Fluid Dynamics for Astrophysics
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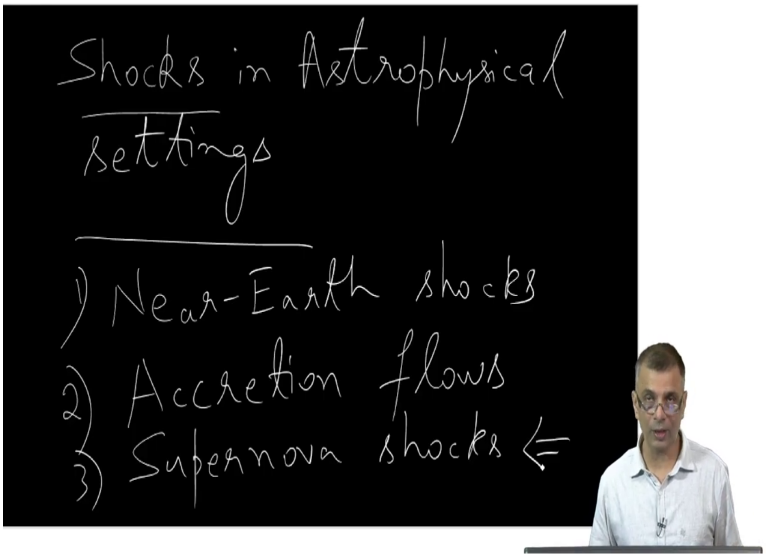
Lecture - 42
Particle acceleration in astrophysical settings: Shocks and non-thermal energy distribution



Hi. So, after having discussed some aspects of accretion disks, accretion onto black holes and the solar wind and so on so forth, let us now move on to a slightly different topic that of Shocks in Astrophysical settings right. We have come across shocks already of course; in fluid dynamics, we have just to review shocks are essentially mathematical discontinuities that are to be found in supersonic flows.

In particular, they are a particular kind of transition from supersonic to subsonic flows. Remember, whenever we were talking about transonic flows a till quite recently, we were not talking about shocks, we were talking about a smooth transition from subsonic to supersonic or supersonic to subsonic right. But, shocks on the other hand, are a particular kind of transition ok. They represent discontinuities in the flow and turns out that shocks are quite ubiquitous in astrophysical settings ok.

And, so, since this is a course on fluid dynamics in astrophysical contexts, we will investigate in what kinds of astrophysical settings shocks are to be found ok. And so, turns out the answer is in many settings ok, for one shocks are to be found near earth and these are the best observed shocks near earth shocks ok.

Shocks are also expected in accretion flows in fact; especially in disk accretion flows ok. Although, we did not discuss shocks ok, because I wanted to keep things simple, shocks are to be found in accretion flows as well and in supernovae and this particular aspect is what we will discuss in some detail ok.

But, before that I thought I would give you a very quick, you know overview of what shocks are I mean you know and why shocks are interesting in astrophysical settings ok. It is not simply the fact that you know shocks are to be found. They are they perform a very useful you know role in astrophysics; they are kind of unavoidable ok.

There have to be shocks in order to explain certain observations and that is why we want to understand how shocks arise. Before going on I would just like to tell you that these are the best observed shocks right, and near earth.

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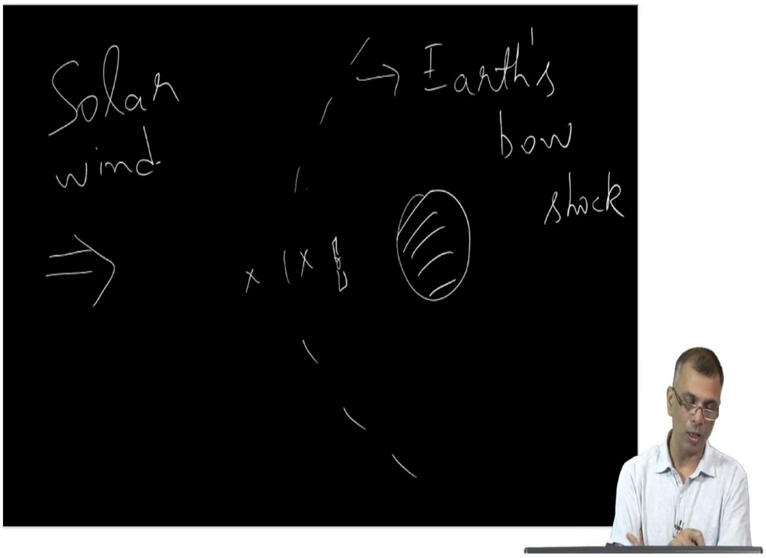

