Fluid Dynamics for Astrophysics
Prof. Prasad Subramanian
Department of Physics
Indian Institute of Science Education and Research, Pune

Lecture - 63
Sun's atmosphere - Solar Corona and the Coronal Heating Problem

So, what I thought, I would do at the very end of the course is give you some more astrophysical examples right. And for these two lectures, what we will be doing is I will be giving you examples from the solar corona. Two reasons, one is it is my field, I work on phenomena in the sun sun outer atmosphere which is called the corona. We have already discussed some of these things.

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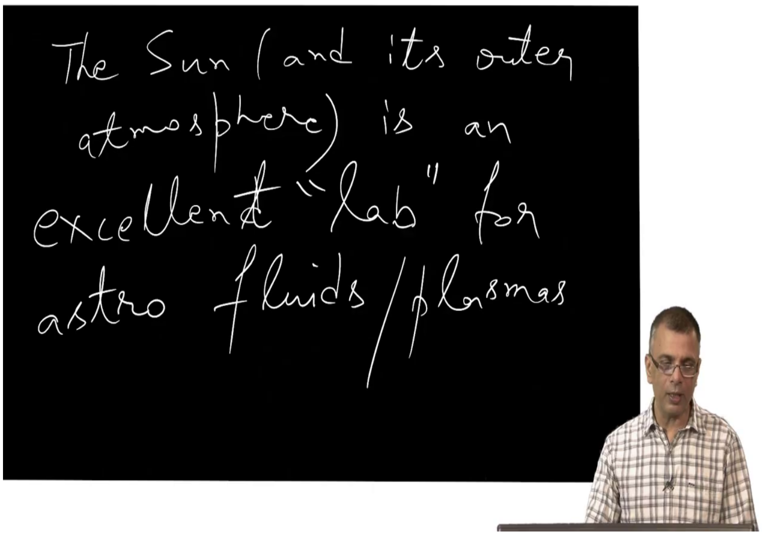

Second, there is no better lab so to speak the sun sun and its outer atmosphere is a great lab for testing out astrophysical applications of fluid dynamics, is an excellent lab for I put lab in apostrophe for astrophysical fluids and plasmas. The meaning of this statement will become a little clearer as we go along ok.

In particular, what I will be focusing on is we have talked about the solar wind remember, I mean when we talked about the solar wind and reconnection both in one unified way. We have already talked about this.

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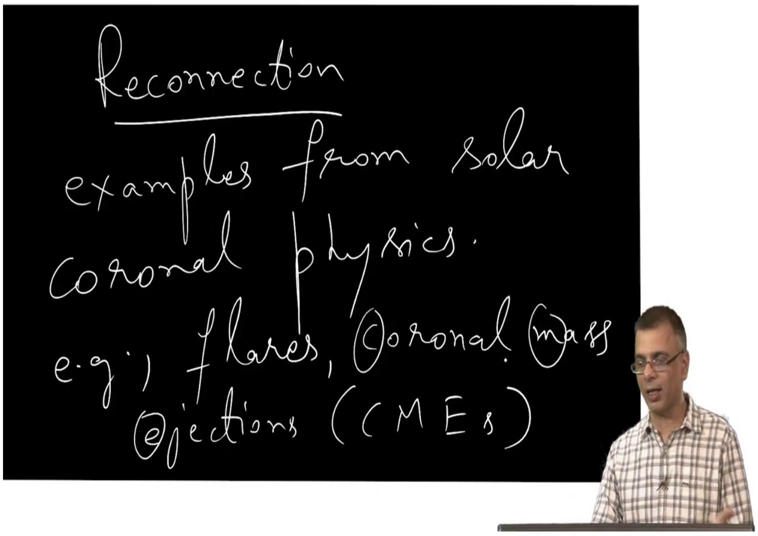

But for the time being, what I will focus on is the phenomenon of reconnection, because we have been discussing reconnection of light right. And how reconnection is a means of energy release, how you know reconnection is a way of converting excess magnetic energy into heat into heating the plasma and in accelerating particles and so and so forth.

I will show you examples of this particular phenomena not direct, it is not really possible to directly emerge reconnection directly say this is where reconnection is happening, but to the extent possible these are some of the best examples of the fact that reconnection has to be happening in these phenomena ok. Examples from solar corona physics, this is what I will be showing you in particular example such as flares, coronal mass ejections which are often called CMEs, for coronal mass ejection CME ok.

So, I will show you some of these examples some very spectacular data. As we always say pictures are equal thousand words, movies are even more ok.

