Plasma Physics and Applications

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Week : 01

Lecture 02: Introduction to Plasma - II

Hello dear students. So in this lecture we will try to understand some more aspects of plasma. So we have seen what is plasma and why plasma is referred to as the fundamental state of matter and we have understood how plasma can be produced and where plasma can be formed. Now some more aspects we will try to understand about plasma itself. So this is a figure which shows ranges of plasma. So on the y axis you have electron density.

So the defining characteristic of plasma is the number of charge carriers. You see we have defined plasma as an ionized gas. So number of charge carriers is let us say number of electrons per unit volume. So this defines the strength of plasma.

Not all plasmas will have equal number of electrons per unit volume. So on the y axis you have electron density and on the x axis you have electron energy in electron volts. Energy has the units of eV. What is eV? Charge times the potential difference. So in plasma we generally write temperature in the units of eV.

We will discuss why temperature is expressed in the unit of electron volt but not let us say Kelvin or centigrade. We will come to that but for now let us say the temperature is also a measure of energy. So how much you give temperature to a particular atom or molecule? It tells you to what energies it may reach. So if you see all these that appear inside this square is you have galactic plasma which has very low number densities 10 to the power of minus 5 electron per cubic centimeter. So it is in a very small space you take this let us say assume that this is 1 cubic centimeter.

There are 10 to the power of minus 5 electrons. So there are number of electrons per unit volume let us say per meter cube will be very less. And at the same time the energy is also very high. This one the intercept on the x axis gives you the electron energy and interstellar plasma also exists in a very low energy state but at also very low number densities. So if you go along the x axis or along the y axis what you see is if you go to the center of the sun which is at a very high temperature and also at a very high number density.

So within this volume of 1 centimeter cube you can expect 10 to the power of 25 electrons to be stuffed in. So this is called as a very hot and dense plasma. And this plasma is generally referred to as very cold and very weak plasma. Cold refers to the temperatures and weak refers to the number of electrons per unit volume. So you have everything in between so you have chromosphere, the region of the sun's atmosphere, photosphere is the surface of the sun, the disk the visible disk that you see is referred to as the photosphere which happens to be at let us say 5800 to 6000 Kelvin that is the standard temperature.

So at that temperature if you go and measure you will find nearly 10 to the power of 15 electrons per unit centimeter cube. So the point is plasma can be found at very high temperatures or at very low pressures and the number of charge carriers, number of electrons per unit volume will very wide range of let us say 10 to the power of minus 5, 10 to the power of 25. All these states of matter or the gases are referred to as plasma. So flame is just referred it can be related to earth, ionosphere is related to earth, the magnetosphere is also related to earth. Everything else seems to be a fusion is a process what that we are familiar with is also related to earth.

So all these places you can find plasma with these defining characteristic number of electrons per unit volume. So how do you characterize plasma? So not all plasmas are same, you cannot compare the astrophysical plasmas to the plasmas that you see in a fluorescent lamp or in a fusion reactor. So all these plasmas are different. How are they different? They are different by having different number of electrons per unit volume. They are also different with the available temperature inside it.

Now most importantly you can have weak plasma or you can have cold plasma, you can have very hot plasma. So here it is very important that when you say weak or when you say cold you are referring to the situation where there are no collisions inside. We will come to that later. So characterization of plasma presents a freely moving charged particles and a very large number of these charged particles is a necessary condition for the plasma state to exist. Let us say you are given a gas chamber and if you are asked to say something about the state of matter you can say gas.

But let us say if you think that there are lot of charged particles inside that gas, in that gas would you say that as a plasma? No, you will not say that as a plasma. Therefore you make sure of few other conditions. What does it mean? It means that plasma has to have the charged particles no doubt about it otherwise it is a neutral gas. But merely having charged particles is not enough for a gas to be called as plasma. This is the basic underlying message.

So not every ionized gas is plasma but every plasma has ionized species inside it. What is the difference? What is it that is stopping you is going to be discussed in what is called as plasma criteria. What it will tell you is it will give you a set of rules only upon satisfying all these three rules. You will call an ionized gas as plasma. Now what you have to understand here is the most important fact that not every ionized gas is plasma but every ionized gas has ionized particles in it.

Plasma does not have to contain only charged particles more important neutral species can also exist along with it. The relative number of neutrals and charged particles together will affect the features of the system. That means the concentration or the abundance of charged species with respect to the neutral atoms will decide how the system will behave or the overall characteristics of the system itself. For reference, we can say that typical ideal gas concentration is 10 to the power of 19 atoms per unit volume per cc for cubic centimeter. Under STP conditions you take a centimeter cube volume you will realize that there are 10 to the power of 19 atoms inside it.

Do you call it as plasma? No. Protons near earth space, so we have the earth. In the proximity of the earth because of this sun's radiation that is coming from the sun of course there are nearly 1 to 10 protons per unit volume per cc. This is plasma this is definitely plasma. Now you may ask why are you calling something of a very low concentration as plasma and why are you not calling such a high concentration gas as plasma.