And so, these kinds of shocks are formed when you see here would be the earth ok, and the solar wind is supersonic by the time it reaches the earth ok. So, the solar wind is essentially impinging on to the obstacle that is the earth, ok and that forms what is called the bow shock something like this ok.

So, this would be the earth's bow shock and these are the best observed shocks ok, because you see you have spacecraft stationed here, say this would be my spacecraft those little sails and so on so forth. And many times this spacecraft can actually, sample both the downstream side of the shock which would be here and the upstream side of the shock.

They actually, go back and forth between the shock and they obtain very detailed observations, remember what the shock is simply a discontinuity in all physical quantities such as velocity, pressure, density all of these things and there are sensors inside this spacecraft.

And, the spacecraft move up and down you know, otherwise you never know whether the shock is there or not they move up and down and they sense that there are they actually, take detailed measurements of the fact that there are you know large jumps in these physical quantities between this side and that side.

And therefore, you are certain that there has to be a shock there and then you try to figure out well, why should there be a shock and then you reason that that is probably because, the solar wind which is impinging upon the earth and the earth is a solid obstacle.

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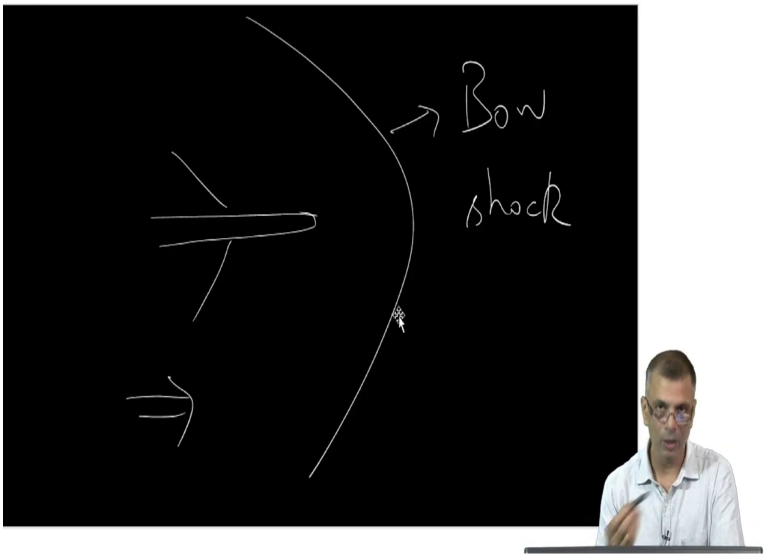

And, it forms a bow shock much like the other very well known example which is that of a bullet or of a say you know very sharp object a sharp nose object like this, this could be a bullet or it could be an airplane for instance, and when it is flying supersonically it forms a bow shock ahead of it and this would be a bow shock.

So the earth's bow shock is very very similar to that ok, it is very very similar to this and hence, in these kinds of situations of course, you know you have these are lab situations and you so, you would have very detailed measurements on both sides of the shock and you would be able to you know figure things out.

In astrophysical settings this is the best you can really do by way of actually measuring the different quantities like the velocity jump, the density jump and so on so forth. The earth's bow shock is your best chance of the doing so, because any other astrophysical setting such as supernovae, black hole so on so forth, are too far you know.