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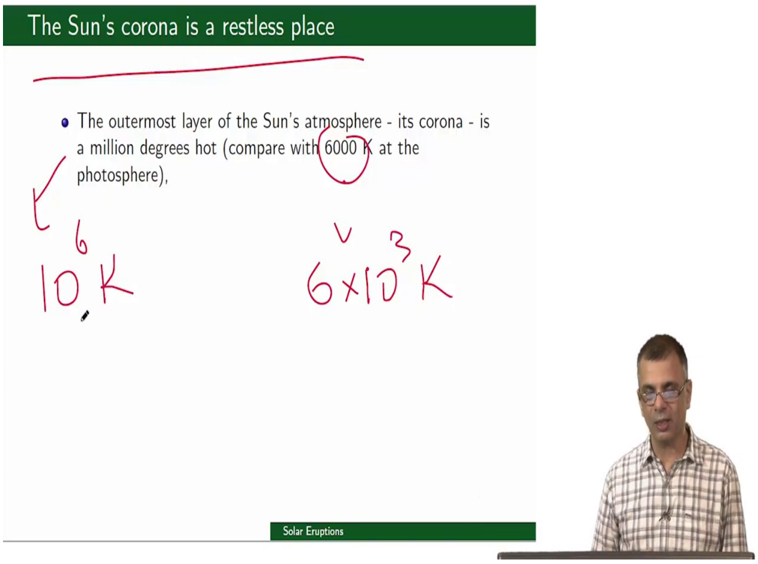

So, by way of an by way of an introduction you know this it is it is words emphasizing over and over again that the sun sun's corona is a restless place. What is the sun sun's corona? Well, it is a outermost atmosphere, it is a outermost layer of the sun sun's atmosphere.

In some sense, we in on the Earth at least up until the magneto sphere we are also part of the sun sun's corona.

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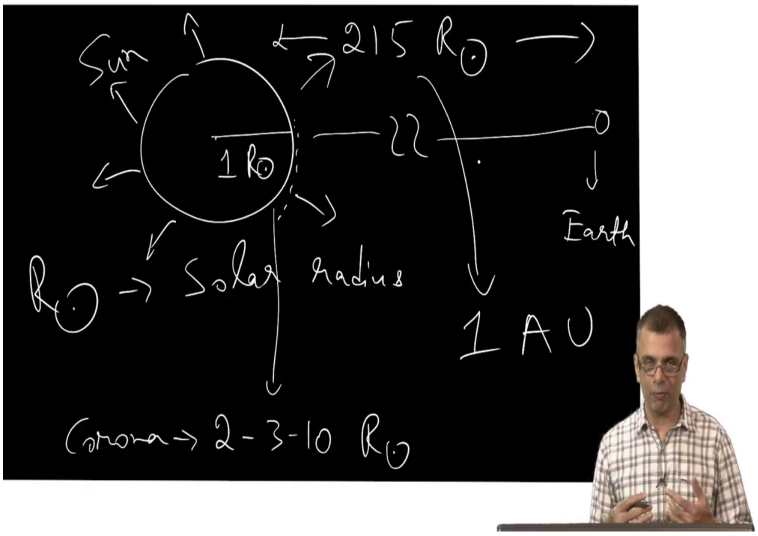

Although we are as far as 215 solar radii away from the sun sun, so just to give you a sense of perspective, so the sun sun is here right, say and this would be one solar radii say that is the sun, and the up until the from the this is symbol for solar radius ok.

So, this would be the what I drawn here is roughly the photosphere, the observable surface of the sun sun. And the corona would extend up to somewhere like this ok. The corona would be up to about 2 to 3, 2 maybe as much as 10 solar radii say to about 10 solar radii ok. But we on the Earth ok, ok this is the sun sun. We on the Earth are situated at 215 solar radii away from the sun sun. And this 215 solar radii, this is often called one astronomical unit. So, this is something to be kept in mind.

So, we will be focusing on stuff on eruptions and everything happening very, very close by somewhere here ok. But the effects and the solar wind is of course blowing out right is blowing out.

And on top of a of the study solar wind, there are also these blobs call coronal mass ejections which are being ejected. And sometimes they reach the Earth ok. And just to give you a sense of the distance, I mean this is not dot drawn to scale of course, I mean you know this is just 1 solar radii and that is why I have drawn this we are very far away ok – we are 215 solar radii away.

And our Earth magneto sphere as such is impacted by the solar wind, and also by the transient phenomena such as coronal mass ejections which are ejected from the sun sun. So, I just wanted to you know emphasize that. And we and the fact that you know the sun sun's corona is not a nice place it place, it is quite restless lots of things keep happening ok.

