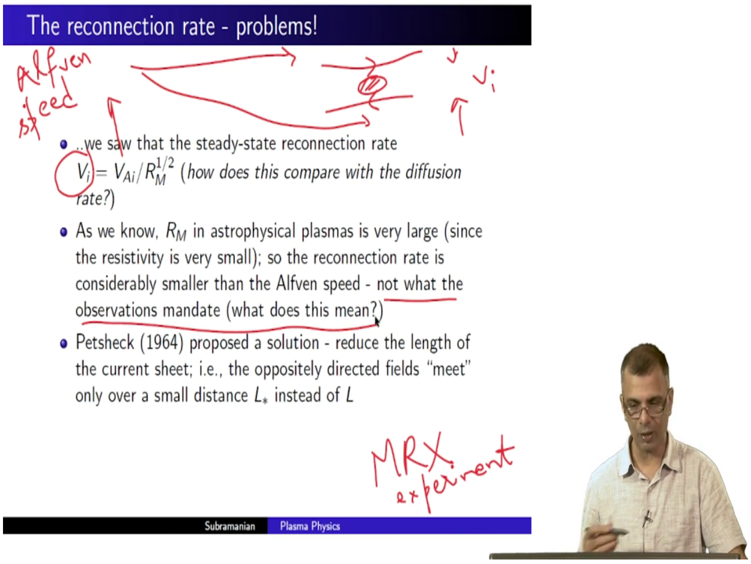
Fluid Dynamics for Astrophysics

Prof. Prasad Subramanian
Department of Physics
Indian Institute of Science Education and Research, Pune

Lecture - 62
Non-ideal MHD: Magnetic reconnection – The Petscheck model

(Refer Slide Time: 00:15)



So, the last time if you recall, we were discussing what is called the reconnection rate somewhat paradoxically call the reconnection rate. It is really the reconnection velocity this thing right, which is essentially the velocity at which the two oppositely directed field lines you know are being forced to meet if you were, ok.

And, the velocity at which in these two oppositely directed field lines are forced to meet determines the rate at which magnetic flux is eaten up or annihilated in the small reconnection region right here, right. So, this is what we were discussing in the last time..

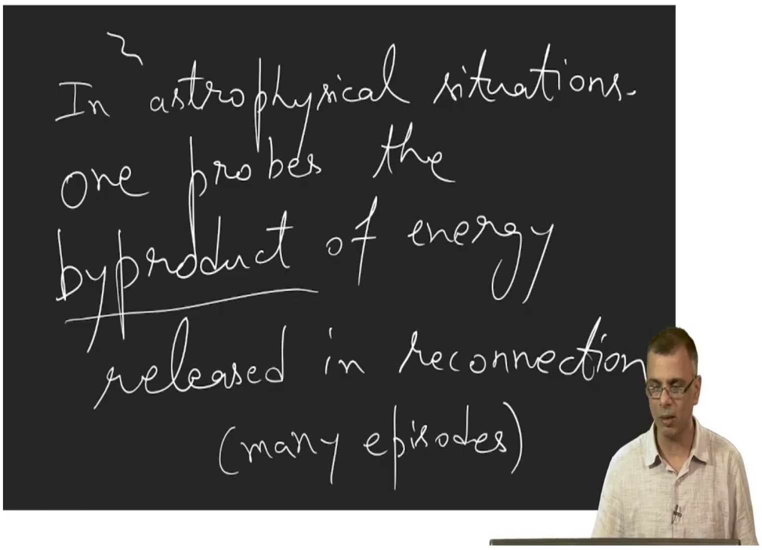
And, we saw that the steady state reconnection rate or the reconnection velocity goes as V A i divided by, V A i being the Alfven speed. This is the Alfven speed in this region essentially or in this region not in the reconnection region, ok. So, that is what it means. In other words, the Alfven speed in the undisturbed fluid fuel. The Alfven speed in the region of the fluid which is not being subject to reconnection ok.

