Introduction to Astrophysical Fluids
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Lecture - 43
Description of a plasma

Hello, and welcome to another lecture session of Introduction to Astrophysical Fluids. In the last lecture session, I gave you a very superficial zeroth level introduction to Plasmas. Once again, this course is only to give you a very superficial introduction to plasma, and we will mostly be interested in the fluid aspect or the continuum aspect of a plasma.

However, in this lecture, we will also discuss some aspects, I mean just like we did it for neutral fluids, some aspects of the different levels of dynamic dynamical theory, starting from the very particle description to the continuum description for a plasma.

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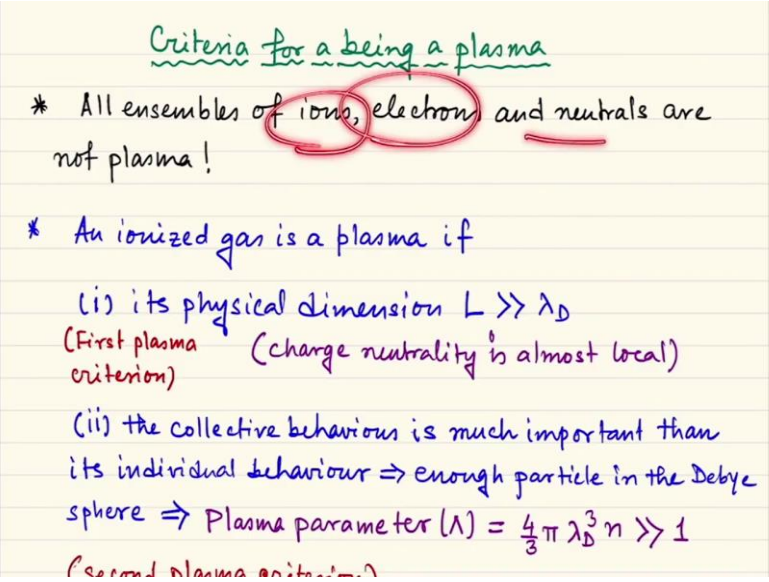

So, we all know now roughly what a plasma is. So, just start this lecture by just characterizing formally a plasma. So, we know that plasma is nothing but an ensemble or a collection of ions, electrons and neutrals, and plasma is in general obtained by heating or I mean applying sufficient amount of energy to a gas. So, plasma is called fourth state of matter. So, this is an ionized gas.

So, this is of course, the definition I mean practical definition of a plasma, but we have to be careful that any arbitrary ensemble of ions electrons and neutrals they are not a plasma. So, we really need to specify the characteristics of a plasma, so that we do not just call any arbitrary ensemble as plasma, but to know that there is only a specific class of the ionized gas the they are called plasma, and how to characterize that?

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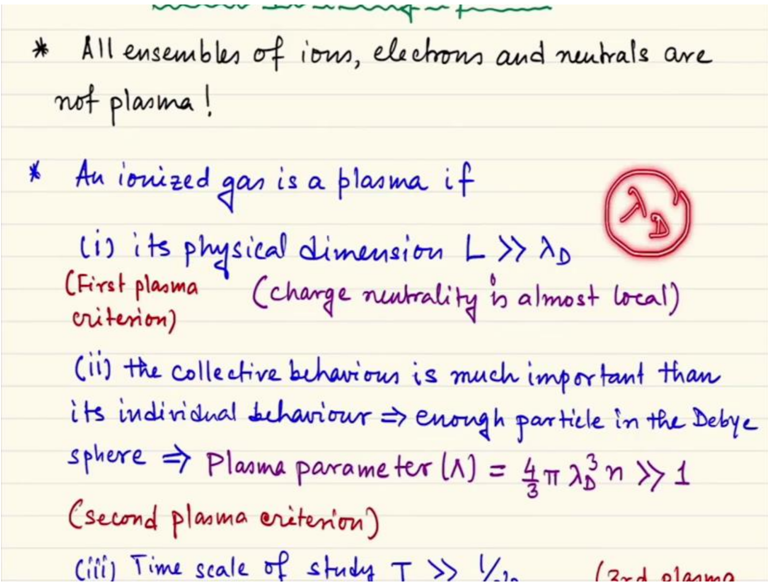

So, we have several criteria. First one is that its physical dimension which is capital L should be very very greater than the Debye length of the system, and this is known as the first plasma criterion, and that is completely very intuitively very well justified because we already said that for a gas ensemble to be plasma the first requirement is that the ensemble should be quasi neutral right.