And the corona is a million degrees hot about you know million meaning about 10 raised to 6 Kelvin, compare with this is about 6 times 10 raised to 3 Kelvin at the photosphere. At, at the very base, it is only about 10 raised to 3 Kelvin, 6, 6 times 10 raised to 3 Kelvin, almost 10 raised to 4 right.

But, but as you go away, as you climb up in the atmosphere, you come to a place the outermost layer of the of the sun sun which is called the corona which is a million degree hot, rather strange you know a you are actually moving away from the central energy source which is at you know at the center of the sun sun the core of the sun sun which is where nuclear fusion is happening. And so you are moving away from the energy source, but you know you are getting harder.

As such it seems to violate the second law of thermodynamics, but not really ok, the first law actually. But we will find out that that is not really the case, but nonetheless this it is a very interesting. This, this thing called the coronal heating problem, why is the corona being heated, how is a corona being heated, this is one of the most interesting problems in all of astrophysics.

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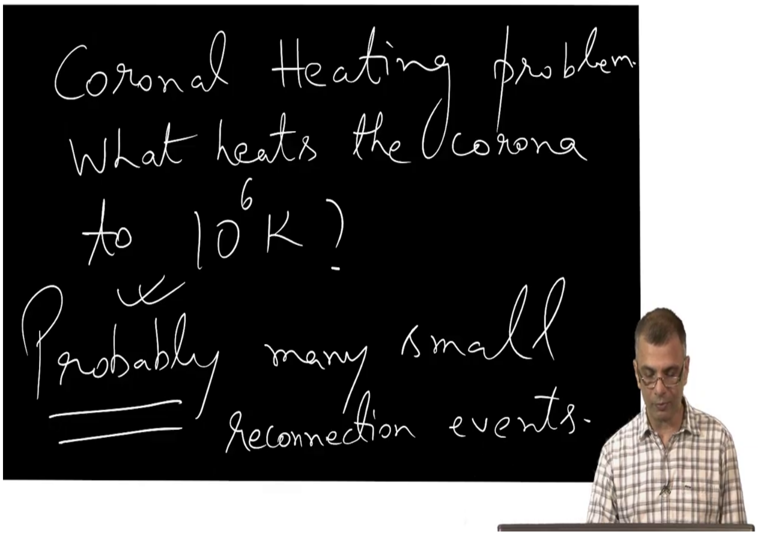

The coronal heating problem: What heats the corona to a million degrees? This is a question we are asking ok. The answer is probably many small and you got it reconnection events. And I emphasize the word probably because we do not really know for sure, anyhow getting back to a narrative right.

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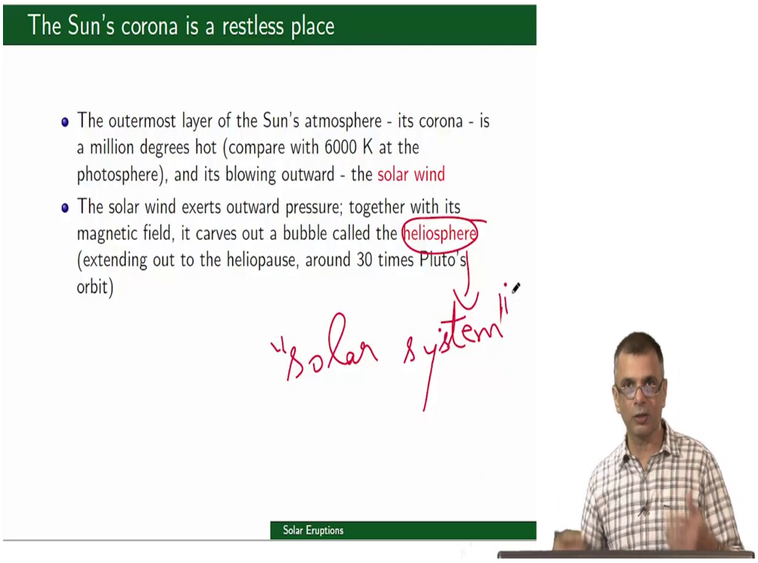

So, now outer atmosphere as we know is it is not static either, it is blowing outwards it it s blowing outwards to form what is called the solar wind. And we on the Earth, we on the Earth here are immersed in the solar wind, even though we are so far away ok. We are immersed in the solar wind. And the solar wind exerts outward pressure. Of course, it is flowing outwards and it is exerts outward pressure.