So, reconnection being microscopic phenomena, there is little hope of observing it directly ah. Yeah, except of course, in lab situations and we will talk about that a little bit there are experiments such as the magnetic reconnection experiment ah, the MRX experiment. I urge you to Google it – MRX, ok and experiment.

So, in such experiments of course, it is possible to actually you know stick a probe into you know the so called reconnection region and figure out the actual geometry of where exactly the reconnections happening and do wonderful things like that right.

The trouble is in these lab experiments the conditions I mean it is very difficult to achieve the kinds of very high Reynolds numbers that are of not to be encountered in astrophysical situation. So, while they are instructive they are not quite the same, alright. So, that is one thing the other thing is of course, in astrophysical situations you are not really probing the reconnection region per se what you are probing is a very indirect quantity which is the byproduct.

(Refer Slide Time: 03:09)



And I emphasize this what you are really probing is a in astrophysical situations. One probes the byproduct of energy released due to reconnection or in the reconnection process this is what one really probes.

So, you see first of all it is not most of the time it is not just one reconnection episode it is many reconnection episodes. So, probably many episodes in other words there are many fire crackers going on ok episodes of reconnection. And one typically cannot does not have the time resolution to resolve one episode by another, more or less sort of averages over several episodes of reconnection that is one thing.

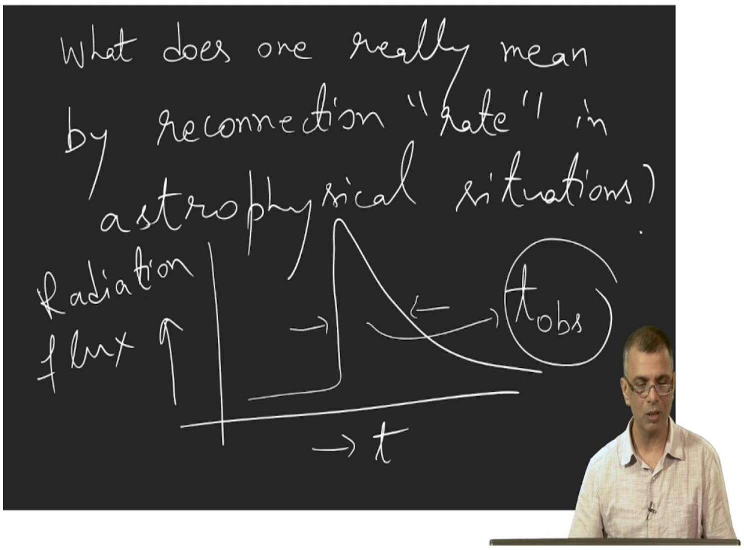
Secondly, so, the energy is released that is we more or less comfortable with that that is one thing, but you know what is actually observed in astrophysical situations is a byproduct of the energy released which is the radiation released, ok. So, the energy released in reconnection episodes heats up the plasma and the heated plasma emits radiation and that is what you observe in astrophysical situations.

So, I want you to be very clear that you know when we talk about reconnection in astrophysics we really not we are not really in a position to probe you know the astrophysics of the reconnection, we are really investigating very very indirect effects ok at any rate. So, the reconnection rate is generally you know taken to be this and is related with the Alfven speed in the non reconnection region in the bulk fluid by this relation where R sub M is the a magnetic Reynolds number ok.

Now, as we know it is suspected it is generally suspected that the magnetic Reynolds number in astrophysical plasmas is very very large, ok. It tends towards infinity I mean your numbers range from you know 10 raised to 4, 10 raised to 6 to even more ok. If you look up the you know definition of the magnetic Reynolds number you will see that the resistivity appears in the denominator. So, the smaller the resistivity the larger the magnetic Reynolds number and that is often the case in astrophysical situation.

So, what this means what this essentially implies is that because this is very large, the reconnection velocity or the reconnection rate is considerably smaller than the Alfven speed ok. So, now, let us also be very clear about that ok.