So, first of all, it should have a global quasi neutrality, and also you can see that if we say this type of thing that the physical dimension L is very, very greater than this λ_D, then we can also say that the charge neutrality is also achieved at the very local level.

Why is that? Because if you remember that λ_D is the length scale below which the charge neutrality cannot be expected, but beyond which the charge neutrality is always true.

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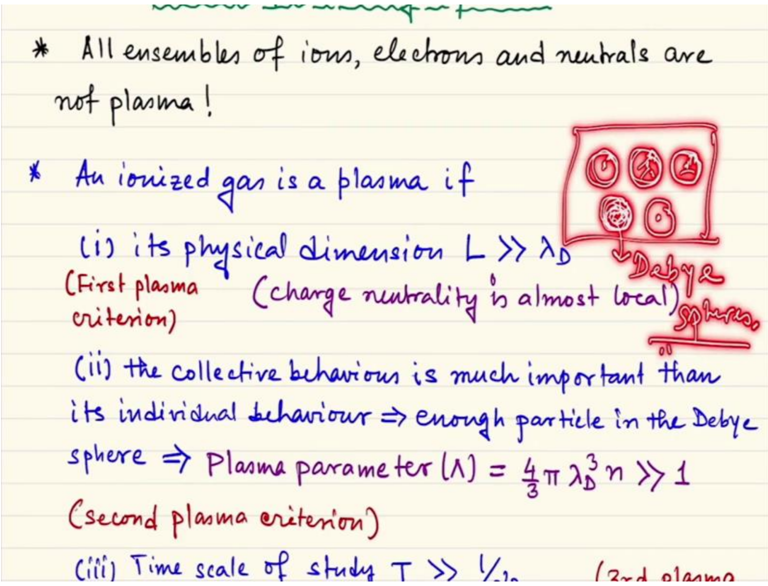

So, if your plasma is like an ensemble like that and you have several spheres with radius equal to Debye length, so just inside that sphere you can have violations in charge neutrality. But just if you take these spheres as the unit of your system, then your system will more or less behave as a neutral particle because you cannot see any charge neutrality, any violation to charge neutrality beyond this sphere, these spheres are known as Debye spheres.

The thing is that if your Debye spheres are very, very small with respect to the global dimension of the plasma system, that means, if they are like this then you can simply say that almost locally that means, the length scale over which some plasma parameter can change considerably.

So, over that length scale, if you can expect the charge neutrality, then you can say that my system is locally also charge neutral, of course, quasi neutral as I said that the charge density should be roughly 0. It should be negligibly small and not exactly equal to 0. If it is exactly equal to 0 that is something bonus, but in general it is not really necessary.

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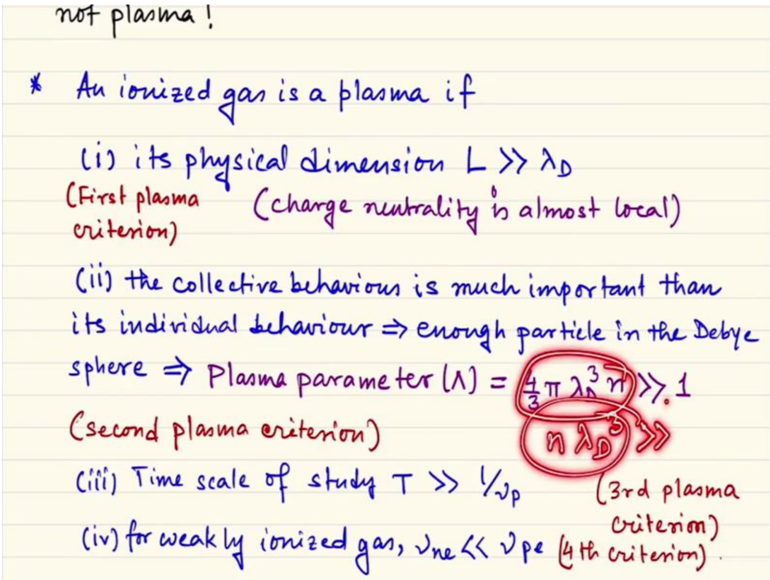

Now, the second criterion is the collective behavior and that is very, very important for a plasma once again, and for a plasma, the collective behavior of the particles is much more important than its individual behavior.