There is no way you are going to be able to send a spacecraft out there ok whereas, near the earth you can have spacecraft and these spacecraft sample both sides of the shock and they actually, explicitly verify that there are jumps in these physical quantities and hence, you are able to confirm that there is a shock there.

Now, coming on though going on though this is really not you know, I would say that in astrophysical settings it is one thing to sort of figure out that there are shocks in that is that is a matter of some fundamental interest.

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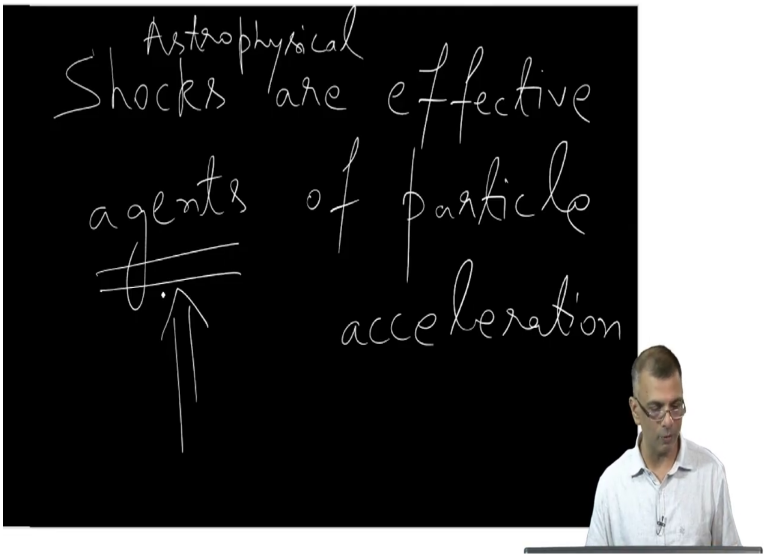

But, more importantly shocks are very good agents for accelerating particles and this is really shocks are effective agents of particle acceleration off or far, if you will particle acceleration and I will explain a little bit about what particle acceleration is as opposed to heating. And, so, this is what I wanted to cover first before going on to supernova shocks.

But, the main thing I wanted to you know bring across here, is that really the utility of shocks in astrophysics is that of they are very good agents ok. The point is you observe accelerated particles, you observe indirect signatures of accelerated particles and in a minute I will explain what I mean by accelerated particles.

And, so if these particles are being accelerated so efficiently, you have to search for agents ok. Who is accelerating this particle so efficiently and turns out that shocks are natural agents ok. So, then you say ok, well if shocks are natural agents can we investigate how they are formed and can we sort of draw up elaborate or to the extent possible to elaborate plausibility scenarios to figure out how these shocks are formed ok.

So, this is really the context in which we study astrophysical shocks, I should say astrophysical shocks are effective agents of particle acceleration. So, the utility of shocks is here ok, they are very good agents for particle acceleration and so, this is what we will focus on.

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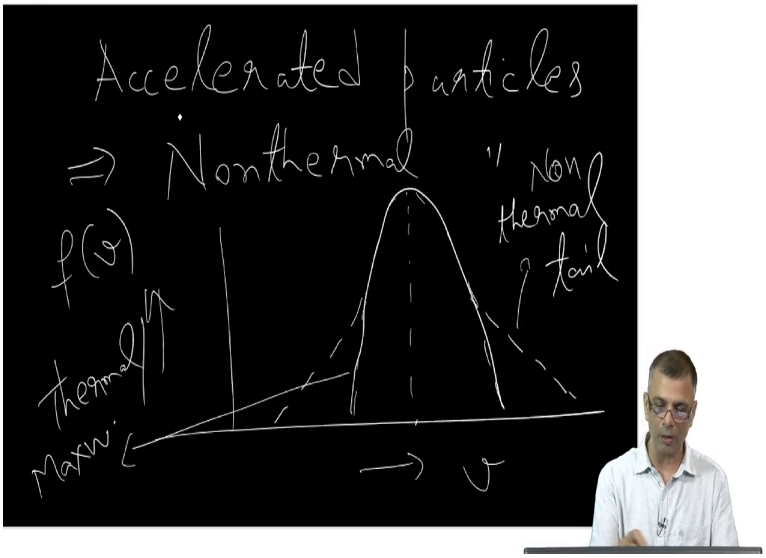