(Refer Slide Time: 06:08)

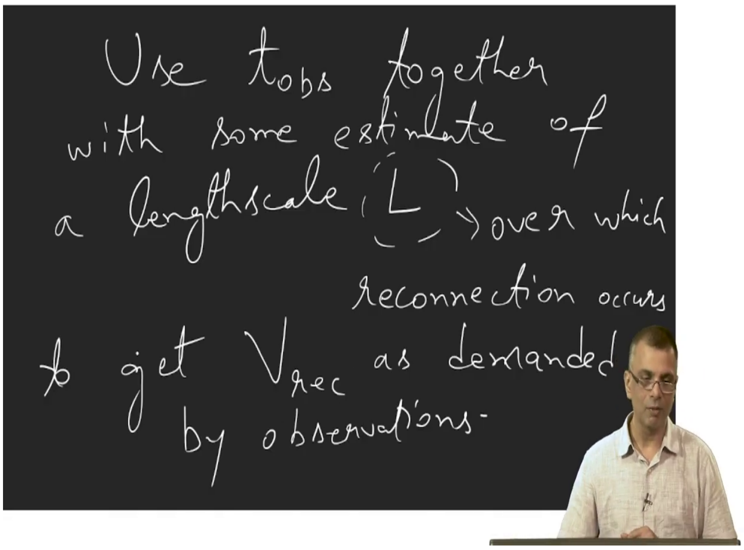


What does one really mean by reconnection or rather in astrophysical situations? Ok. What does one really mean? As in it is not as if you know we are able to probe the reconnection region in astrophysical situations it is not like that, right. So, what one really means is that like we said we are really observing the byproducts of reconnection. So, we are really observing radiation and this is something we discussed in last time also and I want to you know radiation flux.

So, what one really observes is something like this, ok say a radiation flux as a function of time and one in a solar flare for instance at some particular wavelength say X-rays or sometimes gamma rays, but ultraviolet or you know even lower energies or longer wavelengths like the radio. A typical you know light curve would probably look like this something with a very sharp raise ok it is not really vertical it is just that it is you know relatively slow decay.

So, many times you have access to this you have access to some kind of a full width half maximum kind of quantity and this would be you know a observe time scale this is really the only observation quantity that you have access to and then one uses this t obs.

(Refer Slide Time: 08:00)

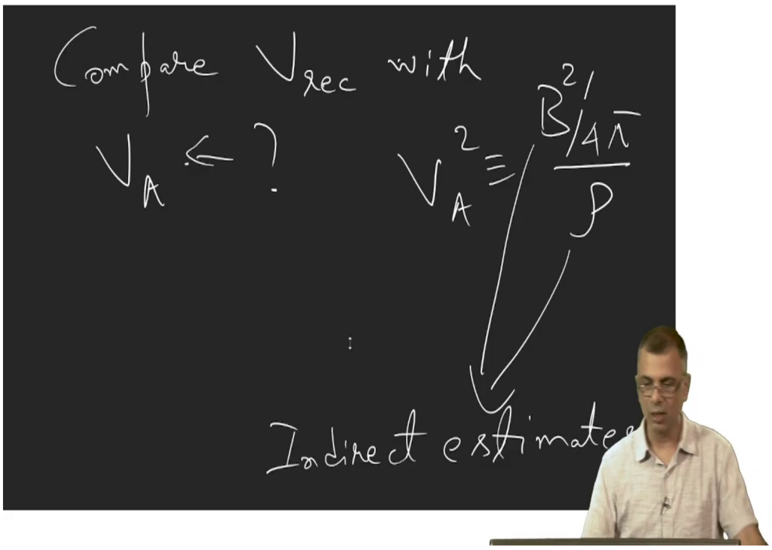


You use the t obs together with some estimate with some reasonable estimate with some estimate of a length scale of you know a length scale and what do you mean by the length scale? Well, you know some guess about the length scale over which where you think the reconnection is happening occurs ok.

So, you use t obs and L to get some kind of a V reconnection L over t obs would give you V reconnection as demanded by the observations. So, this is one thing ok. So, you realize that this V reconnection is a rather indirect thing. First of all you are thinking you are thinking that this is really this is most likely not the byproduct of one episode of reconnection. This is most likely the byproduct of several episodes of reconnection.

