects and different things. So I showed this in the introductory video as well. This is the entire electromagnetic spectrum.

And we will be mostly concentrating on the lower side of the frequency range or the higher side of the wavelength range. That is the radio band. But apart from that there are different other electromagnetic spectrum ranges where like x-ray, gamma ray, ultraviolet, even some part of infrared which cannot be observed from the surface of the earth. That earth's atmosphere actually cuts off and prevents it from reaching the earth's surface. So hence we have to fly space telescopes to observe on those bands.

We are lucky to be in the radio regime that most of the wavelength ranges are actually accessible from the surface of the earth. And only if we go very low in the frequency or very high in the wavelength, the earth's ionosphere which is a plasma layer, that actually cuts off the radio waves from reaching the earth's surface. But that is a minor range provided the major part we can actually observe from the ground. The other thing, advantages over other wavelengths is like the optical. We can still see from the ground.

But the tropospheric layer of the atmosphere actually bothers us from observing it on a cloudy day or a rainy day or those kind of times. Hence you will see most of the optical telescopes are on a little bit higher altitude than the radio telescopes. And another major obstacle is we only observe in the night time when the sun is down. In the case of radio, the sun is a major source. But we can avoid, if we avoid looking towards the sun, even in the daytime we can observe very well.

So when we talk about wavelengths, typically a few centimeters down to a few meters is what we concentrate for this course, essentially, which kind of ranges from a few tens of megahertz up to a few gigahertz in frequency. So just to give you an example, an elaboration, that this is a field of view which we can see from the surface of the earth. And we can observe it in other wavelengths. So optical is there, there is some infrared color which can be observed from these space telescopes. But you don't see much beyond that.

If I just go to the next slide and show you that this is the picture which you actually can see, which you were not seeing before. And that is the new addition of information is coming from the radio observations. So one interesting point to understand is just like human eyes are only sensitive to the visible part of the electromagnetic spectrum, different parts of the electromagnetic spectrum can only be seen or observed by specific telescopes, specific detectors, which are built only to operate in those regions. It's not possible to have a single detector which can go from say gamma rays down to radio wavelength. It's not possible.

The technology is different. The wavelengths are quite different. Even within the radio band, you will see as the course progresses that it is difficult to have, almost impossible to have a single receiver system which operates from few megahertz range up to few gigahertz range. So there will be separate sub-wavelength bands within the radio waves which we'll be talking about soon. The message from this comparison between the last slide, which was this one, where we didn't see anything like the expression which we're seeing over here, is the fact that we have now overlaid a radio image on top of other multi-wavelength observations.

And you can start seeing some structures which were not visible before. This is a classic manatee enabler. And you can look up this in the Google and learn more about it. The construct to display this image was to make you understand that there are certain things which are visible in the radio which are not available in the other bands. That's why observing in different wavelengths is so important.

Continuing on the same topic, I would say just this is a very famous picture of our own galaxy, the Milky Way, and observed in different parts of the wavelengths, starting from a radio continuum band of 408 megahertz going up to 1.4 gigahertz, then 2.5 gigahertz, then at the molecular hydrogen level, infrared, mid-infrared, near-infrared, optical, x-ray, and gamma rays. And you can see for each wavelength, the universe, the Milky Way, appears different than before. That means there are different physical processes, astrophysical processes taking place at these different wavelengths.

And so if you really want to make a complete understanding about a particular source, about a particular object in the cosmos, you need to understand and observe at different wavelength bands. Only then you can reconstruct the information about the particular object completely. This theme is very, very popular, very common now, and so you not only observe astronomical objects only at a particular wavelength band, but also observing other wavelengths. This particular course will, unfortunately, only restrict our discussion to radio, and time and again we can compare our results, our information with others. This is an M51 galaxy, and you can see how, again, the same theme applies to that, how it looks in x-ray versus UV versus optical versus in H1 - 21 centimeters, that is

1.4 gigahertz, optical HST data, Hubble Space Telescope data, carbon monoxide line emission at 2.6 millimeters, then radio continuum, mid-infrared and near-infrared. So at every wavelength bands, it gives you a new information. Collecting all the information from different wavelength bands will help us to make a complete understanding of what's actually happening in this particular object. In astronomy, we are a little bit handicapped, that we cannot actually go near our objects and study them because they are very far away, unlike remote sensing, where you look towards the Earth, upon the Earth from satellites, but also you have the luxury to come down and actually go and verify the ground truth.