Now, what really do I mean by particle acceleration right? Now, what I mean by accelerated particles and these particles can be anything. These particles can be protons, they can be electrons, anything turns out that electrons are the ones which are most efficient radiators. So, most of the time when we talk about accelerated particles, we are really referring to electrons ok.

Let me finish what I was trying to say, what I mean accelerated particles I really mean non-thermal particles. I use this nomenclature, because these two things are you know used interchangeably in astrophysical, people sometimes say non thermal particles, sometimes they say accelerated particles, they are one and the same thing.

Now, what really do I mean by non-thermal particles? Well, particles that are not thermal as simple as that ok. So, consider for instance, you know say a distribution function with either velocity or energy on the x-axis like for concreteness, let us just say velocity and the distribution function f of v on the y- axis and a Maxwellian distribution would look somewhat like this, somewhat like this ok.

So, this would be let me join this and this would be I am not very good at drawing these things right. So, this would be a Maxwellian a thermal distribution ok, thermal distribution which is peaked around some velocity right. So, this would be the root mean square velocity and it falls off very sharply, it falls off exponentially as we know. This would be a thermal or thermal slash Maxwellian distribution, right.

Now, what do I mean by non-thermal? Anything, that is not this really. In particular, what we observe most of the time in astrophysical situations is that there is a very often a non-thermal tail, in other words there is an enhancement at higher velocities and since, where velocities can go either way positive or negative, I will draw this here also. This is what a one would call a non-thermal tail.

Why tail? Well, you see we are talking about the tail of the Maxwellian distribution, when you are talking about the highest possible velocities that can be expected at a particular temperature, you certainly find in many settings that there is a non thermal tail ok. You cannot possibly explain this tail by appealing exclusively to thermal Maxwellian this is the rub ok.

And, therefore, this is called a non-thermal tail and so, these are the kinds of particles that we refer to as non-thermal particles or accelerated particles ok. So, this is the deal.

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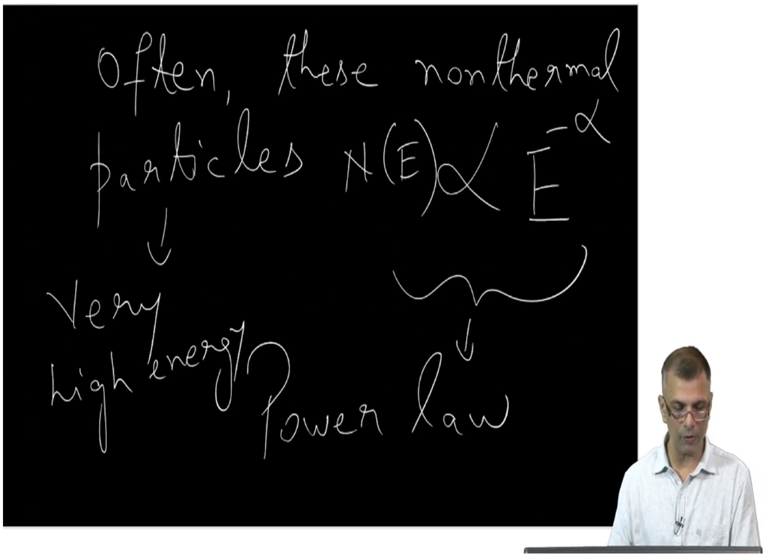

And, often these non-thermal particles, the distribution function of these non-thermal particles a number per unit energy it does not follow a Maxwellian, it follows a power law like this, where this is the index of the power law ok. So, this would be a power law distribution of energetic particles. It would be something like this right here. This would follow v raise to minus alpha kind of distribution ok.