Number 1 ok – so, what you are really seeing is an average is an average effect due to several reconnection episodes ok. Number 2 you also have to have some idea of a length scale and in some situations like in the solar corona you do have you know some access to imaging and so, you have some idea of the length scale and from that you get a V reconnection as demanded by the observations.

(Refer Slide Time: 09:50)

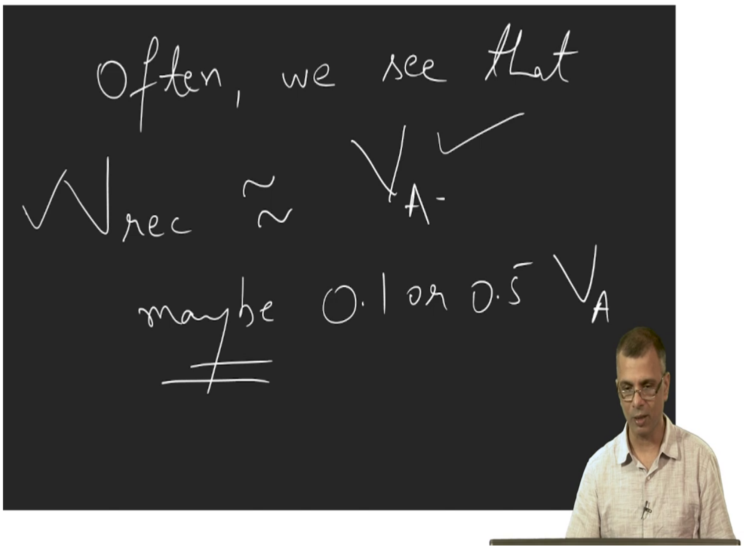


And, you compare V reconnection with V Alfven now in order to do you have any idea I mean how much rather a fairer question to ask could be how much of an idea do you have about V A? because the V A you see is you need to know the magnetic field and you need to know the density I think this is 4 maybe not 8 it is probably 4.

So, so, how much of an idea do you have about the magnetic field in the region that you are interested in? You have some very indirect estimates both about this and this you have rather indirect estimates, but nonetheless those indirect estimates are the best we have and therefore, you have some indirect estimate of the Alfven speed, ok.

So, what you then do is you compare the reconnection speed the observationally demanded reconnection speed which as we said is obtained rather indirectly estimated Alfven speed.

(Refer Slide Time: 11:12)



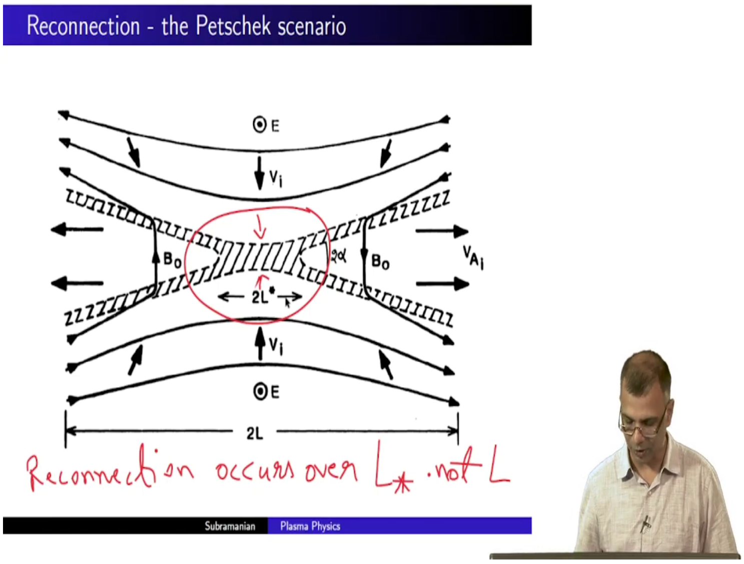
And, then you see that often, we see that V reconnection is not too different from V Alfven maybe 0.1 or 0.5 times V Alfven. I say maybe because everything is little uncertain our estimate of V reconnection is little uncertain, our estimate of the V Alfven is uncertain ok. But, at any rate we generally in astrophysical situations it is generally observed that the reconnection the demanded reconnection speed, reconnection speed which is mandated by the observations is not too different from the Alfven speed.