We will discuss why. Using a tiny fraction of air should get a charged particle gas. Not every charged particle gas is a plasma. So, is there any condition or is there any cut off that needs to be passed only then you call this as plasma in terms of number densities. I would say strictly no. The plasma criteria is more deeper in its understanding or is a more convincing parameter for characterizing something as plasma.

So, how do you characterize plasma? The essence of this slide is just that by just having charged particles we cannot call a gas as plasma. So, this ambiguity can be resolved only when we try to understand what is called as plasma criteria. This will tell you this will give you 3 rules 1, 2, 3. Upon satisfying all the 3 rules only you are going to call a gas as plasma. Now most importantly this is not a 2 directional arrow.

Every plasma is a gas but not every gas is a plasma despite having charged particles. Why do we study plasma? What is the importance of plasma in today's science and technology? Plasma has come a very long way since its humble beginnings but plasma is still there is a lot of things that we do not know in plasma physics how things function in plasma physics. It is a highly complex and highly involved subject which requires very deeper levels of understanding using mathematical tools. So, I will try to present few situations where plasma physics or the understanding of plasma physics can be very useful. So, being a physicist I will try to put forth the perspective as I see the things or from a physics perspective.

So, plasma physics was first advanced to study the thermonuclear processes such as fusion etc. Why plasma physics is needed? Because you are encountering a gas which is electrodynamical in nature. Electrodynamics or if you consider the fundamental nature of electricity and magnetism you do not require a medium for these effects to permeate from one place to another place. But now you are seeing a medium a gas which is basically gas with enough number of charged particles but also getting influenced by the electromagnetic fields. So, in order to understand what happens inside and how the matter that is a product of this nuclear fusion can be understood plasma physics was basically formulated.

So, it was initially thought the plasma may be studied in a similar way as we deal with a neutral gas. This is what the entire discussion that we had so far converges to the simple fact that plasma physics can be identical to the fundamental thermodynamics or the way we deal with the neutral gas. Initially we thought plasma is just another gas so why cannot we use the kinetic theory of gases to understand physical and dynamical processes that happen in plasma. No we cannot do that. So plasma cannot just be considered as a fluid due to the electromagnetic interaction.

So, I have studied so many number of times already but that plasma ability to be influenced by the electromagnetic fields makes it unique. Thus we have to treat plasma as a conducting fluid this is the most appropriate or most easy definition for a plasma. What is plasma? Plasma is just a conducting fluid. So, you combine the loss of hydrodynamics and the loss of electrodynamics you get what is called as a magnetohydrodynamics. So this is the branch of physics which is used to understand plasmas the behavior of plasmas the description of plasmas.

Which means that the basic physical property of plasma is critically different from that of a neutral gas. We cannot simply use the kinetic theory of gases to understand plasma physics. So this is the branches critically different from the other branches. So how different is it? In neutral gas inter particle collisions dominate but in plasma wave particle interactions prevail. We are getting more to the deeper understanding of plasma physics.

So in neutral gas inter particle collisions interatomic collisions dominate but in plasma wave particle interactions prevail. Because since the moment you introduce electrodynamics you have to have a provision to include wave particle interactions inside the medium. So all of this are happening inside the gas itself where the particle is interacting with a wave. So there exist many instabilities in plasma while very few instabilities may occur in gases. So, instabilities so understanding this instabilities is very important is very critical for designing a fusion reactor or anything.

There is a provision that there can be many instabilities in plasma while very few instabilities will exist in neutral gases. So understanding instabilities is very important for designing applications. And plasma turbulence can greatly modify the physics of plasma. So associated with the instability we talk about turbulence. These are very complex physical processes they cannot be just defined just like that.

In time we will try to understand the meaning of these instabilities and turbulence etc. So plasma turbulence can greatly modify the physics of plasma. As a result many new physical processes can take place in plasma that are not possible in gases. There is a huge possibility in which we can encounter many new physical phenomena. So what does it mean? In a nutshell what it means is as a result we must recognize plasma as a new branch of physics and in general plasmas should not be treated as a gas despite the fact that for perception sake plasma is just a gas with many number of electrons and ions.

So plasma physics should be treated as a new branch and should not be confused with a gas. So where do we use plasma physics? We use plasma physics in space physics in understanding processes in space, astrophysics, accelerator physics etc. So in the stellar and solar physics in the interstellar or in the interplanetary space it is just the plasma which is present. Thus it is very important for us to understand this branch of physics to know what is happening in these places. So what is being done already in plasma physics? I will present a couple of slides which will tell you what all happened in plasma physics in different disciplines.