And together and it is also a magnetized wind although you know our treatment of the solar wind did not include magnetic fields it is a fact that and in the grows features of the solar wind can be explained even without magnetic fields. But there are some very important things that cannot be explained without magnetic fields that is the fact that the solar wind carry is magnetized it carries magnetic fields ok.

And so, together with the magnetic field, it carves out a bubble called the heliosphere. And it extends out to the heliopause about 30 times Pluto's orbit. So, taken together this would be what is called the solar system I mean you know this thing is the outer limits, you could also roughly call this a solar system ok. Up until the point where you know the solar wind keeps blowing so to speak. So, that is.

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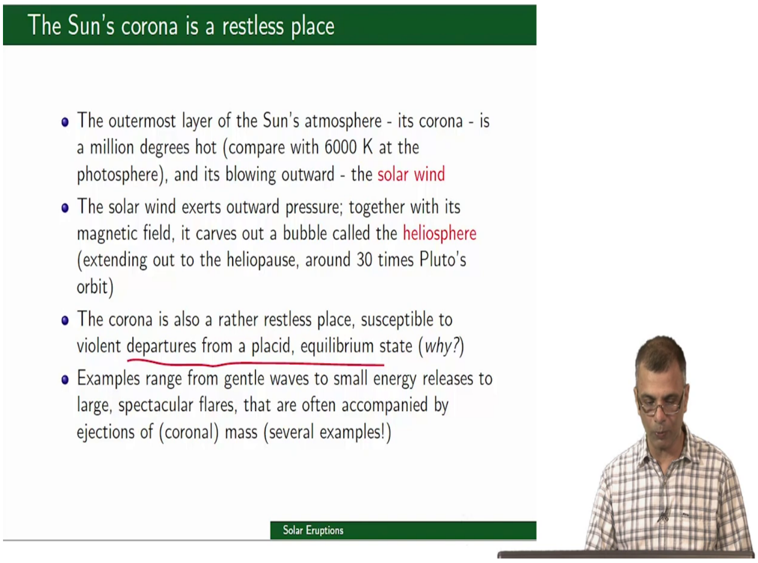

The other thing is the corona as such is also a rather restless place. It is susceptible to violent departures from the placid equilibrium state. And it is worth wondering why? Why is this so? Ok, the answer is not easy, but this is a fact ok. And examples of departures from a placid equilibrium state range from gentle waves to small energy releases to large spectacular flares that are often accompanied by the ejections of you know of coronal mass ok.

And so, here is a place where I want to show you several nice little examples. Let me start with the gentlest things first gentle waves to small energy releases, so that you have an idea of what is going on in the corona most of the time ok, a pretty much all the time one would argue, and then I will go on to illustrate some of these larger more spectacular events.

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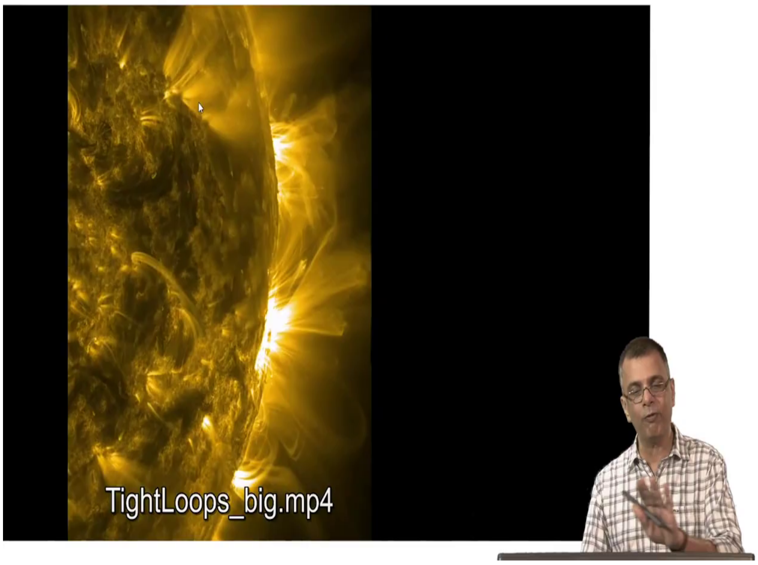

So, let me play this movie. And what this as is you can see this is real data by the way. This is data taken by the atmospheric imaging assembly. It is taken about taken by spacecraft NASA spacecraft right. So, I will keep playing this movie because it is so a it is so spectacular, and there is plenty to talk about it right. So, now, you can see the solar surface kind of rotating ok. And this is what one would call the limb of the sun sun ok. This is the edge of the sun sun so to speak.