Whereas, what do we have here? What do we have from the reconnection rate as predicted by the Sweet-Parker model the model that we you know saw the last time this model ok.

The reconnection rate predicted by this model as designed from these three equations is that the reconnection rate is considerably smaller than the Alfven speed ok the reconnection velocity is considerably smaller than the Alfven velocity because the you know magnetic Reynolds number is much larger than one right.

So, this is what I mean by saying that this is not what the observations mandate. So, it took us a little while to sort of you know understand what this sentence means, not what the observations mandate ok. So, now, what do we do? Ok. Well, Petscheck in 1964 proposed rather unique solution. What he said was you what you do is you know that there is a thickness of the reconnection region and then there is a macroscopic length of the reconnection region.

(Refer Slide Time: 13:19)

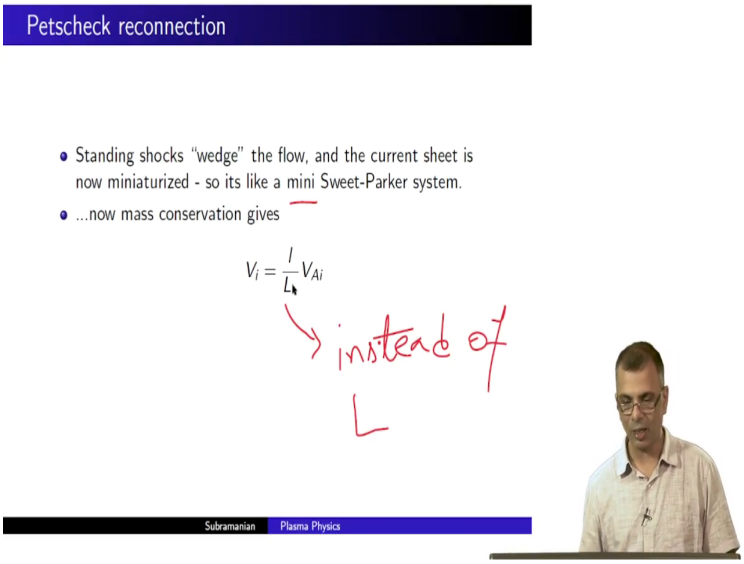


What he said was if we can find some way of reducing the length of the reconnection region like this in other words, yeah. So, the reconnection really happens here just here ok not over the entire capital L, ok. So, the thickness of the reconnection region is of course, this ok, but what you do is the reconnection geometry is now altered ok. So, that the reconnection is really happening over a much smaller region whose you know lengths whose dimensions are now L star, ok.

The reconnection happens occurs over L star not L where, L star this thing this length scale is considerably smaller than L, ok. So, that everything else pretty much remains the same you have got the V, you have got the electric field pointing out of the plane of the paper and so on so forth and you have got the you know the oppositely directed field lines being you know pushed in at a rate V i which is of course, that the rate at the velocity V i is of course, you know governed by what goes on in this region naturally.

But, then the only thing is instead of the this kind of the geometry the geometry is slightly altered like this ok there is an angle alpha and so, the reconnections actually happening only over L star.

(Refer Slide Time: 14:58)



What happens then, yeah. So, what happens is the standing shocks out here what happens is you see even in the Sweet-Parker scenario we saw that after reconnecting the field lines can snap apart they snap apart. And, in doing so, they drag the fluid I mean because of the speed at which they snap apart, this fluid the fluid flows quite fast in this direction in that direction.

And, often the speed at which the fluid flows exceeds you know some characteristic speed and we know that there are several characteristic speeds in magneto hydrodynamics there is a Alfven speed. Well, this is sound speed of course, this is sound speed, this is Alfven speed, this is slow magneto sonic speed and then there is a fast magneto sonic speed.