But in this case, you have to rely on multiple observations, same wavelength observation by different telescopes to validate the results of each other. Those are the things astronomers do follow. Another classic example of Centaurus A, again you can see for different wavelengths going from X-ray, UV, optical, mid-infrared, radio continuum, H1, 1.4 gigahertz, how the information varies. And if you make a composite image, you get a complete understanding of the object.

Okay, having said so, I hope we have explained sufficiently that the need to observe a particular source at different wavelength bands. Similarly, within the radio wavelength also, the different processes taking place from one end of the spectrum to the other end. And so it's very vital that we do observe at different wavelengths, even within radio spectrum, and make our conclusion about the particular object. Going to the next theme is just to give you a little bit of understanding of the size and the mass scales and the need to have the very essential, something called resolution on the sky. That will determine the important specs of the radio telescopes, which will come in a little bit later.

So an overview, this is our planet Earth. And the planet Earth on the left hand side has a mass of about 10 to the power 24 kilogram and a radius of about 6,000 kilometers. If you go to the nearest satellite, which is our moon, the radius, the size is significantly lower, about 2,500, about 2,600 kilometers in radius and the mass is significantly lower. If I approach our nearest star, which is the sun, the mass of the sun is about 10 to the power 30 kilogram and the radius is right now about 7 times 10 to the power 5 kilometer, not just in thousands, it's about 100 times larger than the size of the Earth. For the Earth, we had around 6,000 kilometers roughly.

And for the sun, we have 600, about 700,000. So about 100 times larger than the size of the Earth. If you go to the solar system scale, it's measured now in a different unit called astronomical unit. One AU or astronomical unit is roughly 10 to the power 8 kilometers. So sun, which is 700,000 kilometers, 7 to the power 5 and this is 10 to the power 8, so thousands times larger in dimension than the solar radius.

And so the size of the scale of the solar system is roughly about 122 AU, so about 10 to the power 5, 100 AU, the size of the solar system. So one AU is about roughly 10 to the power 8 kilometers. So it is much larger than the solar size and you can see the dimensions changing. So as we are zooming out from the sun, from our planet to the sun, to the solar system, the sizes are growing. A typical galaxy, which is a collection of stars and they're gravitationally bound, so roughly the size of a galaxy is about 100 kiloparsec.

Now again, it was AU which we started because as we move to larger and larger scales, we have to define larger units of length. Kilometer will not be sufficient. So one AU was about 10 to the power 8 kilometers. The galaxy, we are not able to measure in AU. We have to measure something called in kiloparsec.

So one kiloparsec is about 3 times 10 to the power 16 kilometers. And 100 kiloparsec is typically the size of the galaxy. So which means that 3 times 10 to the power 18 kilometer is roughly the size of a galaxy. So you can see from 600,000, sorry 700,000 kilometer radius of the star, our nearest star of the sun, we are growing up to about 10 to the power 18 kilometers, which is the size of a galaxy. Then several galaxies form galaxy clusters.

Each cluster has roughly a size of a few megaparsec. So it was kiloparsec. This is megaparsec. And it grows further. So just to summarize, it grows like from the earth, you are zooming out.

The solar system is again zoom out. The galaxies, the galaxy, then the local group, then local super cluster. So as we zoom out, finally, at the background, you see something like a cosmic wave appears. So at larger scales, universe appears to be isotropic, but not quite. And at lower scales, you can see individual objects. So if I, depending on what kind of science we do, the astronomers are also not, does not do, all of them do not do, are concentrating on the similar size topics.

Some people are interested in studying planets. Some people are interested in studying stars, star formation. Some people are concentrating on the galaxies. Some on galaxy clusters. And some even beyond large scale structures, cosmic wave, in understanding how the universe evolved from the beginning of the Big Bang till now.

So they are studying mostly large scale structures involved in cosmology. So depending on your object of interest, the telescope you choose should have the right resolution to be able to discriminate the one planet from the other, or one star from the other, or one galaxy from the other, or one galaxy clusters from the other, or the resolution can be poorer to see large scale structures. This actually is very important. There are two important features of a telescope. One is the field of view, how much can you look at at a given time, and how distinctly you can look at how much of a resolution you have to differentiate between a star which is towards this angle from the other star which is towards this.

And that makes, this too makes the most important aspects of building up a telescope, just like another radio telescope. Yeah, so beyond that cosmic wave we've come to study cosmology. This is something which is close to our heart. And you can see that as the Big Bang happened and the beginning of the formation of the universe and how the universe evolved and towards the present day scenario when we have the evolved galaxies, stars, and black holes. So they all make very important science cases to build a telescope.