So, the requirement for this being true is that we should have enough number of particles in that Debye sphere. So, once again, if your Debye spheres are consisting of one or two particles, then actually the charge neutralities are constituted only by one or two particles.

So, if you are now seeing the system, you can actually say that the representative particle which is in a Debye sphere for this ionized medium is almost of the same scale of a real particle, so then individual particle behaviors cannot be neglected.

But if every Debye sphere is consisting of a large number of particles, then you can say, the representative particle, the Debye particles of my ionized medium is much more greater or consisting much a very large number of the ions and electrons, so that the individual ions and electron properties are not really important always.

Of course, in explaining several phenomena, we need to use the information about the individual behavior of the particles, but we are not going into this. So, this is something, once again we are not saying that the individual behavior will be exactly 0 or totally nullified. We are simply saying that the collective behavior is much important, and the requirement for this is that we have to have enough number of constituent ions, electrons inside the Debye sphere.

And then we roughly define parameter called plasma parameter, well, this is roughly the number of the particles inside a Debye sphere. So, the volume of the Debye sphere is this $\frac{4}{3}\pi\lambda_D^3 n$, and n is the number density.

So, sometimes you can see this as a plasma parameter in several books it is simply written in λ_D^3 that you can also write as plasma parameter. But whatever, this is just a matter of convention in both cases. So, this one $\frac{4}{3}\pi\lambda_D^3 n$ should be very, very greater than 1, so that is the requirement, and this is called the second plasma criterion.

Now, the third one is also very true. So, we just talked about the quasi neutrality in space. Now, we talk about the quasi neutrality in time, that means, the charge neutrality if it is part out very weakly, then the corresponding species will try to respond in such a manner that the quasi neutrality is achieved or retrieved in a time which is equal to $\frac{1}{\upsilon_p}$, υ_p is nothing but the plasma frequency.

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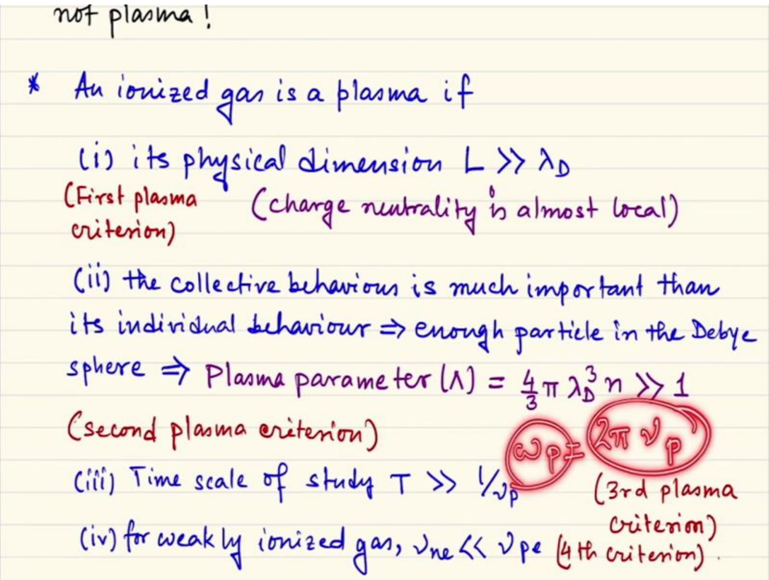

Now, ω_p is called sometimes the plasma frequency, in most literature, but this is nothing but 2π times the real plasma frequency. This is the angular plasma frequency.