So, this is the kind of accelerated particle distribution, which we hold shocks responsible for. Before, we go ahead I want to say one thing very very clearly, shocks are a fluid phenomenon right, whereas, these particles that we are talking about these are not part of the general fluid. These are test particles ok. So these non-thermal particles these are very high energy.

In other words, they form part of the tail of the distribution whereas; when we talk about the fluid, we are talking about this part the low energy part. When we talk about the accelerated particles, we are talking about the very high energy part ok. And so, the mean free path for these non-thermal particles is much longer than the particles which form the bulk of the fluid. And so, they are not really part of the fluid ok.

And, we know this you know when we talk about fluids there are no particles right. There is no meaning in talking about particles inside a fluid the whole point of talking about a fluid is that you are smoothing over the particles and you are really talking about the continuum ok.

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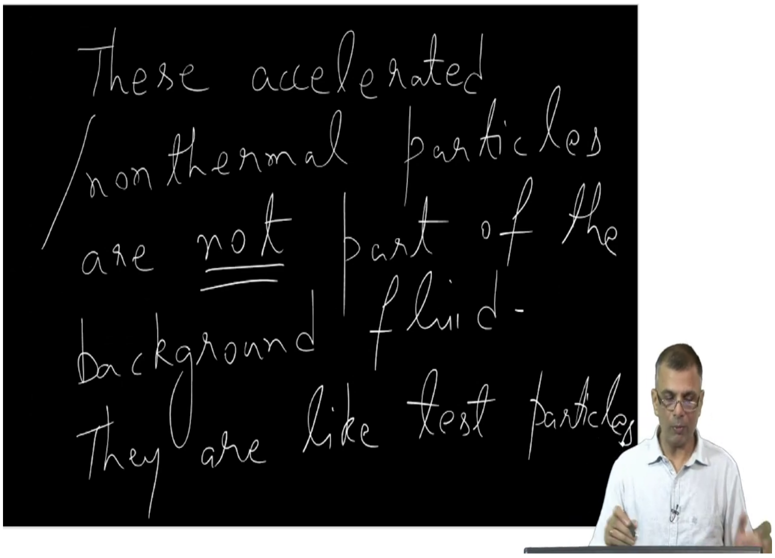

So, I want to emphasize this these non thermal particles, these accelerated or slash non thermal particles are not part of the background fluid, is very important ok. They are like test particles. So, why is that?

Well, because, these accelerated non thermal particles are very high energy ok. And so, they form part of this non thermal tail and the higher the energy the longer the mean free path. So, you know their mean free path is so large that you cannot justify them as being part of the fluid. So, they are really you really have to follow them in a particle wise nature you have to follow them particle by particle ok.

Whereas, the background fluid would be these low energy particles, these guys and the shocks and other things are mathematical they are discontinuities in the background fluid ok. So, the shocks are a property of the background fluid ok, and they serve as agents to accelerate particles and so, the accelerated particles are essentially test particles which are sampling the shock which is formed in the background fluid ok.

And, so, this test particles get accelerated. They gain more and more energy ok, and in many settings in astrophysics, you find that these accelerated particles have very unique signatures and so, what you are actually observing are signatures of these accelerated particles. Those are the real observables in astrophysical situations.

So, you observe these signatures of these very high energy particles and you conclude that these are particles that cannot be thermal, they have to be non-thermal and then you ask the question well, how did they get to be non thermal? Ok, you ask the question how did they get to be non thermal and then you conclude that they have to be scattering off of some scattering centers, we will deal with that in a minute.

And, so, then you come to the conclusion that you have to have agents that are accelerating these particles and then you ask well, what could these agents be? And the answer is well, one of the possible agents are shocks in the background fluid, and these shocks are very effective agents for producing these accelerated non thermal particles.