Just to summarize the concept, the resolution of a detector is kind of the wavelength of operation over the size of the detector. We will come to that, all these things in more detail as our course progresses. But this is the basic concept you should be familiar with, that as the wavelength increases, the detector size also should increase to maintain the same resolution. Just for an example, a use case is, supposedly we have two telescopes, one operating near x-rays, another one operating in radio. The x-ray wavelength is much, much smaller than radio wavelength.

So if I want to look at the same object with same kind of a resolution, I need to have much larger radio detector to be built than the x-ray detector. So this is the conceptual fact you should build up from now. So for a shorter wavelength, small detectors are sufficient, longer wavelength, large detectors has to be built to maintain the same resolution. However, this is not the only part of the puzzle. Another part is if you make a larger detector, you also get lots of photons.

So to increase sensitivity, you need a larger detector. But anyway, we will come to all of those conflicts and resolve them one by one as the course progresses. So as we know, so we can expect as radio wavelengths is larger, so all radio telescopes will be also larger in size. If I can have a camera in optical wavelength, which can fit in my hand, that may not be the case for a radio telescope. So like rightfully so, this is a little list of the single-dish telescopes built in 1957.

There was this 676 meter Jodrell Bank telescope built in the UK towards your lower left. Then in Parkes, this is a 64 meter telescope. In Parkes, it was built towards the upper side on the left.

Then the F.S. Burke telescope, 100 meter plus telescope, on your right lower panel. And then finally, 300 meter telescope Arecibo in Puerto Rico, built in 1970s, 300 meter, the largest telescope built at that time. And Green Bank telescope, 100 meter, fully steerable telescope, which is also very important. And we will take the reference of this to discuss a lot of concepts of single-dish observations as we proceed through the weeks.

This is the Parkes telescope. And you can see that this is the telescope. So basically, actually come from the sky, they hit the dish, gets reflected and hits the central part, which has all the receivers over here. And then the signal is sent back to the lower part of the dish, the kind of the assembly and that they have other back end receivers to process the data. Now curiously, the center of the dish has a little bit denser mesh than the exterior.

And that we'll discuss later when we come. But because of the size, the gigantic look and the state of the art engineering, these dishes actually can point to any part of the sky with few arc seconds of accuracy. And they're really engineering marvels. And so something which is kind of state of the art also attracts the movies. So this was one of the movies made surrounding this particular dish, also named the dish of the parks. The next one, which is quite, those are the largest telescopes, even since the beginning of its inception and was there still it was operational, um, till another one came, I will mention it in the next few slides next.

This was a little bit different than the other telescopes, because this is fixed on the ground. It actually cannot move like the parks. This is fixed on the ground. However, there are different maneuvering with the central feed system. So the race comes reflects on the dish and gets collected by the central assembly.

And you can move them, orient them to be able to point to different parts of the sky, but in limited fashion. Again, this also attracted a lot of tourists as well as filmmakers. Unfortunately, this recently collapsed and is decommissioned now. It became quite old and so it's no longer operation are a sequel.

Here comes the successor. This is a 500 meter telescope built in China, and it is called the fast telescope. This is the largest telescope ever built. And it's also fixed on the surface of the earth. It cannot exactly move or point to different directions. And it can, there are hydraulics fitted below, which can point the surface, deform the surface such that it can limitedly point and track sources on the surface of the, on the sky.

This is the largest telescope built so far. Now, as you know, this is already 500 meters. Now, as I said, as you need to go to higher and higher wavelengths, you need to build larger and larger telescopes. So, the size of the telescope is quite a bit of a requirement to get the same resolution. However, at some point, the size becomes a big limitation also. It cannot keep building like 500, then one kilometer, then 10 kilometers.

It's impractical, huge cost, and very difficult to maintain. So, astronomers generally rely on something called interferometry, where instead of using one large dish, you use multiple smaller dishes. And you let the signals from each of them actually correlate with each other. Again, don't worry, all these terms are, can look and be, sound very superficial right now. But as we proceed, we will explain the detailed concepts and so you feel, you know, informed. So, the, one of the earlier interferometer is this very large array built in New Mexico, in United States of America.