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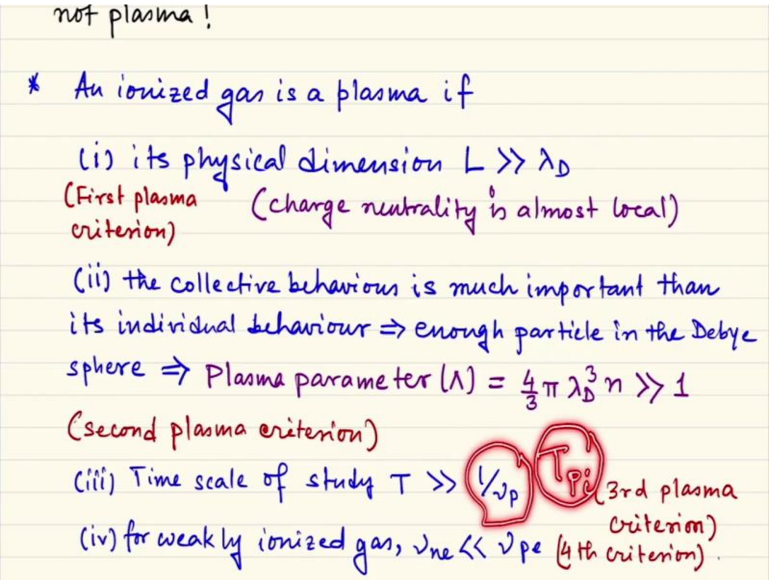

So, $\frac{1}{\upsilon_p}$ is the time required for any species. So, if it is T_{pi} that will be for the ions, if it is T_{pe} that will be for the electrons, it is the time required to get back or to retrieve the state of quasi neutrality again in time. So, an ionized gas to be plasma, the time scale of study of the system should be very, very large with respect to $\frac{1}{\upsilon_p}$. .

So that we can never see this transient phenomenon of the charge imbalance.

So, we always study the system in such a time scale that the charge imbalances are not really of importance, so that is the thing. But of course, there are several phenomena where charge imbalance, they cause something very important.

So, we are coming to that. But these are very, very rough primary criteria of a plasma. You have some static ionized gas medium, and with respect to which now we have to conclude whether this gas medium is plasma or not, then we use all these criteria.

Finally, for weakly ionized gas, if the gas is not sufficiently ionized, that means, the plasma is nearly a cold plasma if you remember, then what happens, then for this to be a plasma the corresponding criteria is that the frequency of collision between the neutral and the electrons because now the medium is consisting of a large number of neutral particles, should be much, much less than the plasma frequency of the electrons.

Otherwise, the charge neutrality would not be preserved. So, this is called the fourth criterion.

So, if the charge neutrality is broken by a weak perturbation, and then after that if the collision between neutral and electrons, they are very frequent, then the particles do not find much reason to get back its original position of charge neutrality once again.

That is why, once the charge neutrality is broken, it is very difficult to get back the charge neutrality again. If your collision between the neutral particles and electron is sufficiently large, and that is not what we want to get back the quasi neutrality. So, this is the required criteria to get back the quasi neutrality.

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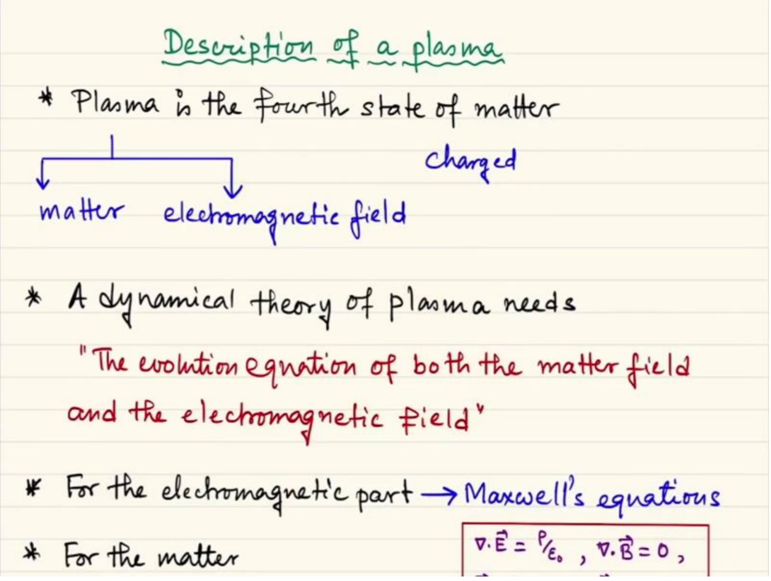

Now, how to describe a plasma in general? We already stated that plasma is the fourth state of matter and so it has actually two components, one is the matter, another is the electromagnetic field because the plasma is charged. So, it has ions, electrons and which are moving.

So, I said in the previous lecture that the charge electrons, and ions, and neutrals, they should be moving, and as they are moving, then in both electric fields and magnetic fields they should be coming into play. Otherwise, you can also think of that is something they are creating.