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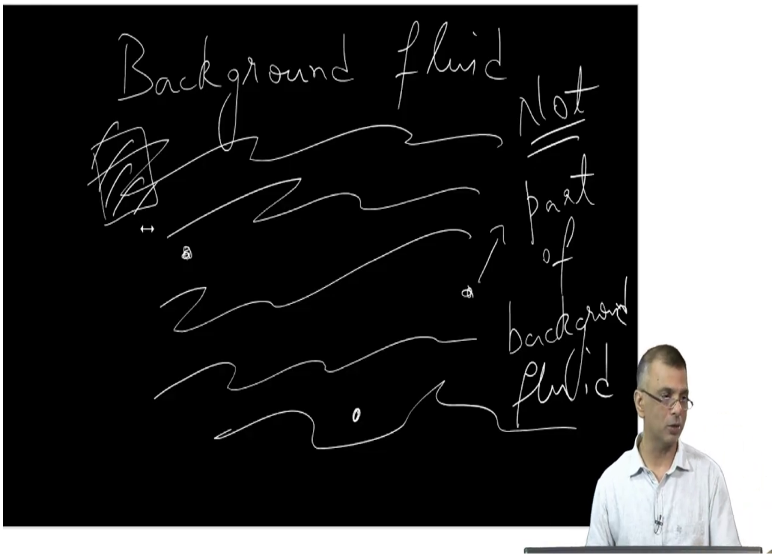

So, I want to close this part of the discussion here, but I want to make this very very clear that the accelerated particles are not part of the background fluid, it is almost as if you could think of the background fluid, So, say the background fluid as some kind of you know some kind of fuzz like this say some blue colored fluid or some something like that ok.

And, many times in this background fluid you might have shocks, but these accelerated particles are if this is blue ok, then these accelerated particles would be red for instance ok, and the accelerated particles are not part of the background fluid, the accelerated particles are just one here, one here, maybe one here.

In the background fluid you have many many many many many background particles of course, that is a whole point right. You have lots and lots you take a little parcel of this fluid and you have maybe 10000 background particles here whereas, accelerated particles you are talking about they are not part of the background, they are discrete very high energy particles.

The main free path between them is very long they are not part of the background fluid. So, these are not part of background fluid ok. That is what I mean by this and the background fluid is the fellow who form shocks and so on so forth ok.

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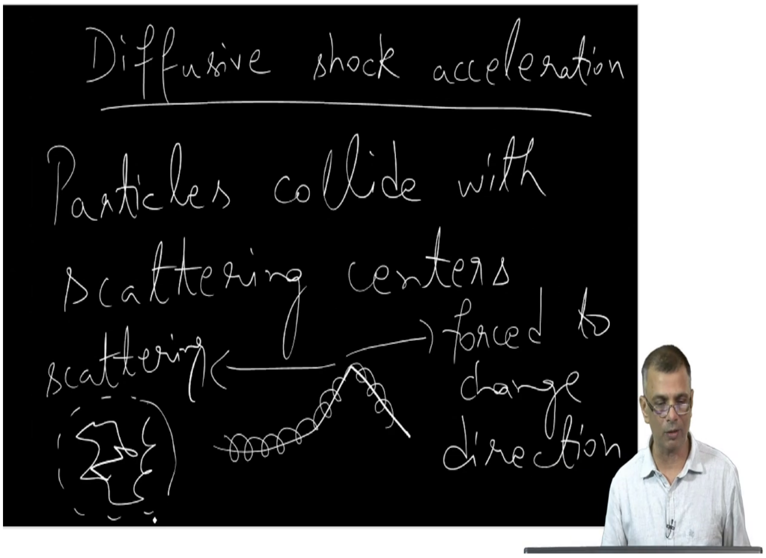

So, now let us move on and let us ask about something called. So, shocks are responsible for what are called diffusive shock acceleration, and we will discuss this in a minute. But, even before that the point is particles how are these particles accelerated? The point is particles, the particles which are these guys which are these guys these large fellows let me write this down.