And anything are above here would be what is called the atmosphere of the sun sun. Now, this is imaging very hot plasma – certainly a few million degrees Kelvin ok. So, therefore, since we are imaging such hot plasma, we cannot we are definitely not imaging the photosphere, we are definitely imaging the corona. So, whatever features you see here ok, by the way this is not taken in an invisible light this is taken in extreme ultraviolet ok.

So, the features that I want you to concentrate on are these things – these little things which look like loops right, and these bright events ok these bright, these, these bright things right. So, the main thing that that you can see here is that these loops seem to be over the time scale of I would say we are looking at a time scale of a few days just judging by you know the time the number of rotations that that I can see here right.

So, we are really looking at a time scale of several days here. And over these several days, you can see that these loops are pretty much static, but not quite so ok. There are departures from equilibrium from whatever the steady state is that is what I mean. You can clearly see that these loops are gently moving sort of waving around as if in a breeze ok. So, this is what I mean by departures you know small scale departures from equilibrium. So, this is one thing I wanted to point out.

The other thing I wanted to point are very, very important are these brightening these little brightening here. You can see you can you can see the plasma is moving from here to here. And you can also see these brightening these are probably signatures of small scale reconnection events, these are what are called active regions.

And I keep talking about these loops as if you are actually seeing the magnetic fields ok that is not true. You cannot really see magnetic fields at all. But, on the other hand, what you can make out is that plasma, what these are this is actually imaging a million degree million a few million Kelvin plasma that is what its actually imaging is not it. So, what happens is plasma likes to flow?

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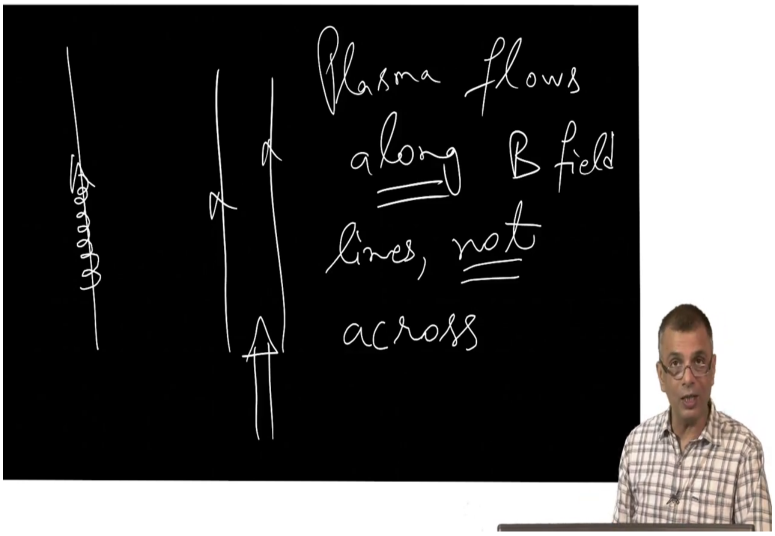

If there is a magnetic field, if there is, if there is a magnetic field bundle like this, plasma will like to flow along plasma flows along B field lines, not across. You can understand this simply from although you know it is really a fluid treatment, you can understand this from the fact that you know particles like to gyrate along, particles do not like the cross magnetic fields right.

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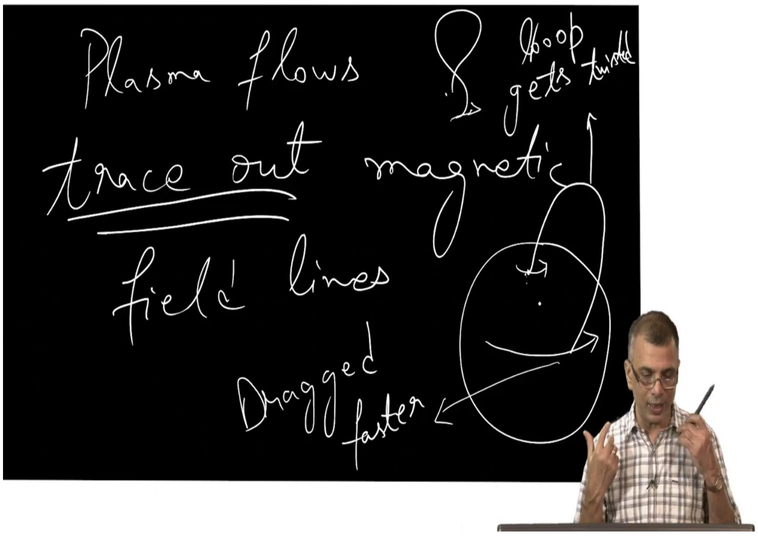

So, when we see these spectacular images and say that these are magnetic field lines what we are really saying is that the plasma flows which is what we are really imaging trace, trace out magnetic field lines.