Now, of course, if you give some external electric or magnetic field, then also the charged particles will be affected by that. So, when we are talking about the fields in a plasma, there are two parts. One is the electromagnetic field which are exerted from exterior, another is the electromagnetic field which are created by the species themselves.

So, that we will try to distinguish when we will talk about the evolution equations of the plasma species.

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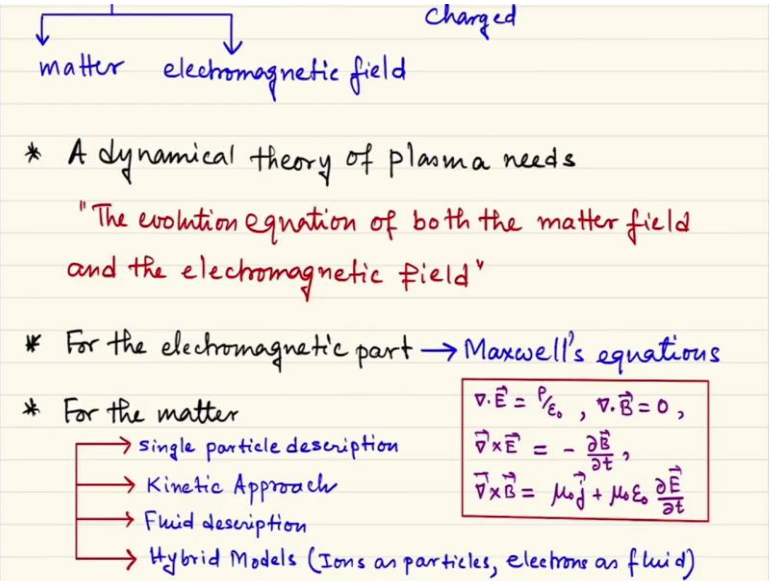

Now, just remember what was our previous objective to make or to construct a dynamical theory for some continuum. So, for neutral fluid, it was just the hydrodynamics. Now, we have to make a dynamical theory for the plasma, so that we can do something for astrophysical fluids, and such a dynamical theory necessarily requires the evolution equation of both the matter fields and the electromagnetic fields.

Now, for electromagnetic fields, we do not have much choices right. We simply know that one is Maxwell's equation. So, the field evolutions are always governed by the Maxwell's equation. So, we do not have much choice there, so, that is divergence of the electric field is equal to $\frac{\rho}{\varepsilon_0}$, This is the Gauss's law. The divergence of B is 0, this is called Thomson's law sometimes, simply says that the magnetic monopoles does not exist.

The curl of E is equal to $-\frac{\partial \vec{B}}{\partial t}$, this is the faradays law, and finally, this is the Faraday Ampere law and which says that curl of B is equal to $\mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$, this $\varepsilon_0 \frac{\partial \vec{E}}{\partial t}$ is the famous displacement current term.

E is the electric field, B is the magnetic field, J is the current density term, ρ is the charge density, μ_0 free space permeability, ε_0 free space permittivity? I hope all of you know about all these things. So, this I am not going into this.

Now, for the matter field, we have several choices either we can write the single particle description like the normal, like neutral molecules and kinetic molecules or atoms or any neutral particles. Then also if the number of the particles is large, then we can talk about kinetic approach under certain conditions. Then we can talk about fluid description.

In plasma, exclusively we have the provision of doing something a bit more special and most people who are doing research sometimes, they want to mostly do research in space plasmas or astrophysical plasmas, but they want to include the effect of particles interaction as well or particle behavior as well.

Sometimes they create hybrid models that means, they are interested in such a length scale or time scale, so that the ions still do not move so much. So, ions still behave as particles and electrons, they behave as a fluid because they are very much mobile. So, they can actually constitute a continuum. How is that? We will talk qualitatively in the next lecture.

So, we have several options. This one, we will be not at all interested. This one, we will start because even for the hydrodynamic case we started from the kinetic theory, and from that, we will just go to this, and then we will talk about the fluid models of plasma. Hybrid model, it is just for your own interest. If you are interested you search about that.