So, these guys right, so, these particles collide with scattering centers and the concept of these scattering centers is a little vague I must say. What could the scattering centers be? Well, for instance, this scattering centers could be kinks in the magnetic field ok.

So, consider a magnetic field like this which suddenly has a kink here. So, this would be a magnetic field and you have a given particle which is merrily you remember a particle you know a charged particle likes to you know gyrate along a magnetic field and if it has already a parallel motion it sort of follows a helical path.

But, you see it is merely following a helical path as long as it can smoothly follow the field line, but if there is a very sharp discontinuity here, then it is forced to change direction to change direction and at this point this would be what a scattering event would be, because that is what scattering is right.

When you have a particle merely moving along it encounters some kind of a scattering center, some kind of a collision it abruptly changes direction. So, this would be an effective collision so to speak ok. So, particles they gain energy via collisions with these kinds of scattering centers ok. And, so, let the gain in energy due to a collision these are inelastic collisions ok, let the gain in energy due to a collision be some beta.

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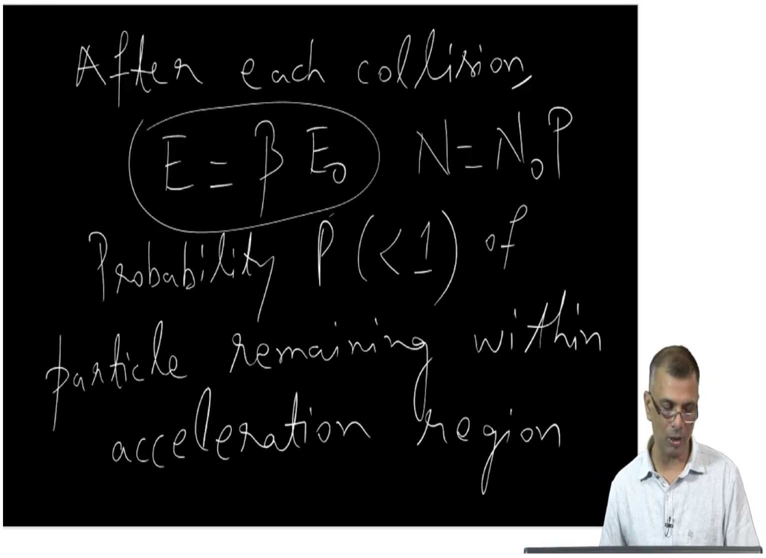

So, that after each collision, the energy of a particle is beta times E naught, where E naught would be the energy before collision and E would be the energy after collision and beta is a gain parameter. So, these are all inelastic collision ok. But, the point is it is not as if so, you have a certain volume ok and with lots of scattering centers, it is not as if a given particle can keep rattling around and keep gaining energy you know indefinitely.

No, there is always a certain probability that you know particles will escape the acceleration region, ok that is because, you see there are lots and lots of scattering centers like this like this you know. For instance, there can be many many many many scattering centers like this

And, so, at each of these kinks particles can you know gain energy, but at the same time they are also performing a diffusive random walk. And they can walk out they can walk out of this acceleration region. This would be the acceleration region and they can walk out of this acceleration region.

So, there is a probability P which is of course, less than 1 that of particle remaining within the acceleration region. So, the acceleration region or collision region if you will ok, so, there are two things happening here, number one after each collision there is an energy gain given by this and the amount of energy gained in each collision is beta, at the same time after each collision the number of particles is equal to N naught P.

So, so N naught times P so, after k collisions you see the number of particles remaining would be N naught P raised to k and P is less than 1 right and after k collisions the amount of a given particle would have you know this is ok. Let me erase this for the time being since, I have not written k collision since I have written after each collision I will I will keep this as it is.

After each collision there is a non zero you know, but less than 1 probability that particle will escape the collision region and that is given by this and after each collision you know the energy gain is E is equal to beta times E naught, ok.