This is what we are really saying ok. This is an example of gentle waves, I would say we saw you know we saw examples where you know the magnetic field lines were sort of bending the little bid over the time scale of a few days over the time scale of some you know say about 30 percent of a rotation, may maybe less than 30 percent of a rotation.

I am estimating this from the fact that it takes 27 days for to for the sun sun at least at the equator to complete one full rotation ok. And we also saw some examples of small energy releases. You can see that there are these brightening right. These are probably what the small scale energy releases are ok and this is probably due to reconnection ok. So, this was one example.

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This is yet another wavelength this is in three, three naught four angstrom. And this not on the same day, this is on a different day ok. You see this little spray here, you see this little spray here, and plasma coming back right. So, this is yet another example of small scale energy relations. This is not a large flare or a large energy release or anything. It is actually quite small scale.

There, there is some brightening here, so that is a good example of what I would call a spray the nomenclature is quite obvious it looks like a spray. What means sprayed out a outward? Well, it is plasma that is being spread outward that is that is the answer ok. These are examples range from these kinds of gentle waves; two large spectacular flares that are often accompanied by ejections of coronal mass which as we said they are called coronal mass ejections ok.

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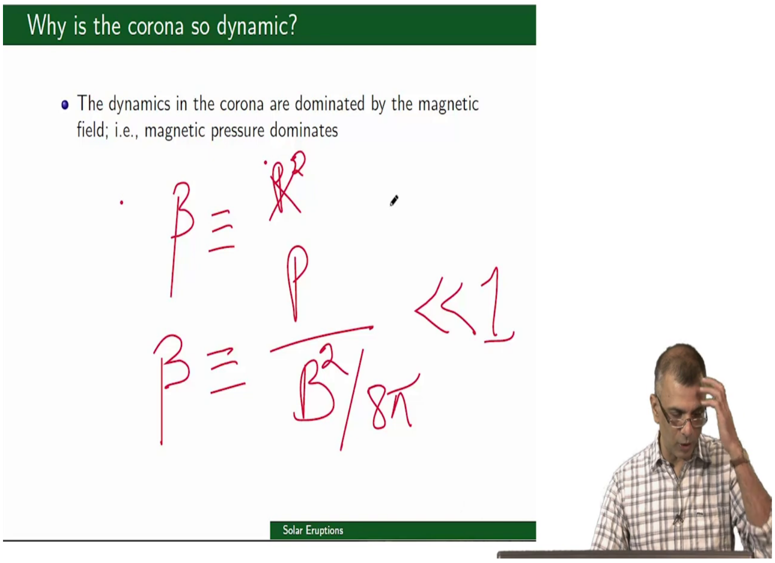

Now, before playing movies of flares of coronal mass ejections, it is worth discussing why the corona is so dynamic? Why are these motions always present in the solar corona either gentle motions or sometimes violent eruptions? I have I have not shown examples of those here, I will show you ok. Why is that?

Well, the dynamics in the corona are dominated by the magnetic field, the magnetic pressure dominates. In other words, the plasma beta which is defined by the gas pressure over the magnetic pressure, this is much much less than 1 in the solar corona. In other words, a magnetic pressure that denominated, dominates this is you know what it is right.

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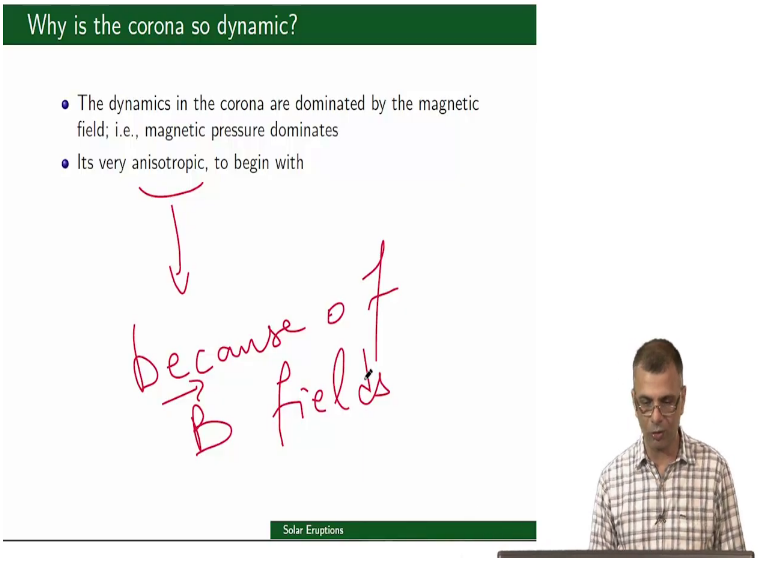

The other thing is the overall pressure is very an isotropic. Why an isotropic? Because of magnetic fields, we know this right we know that the pressure tensor once you introduce the magnetic field the isotropy of the pressure tensor is broken right. In other words, the pressure is very very different along the magnetic field as opposed to across a magnetic field.