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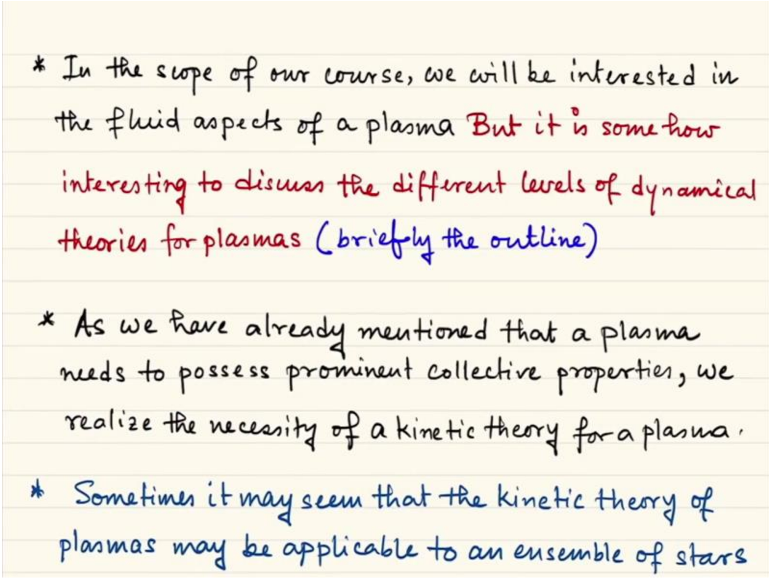

Now, in the scope of our course, we will mostly be interested in the fluid aspects of a plasma. But it is somehow interesting to discuss the different levels of dynamical theory for plasma, at least briefly the outline. So, mostly the transit kinetic theory and the transition of the kinetic theory to continuum theory or the theory of the plasma fluids.

So, now, just remember that what I said that a plasma needs to possess prominent collective properties, and then we realize that the necessity of a kinetic theory for plasma can never be ignored.

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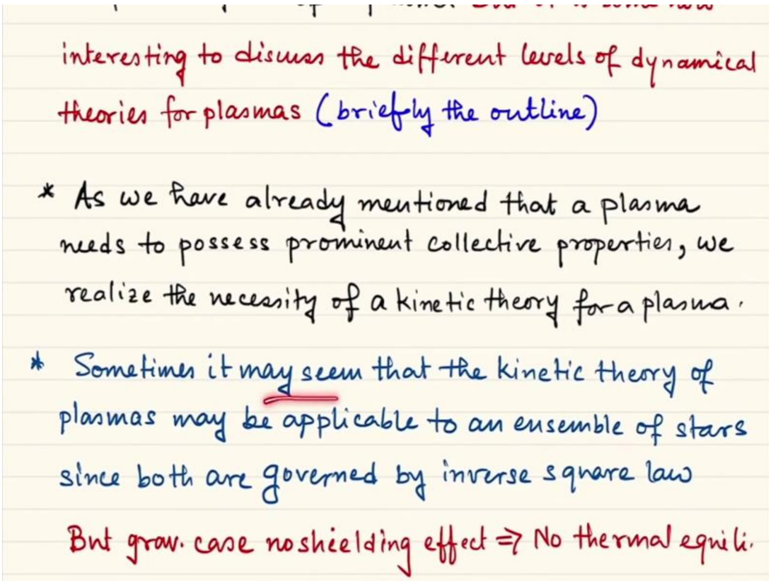

So, sometimes it may seem that the kinetic theory of plasmas may be actually applicable to as ensemble of stars which are governed by inverse square laws because both gravity field and Coulombic laws, Coulomb forces they are both inverse square laws. But remember gravity field being attractive all the time they cannot create any shielding effect.

I mean there is no characteristic length scale like Debye length scale beyond which you cannot see the gravity effect. The gravity effect is always there. So, it cannot help in establishing a local or global thermal equilibrium.

On the other hand, for the Coulombic forces, we have a shielding effect or screening effect, and after a certain length scale basically when you have a large number of particles, there is a screening effect.

After that length scale, you cannot really find the effect of the coulombic interaction, and that is why finally, the total system after beyond the length scales, the total system actually governed by the thermal collisions, and thereby it is still being able to establish a thermal equilibrium only for the coulombic cases and that is the exactly the case of plasma.

So, I end for this lecture at this point, and from the very next lecture, I will start by developing very briefly the kinetic theory, and it is a very interesting aspect it is called BBGKY hierarchy, and after that, I will also introduce the corresponding from the kinetic equations the transition to fluid models, and magneto hydrodynamics.

Thank you very much.