And it has 27 antennas with each of them having a dish of diameter 25 meters. So, each of these dishes are 25 meters in diameter. And there are 27 of them as compared to one 500 meters, you have 27 of them of 25 meters. And so, the resolution now is determined by the largest distance between any of these two antennas.

So, VLA is a very interesting system. It operates on rails, so these can actually move this telescope from one place to the other. It operates in four different configurations. And yes, it's a very important telescope, so a lot of movies were also built on it. One of them is the classic movie Concat. So, this is the most compact, the same telescope, different picture, most compact configuration where it's called in D array and where the maximum distance between any two antenna is about roughly

1.1 kilometers. But then they actually move out from D to C to B to A. In the A configuration, the maximum distance between any of these two antenna is about 36 kilometers. And so, it grows from 1 kilometer-ish to 36 kilometers. So, it gives different resolutions and different other properties which we'll talk as we progress. So, the novelty is in here is that instead of building a single dish with a large size, difficult to operate, difficult to maintain and gradually will become impractical and extremely costly affair, you build multiple smaller dishes and let them signal to correlate with each other.

That's the principle of interferometry which is operational here. Closer to home, we have our giant meter wave radio telescope built little bit north of Pune in Maharashtra. And there the dishes, each of the dishes are about 45 meters in diameter compared to 25 meter in VLA. There are 30 of them compared to 27 in VLA. And they have another novelty in the design of the dish.

I'll come in a little bit. It was built by Professor Govind Swaroop and his team. It is a fantastic telescope at lower frequencies. It operates from 1.4 gigahertz down to about 150 megahertz and has several important science cases to be addressed by this telescope.

If you get a chance, try to visit. If you have already visited, you're lucky. And this is a very important milestone. So rightfully recognized by IEEE as an important milestone. And in March 2021, they conferred this special mention. So GMRT has 30 antennas, as I mentioned, and they are kind of distributed in the same Y shape like the VLA.

The only difference is VLA, the antennas can reconfigure the positions. They can move from one point to the other, whereas for GMRT, they are fixed. So because they're fixed, they're a little bit more in numbers. And to serve the purpose, they have a dense core central square with about one third of the antennas. And then they have these three arms, which kind of mimic the same as the VLA, three arms. One interesting thing about the, you can notice between the VLA and the GMRT is the dish is no longer solid in the case of VLA.

The dish is solid. And in here, you can see it is not a solid one. And it is perforated actually. So to keep the cost low, Professor Swarup undertook this particular novel design of making it perforated so that the cost goes down, but not the performance. And this is something we will again discuss when we come to the different antenna designs and configurations in a later part of the course. As we know that the more fainter signals you need to detect, the more larger telescope you have to build. So the community of radio astronomers across the world has come to a stage that they need really the next generation telescope where you need larger collecting area.

And you need longer distance between the antennas to have a higher resolution, sensitive detection, and large field of view to operate. That makes the next telescope worldwide to be built. It is called Square Kilometer Array. The name comes from, the square kilometer comes from, that is the equivalent collecting area that this telescope will have. It operates, it is designed to operate from as low as 70 megahertz in the frequency up to 14 gigahertz in the frequency.

However, as I said already before, that there cannot be a single receiver built to operate at such large frequency. It also appears that a single telescope design is also not feasible to give it the same performance across this wide band. Hence, the square kilometer array, although being a single telescope, they divide into two sub-telescopes. One which is operational from around 70 megahertz goes up to 350 megahertz or so. And another one starts from where the other one lives and goes up to 14 gigahertz or so.

One of them will be, the lower one on your right hand side will be in Western Australia and the higher one will be in Western Africa, South Africa basically. Okay. And they are both located in regions where it is mostly desert. The population is very less. And one of the reasons is that if you stay close to the very populated areas, human, nowadays we depend really a lot on cell phone transmission, satellite navigation, you know, dish TV, FM channels, lots of other radio wave interactions, which actually pollutes the entire electromagnetic spectrum and makes it difficult for astronomy to succeed.

Hence, we choose a very quiet part of the world where there's less human beings and less pollution from the spectrum usages. And that's why these two are mainly built in the desert areas in the both these two countries. And the good part is India, along with a lot of other international collaborators, collaborating countries is also part of this escape project. And it's really fascinating to discuss and we'll keep coming back to this project throughout the course of this version of this course. So if you are just joining in to learn a lot of, you know, new information about what is the status of radio astronomy, what is the status of astronomy at the current age, one interesting thing which SKA will bring is a lot of data.