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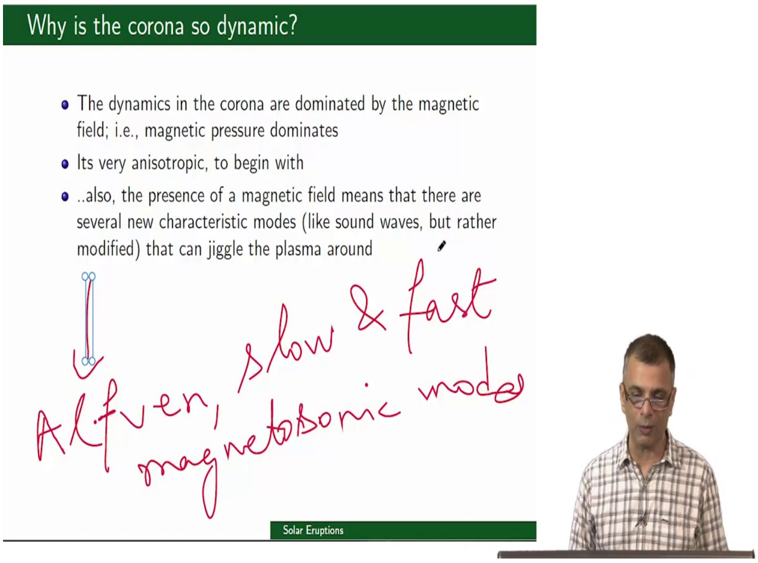

And also we have seen this we discussed this at length, the presence of the magnetic of a magnetic field means that there are several new characteristic modes sound waves , but other kinds of modes such as the Alfven mode, Alfven, slow and fast magneto sonic modes, magneto sonic modes right. So, this is what I mean by saying they are like sound waves but rather somewhat modified.

And these modes can jiggle the plasma around ok, mean much of the movement that we are seeing are probably manifestations of some of these waves. They are we are probably directly observing, maybe not pure waves maybe a combination ok, maybe not pure modes, but a combination of modes, but most likely what we are observing is a manifestation of these of these waves.

So, you see I mean all these discussion we had about waves and dispersion relations and everything, they would not simply draw a academic discussions. Here you go, I mean here are concrete examples and people spend a lot time in analyzing say the time period the observe time period of these waves, trying to figure out what the physical conditions are in the plasma, what the temperature is, what the pressure is, what the magnetic field is and so forth.

And then going back and trying to see if the wave period or if the oscillation periods that are observed there correspond can in some way be linked to these ways. And therefore, we can understand the nature of these oscillation. So, people you know spend a fair amount of time interpreting these beautiful observations ok.

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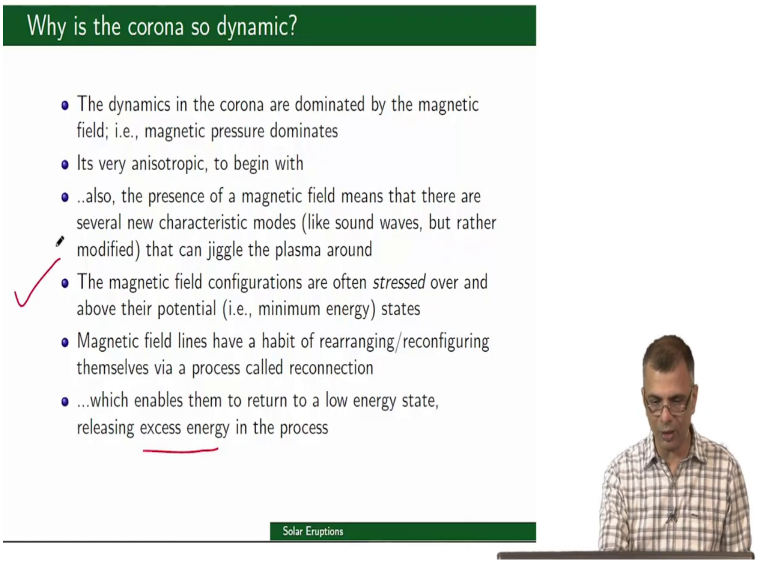

Now, the other important thing is that the magnetic field configurations are often stressed over and above their potential states. Why? I will I will tell you in a minute. And once that happens, the magnetic field lines have a habit of rearranging or reconfiguring themselves via a process called reconnection which we have discussed of course ok. In this process of reconnection, enables this stress magnetic field lines to return to a lower energy state releasing excess energy in the process.