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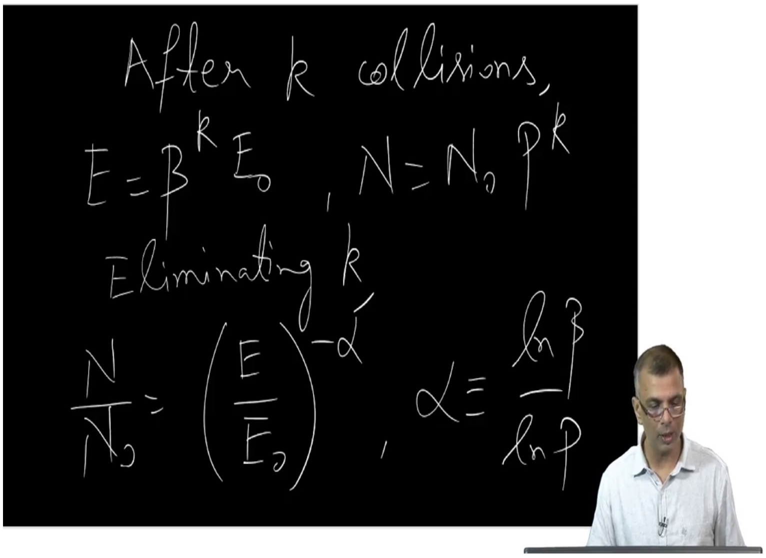

Now, after k collisions what happens is the E is equal to beta raised to k E naught ok. So, this is my way of writing beta and that is not very good and beta ok, and after k collisions the number of particles left in the acceleration region is N naught P raised to k, where P is less than 1 ok.

Now, I eliminate k between here and here I use k here I take a logarithm and I use the k here, and I plug it in here ok. Eliminating k, I get N over N naught is equal to E over E naught raised to minus alpha where alpha is equal to ln beta over ln P.

So, here is what we were after. You remember, that in our discussion of accelerated particles I said that most of the time these non-thermal particles have a power law kind of distribution in other words they are non Maxwellian. This would be a power law tail, ok, and here is a way you could possibly get a power law tail. How is that?

Consider a phenomenological acceleration region and these test particles are sampling scattering centers. What would these scattering centers be? These scattering centers could be magnetic kinks like this, little kinks like this. There are lots and lots of kinks inside this acceleration region.

At each kick the collision is inelastic and we will demonstrate, how this such inelastic collisions can come to be at after each collision there is an energy gain beta, but at the same time after each collision there is a probability that the particle does not remain within the acceleration region, it escapes out of the acceleration region. So, P is less than 1 ok.

So, after k collisions what happens is a given particle has. So, beta is greater than 1. So, a given particle has increased in energy ok, beta raised to k. So, the energy keeps increasing. It goes farther and farther into the non thermal tail, at the same time the number of particles which are remaining inside the acceleration region becomes lesser and lesser.

That is why you see here, the higher the energy the lower the number out here the lower the energy the more the number, but the higher the energy the lower the number and that is exactly what is happening here ok. The higher the energy, the lower the number and in particular if you eliminate k between here and here you get a power law kind of distribution.

So, this would be the number of particles as a function of energy and this has a power law distribution and the index of the power law is ln beta over ln P. So, this is a quick sort of demonstration of how you could get a power law distribution of accelerated particles, due to collisions with some sort of phenomenological scattering centers.

However, I want to again emphasize that these accelerated particles are not part of the background fluid. We have not even started talking about the background fluid yet, the background fluid comprises of very low energy particles. You take a little parcel of these background fluids and there are many many many many low energy particles, they are probably a colored blue ok.

Whereas, these particles accelerated particles we are talking about, they are very high energy particles; say think of these as colored red and they are few and very far apart. They are not part of the background fluid; they are test particles which are sampling properties of the background fluid ok, and getting accelerated in this manner.

And so, now, when we meet next, when we may take up the next part of the course, we will discuss how shocks in the background fluid can serve as agents for accelerating these particles. So, we will stop here for the time being.

Thank you.