So even if you're not interested in astronomy per se, but is a data scientist or aspiring data scientist, SKA is the telescope to look for. The estimated data rate from the low telescope in Western Australia will be around 157 terabytes per second, per second, again 157 terabytes of data per second. And from the mid telescope in South Africa is about two terabytes per second, a little bit modest, but still it is per second. So supposedly we observe an entire day, this telescope will also throw at you about 50 terabytes per second.

So tons of data for a given day. So it's a huge project data-wise. It's a challenge where to store this data, how to analyze this data, and astronomers are, along with software engineers, great minds from computer science, computing communities are really working together to understand and make way to this new regime of data analysis, data science. We need to throw away the bad data, irrelevant data quite fast. We can have to only store the relevant data which is usable and which needs to be stored because storage will become a big, big issue. So it's a very exciting time in terms of contribution. If we have skill sets in data science, high performance computing, in data mining, machine learning, artificial intelligence, this is going to be a very exciting field to come.

So what are we looking at? We have made a telescope, the telescope is made as large as possible. We look into the sky and what we observe, this is how the galaxy appears if we look at it, the full sky. This is a very early map made by Haslam in 1982 and it's still used for lots of purposes, understanding the galactic contribution to a deep sky for several cosmological applications which will come. Sky has been mapped at different frequencies starting from megahertz up to terahertz and we know how the major blocks of the sky components work, like our own galaxy, then certain extra-galactic compact sources, radio galaxies which are active in radio wavelength called radio galaxies, quasars, agents, how they behave, how they work.

But there are lots of queries still pending to be answered. Things like first radio burst becoming a very popular topic now and several other cosmological things like understanding about the very early universe where the universe was still very young, familiar, billion years from the big bang, how the first stars formed, how the first galaxies formed, how the first black holes formed and how they evolved to this current generation, galaxies, stars, black holes. So and several more queries, extra solar planets, are there life which exist outside the earth, are they intelligible, intelligent life which exists and why not. So several things and radio astronomy plays an extremely crucial role in all of them. You can make very deep radio maps, that's what these telescopes are going to do. GMRT does, as you can see here in this slide, but telescopes like SKA will make it much more deeper, much more wider and you can see lots of things, you can even see right now lots of radio galaxies and the lobes and the core and you can see much more and much more deeper, much much deeper than this for the SKA.

Here is another view of another part of the sky. Now again if you're looking at clusters, galaxy clusters, diffuse emission, you can see this is a composite image for background is optical mostly and this foreground diffuse stuff is from the radio and you can see that these diffuse emissions when the radio wavelengths were not visible to us just by the optical and other observations so it's very much required and lots of different information comes just particularly in the radio band. Another important, although quite a little bit higher in the frequency range, but is contextual for this particular course is this telescope called event horizon telescope. This is not a single telescope, again as you said the longest distance determines your resolution. So if you're trying to look very very close to the black hole which is kind of at the heart of any galaxy.

Supermassive black hole is generally at the heart of every galaxy. So if you want to image that, if you want to detect that, that resolution is obtained only if you take the largest baselines possible on the earth. And so this event horizon telescope is actually a conglomeration of several telescopes and operating at a higher frequency because resolution also becomes higher as your frequency goes higher or wave lengths go slower. And this involves another very large telescope called ALMA, Atacama Large Millimeter Array and then several others like Submillimeter Array in Mauna Kea in Hawaii, then Large Millimeter Telescope in Sierra Negra, Mexico, South Pole Telescope in South Pole and several others, Noyama Observatory in France and they form this particular event horizon telescope. So what is the best part? They first imaged the supermassive black hole at the heart of M87 and that was huge, you know, press and for the first time we saw the shadow of the black hole and that's because of this. And you see this is the 40 micro arc second is the the distance so the resolution is tremendous and so you need to go a little bit higher in frequency and also get the largest baseline possible to get this detection done.

But it gets even better then they finally came up with the shadow of the black hole at the center of our galaxy and this is really fantastic and opened up another really important aspect of radio astronomy and this gets really better. So I'm quite excited in being a radio astronomer myself. I hope this introductory video, the first lecture on this particular course is appeared interesting to you and lots of puzzles still, size of the dish, resolution versus collecting area versus sensitivity versus field of view, all those will be answered in the subsequent lectures. In the next lecture, however, we will go a little bit back before taking the plunge towards the forward and we'll review some of the essential electromagnetic theory which will help us to go forward. So stay tuned, thanks for joining us. See you next time.