And this excess energy goes into heating the plasma that is the origin of these brightening, and also accelerating particles and sometimes enabling entire blobs of plasma to be flung out ok. Let us talk a little bit about this point ok because it is not exactly evident how this is. Let me give you at least on the sun sun an example where this could how exactly this could happen ok. So, you see we know that the sun sun rotates faster at the equator than at the poles.

This is called differential rotation ok. So, this arrow shows you know you know faster movement. And we already discussed this in when we were discussing the frozen and condition, and when we were discussing some ideas about the about the solar dynamo, but the way magnetic field is generated. But here is another way of looking at it.

So, now, imagine a magnetic field whose foot point's one is here, a magnetic loop which is like this. One foot point is anchored here, and one foot point is anchored here. You can immediately see that this foot point is dragged faster, faster compared to what compared to this foot point ok. So, this loop what will happen is this loop gets tangled up right, because this foot point moves faster than the other foot point. So, this loop does not remained does not retain its configuration it, it tends to get twisted ok.

Of course, loops cannot cross like this, this is just in two dimensions; in three dimensions, they do not have to cross. But the point is it is much like a telephone cord ok, in old fashioned hands you know landline telephones, you have the cord connecting the hand set to the receiver. So, that telephone cord you know often gets twisted, you must be noticed, it some somewhat like that ok.

So, what happens is this loop, the loop gets twisted ok. When it gets twisted, it is stressed. You can think of this as the lowest energy configuration the potential configuration given boundary conditions here, and there given that maybe this is the this is the positive pole, north pole and south pole that is a boundary condition ok. And you solve the del square phi equal 0 to find out the potential field configuration it would look something like this ok.

Now, because of this differential rotation ok and this differential rotation happens all throughout I have just exaggerated this just to you know show you I just exaggerated this scale ok. It is not like a loop needs one foot point needs to be anchored near the equator and one so close to the pole, no, no. This, this look cord be quite small, but nonetheless because of differential rotation there is a scope for this loop to get twisted. And when it gets twisted, it gets stressed ok.

And what do I mean by stressed? Well, the magnetic field configuration now is non-potential ok and the amount of energy that stored in this magnetic field configuration is over and above the lowest energy configuration.

And the rest we have discussed over and over again which is that this non-potential this stressed or non-potential field configuration relaxes to lower energy configuration via a process called reconnection which is you know cutting and pasting of field lines, and it enables them to return to a lower energy state releasing excess energy in the process.

Hence, we have seen some examples of this kind of energy release. Now, we will discuss flares and so on so fourth in some more detail, but before leaving let me show you at least a one example.

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Here you go, you see this brightening here, this is what is called the flare ok this brightening ok.

This is a very very small snapshot I mean that is a very small region in the sun sun blown up. This is an extreme ultraviolet 195 Angstroms. And this was one of the largest flares ever recorded ever since we started you know getting detailed images of the sun sun.

And so what is the flare well at this particular wavelength you see this brightening out here that is the flare ok. And it is not like this bright that the brightening happens you know only at this wavelength only at 195 Angstroms, it happens all throughout the electromagnetic spectrum.

So, I want you to concentrate in your attention on the brightening ok. And also these large lots of immediately after the brightening, you will notice that there are lots of little white dots ok. What these are? Are, well this brightening is simply photons, but along with the photons ok particles massive particles ok like alpha particle or protons or even heavier particles ok particles with finite mass are also accelerated ok.

And this accelerated particles go and hit the detector ok which is observing this. And so they cause ionization streaks. And so these white dots that you see are actually ionization streaks arising from energetic particles heading the detector. So, they are indirect evidence of the fact that particles are also accelerated in this episode of large energy release ok.

We will talk a little more about flares, and also some about coronal mass ejections which are often accompanied and many times accompanied by such flares ok. The commonality is that both of them represent energy release phenomena, and in both cases this energy release phenomenon is thought to be facilitated by the process of magnetic reconnection ok. So, that is all for today.

Thank you.