So discovery of ionosphere, ionosphere is a conducting layer of earth's atmosphere in which there are lot of electrons and ions. By having these electrons and ions this region gets an ability to interact with the electromagnetic waves. By the means of interaction it can reflect the electromagnetic wave, it can absorb the electromagnetic wave anything could happen. By using suitable frequencies it may be possible to use this plasma layer or the ionospheric layer as a mirror in the sky and we can achieve long distance radio wave communications by the means of or by using ionosphere. Having said that it becomes fundamentally important for us to understand this conducting layer which is if you want to understand that layer you have to know plasma physics or you have to use plasma physics.

So it can be particularly helpful in radio wave broadcasting in understanding the ionospheric effect on electromagnetic waves because electromagnetic waves you are using electromagnetic waves for the sake of for communication and polarization and magnetospheric effects. All these things all these effects are coupled very strongly with advances in plasma physics. Now another very interesting branch of physics is astrophysics. When you consider astrophysical plasmas we have to remember that 99.9% of the visible universe is existing in the plasma state.

So if you want to understand astrophysical plasma, plasma physics is the only branch of physics which can directly deal with these states of matter. So understanding of astrophysical phenomena is very essential and can only happen with the knowledge of plasma physics. So, the more diffusion the more practical and very relevant area of science and technology. So after declassification of many things in 1958 theoretical plasma physics research was able to understand or able to give explanation for many thermonuclear processes and understanding of plasma instabilities is very crucial for the design and for the maintenance of these reactors.

And moving into space we have radiation belts. We know what are radiation belts? These are regions where the particles are trapped. So they look like this. So they have been many measurements. We have an inner belt, you have an outer belt, there have been many measurements in the past to understand how these particles are trapped and what are the energies of typical energies of these particles.

So it was discovered in 1958. So these belts are filled with highly energetic particles and exploration of magnetospheric phenomena starts with the understanding of radiation belts. And in space plasma physics ideas of magnetic field trapping, charged particles, plasma waves, all these different subtopics in plasma physics can be very helpful in understanding this radiation belts. And talking about the laser plasma physics or laser matter interaction where we have seen that it is a method in which you can produce plasma. So it can be helpful plasma physics or the understanding of plasma physics can be very helpful in the development of high power lasers, light matter interaction, understanding light matter interaction, particle acceleration using plasma induced electric fields and so on. So, in a nutshell it is very important to understand plasma physics to be able to devise new applications or to make the existing applications more fine tuned for the industry needs or the technology needs.

The properties of plasma in a nutshell, plasma is electrically neutral in nature although charges but their numbers are balanced leading to overall neutral states. That means the total positive charge is almost equal to the total negative charge. And plasma exhibits something very unique called as a collective response to the electric and magnetic fields. What is collective response? So plasma as an entity although it is a fluid, fluidic medium it will behave as a collective entity to the electric and magnetic field. The response we will try to understand what is this collective response and how we can derive some equations.

But it is a very interesting phenomena where we cannot treat it as a gas. And most importantly let us say if you have a container let us say for example, you pour a liquid what will happen? This will take the shape of the container, the liquid will take the shape of the container. You have a gas so gas will fill the space, if you have a closed space it will fill the space. But plasma will not do that this is the basic difference of plasma and the gas. Plasma will not either fill the space or take the shape of the container.

This is where plasma also differs from other states of matter. Now if you look at the course outline so basically what we have done is we have tried to understand what is plasma? How is plasma different? What are the fundamental properties of plasma? Where do we find plasma? What are the favorable conditions under which plasma can exist naturally? And if you want to produce plasma how can you produce plasma? And we also tried to understand to a brief extent why we want to study plasma physics? Where can this understanding be helpful? Now if you go about the course we have this is designed to be a 12 week course in which we will have 12 assignments, one every week we will have an assignment. These assignments can be problem based or they can also be concept based or memory based. So you have this 12 weeks outline briefly given here.

So these details are also available in the course page. So you have the first unit wherein we are actually in the first unit itself we have introduction to plasma etc formation of plasma, plasma frequency, device shielding and so on. And in week 2 we will try to understand the plasma criteria when do we call an ionized gas as a plasma and when we do not want to give this tag of plasma to the particular ionized gas. And in week 3, week 4 and week 5 these 3, 4, 5 they deal with understanding of plasma as a single particle theory. Subsequently we will move and say plasma it is better to treat plasma as not as a particle but as a fluid. So units 6, 7 and part of 8 we will try to understand plasma processes by assuming that plasma is not a particle rather plasma is a fluid.

Then subsequently we will try to understand waves in plasma and then we will try to understand the applications of plasma. So this course the plasma physics and applications is suitable for students of B.Sc in physics or students of M.Sc program in physics where this course is going to be mathematically intensive you will require a lot of mathematical tools to be able to understand or appreciate what is being done. Although it is mathematically intensive what I will try to do is I will try to derive things here itself while the lecture is being delivered so that you do it parallely and try to develop your problem solving abilities at the same time.

So we will conclude here we will meet in the next class and talk about plasma frequency etc. Thank you very much.