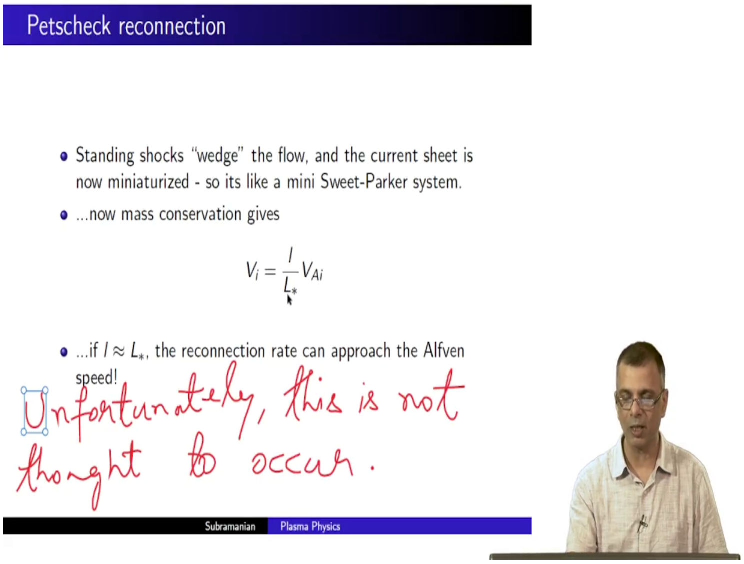
It is generally believe that the speed at which these flows happen exceeds slow magneto sonic speed ok and therefore, there is a possibility of standing shocks slow shocks slow mode shocks occurring here ok. And, so, these shocks can create a wedge in the flow ok and make it you know.

So, because the shocks cannot occur over the these entire you know the at the extent of these outflows is limited ok. These outflows are not happening all over these out flows are happening only over a limited region.

Therefore, the shock can occur only over a limited region, like this ok. Therefore, that naturally creates a wedge like geometry ok and that naturally makes the reconnection region like this you know. So, they wedge the flow and this current sheet is now miniaturized. So, it is almost like a mini Sweet-Parker system. Why mini? Because you know the reconnection is not happening all throughout the microscopic dimension l, but only now only over a smaller length ok.

Now, what happens is if you do mass conservation ok mass conservation now, gives you this instant of the L star instead of when we last wrote down mass conservation like this we wrote L here instead of L star, now we have L star ok, alright.

(Refer Slide Time: 17:19)



Now, you see the thing is if the you know the L star is almost equal to the thickness of the reconnection region, then you see the V I can be almost V A i as quote unquote mandated by the observations that is what we said here.

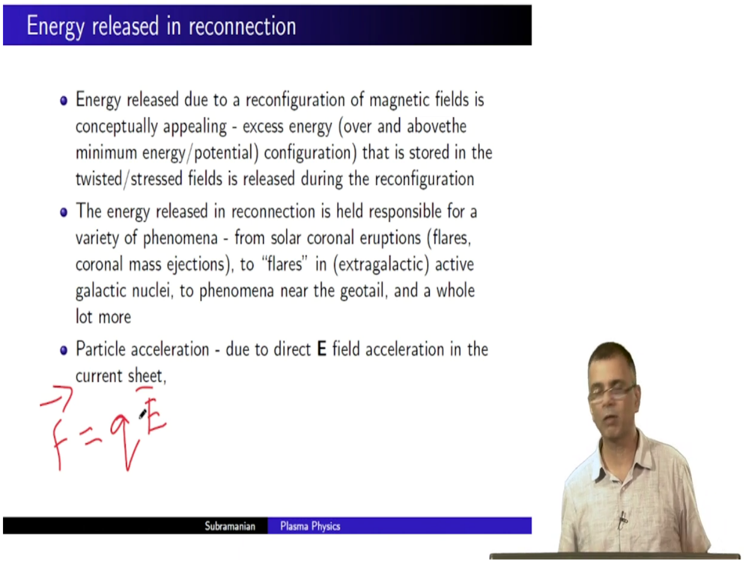
You remember we often we see that the V reconnection means to be almost about the V Alfven speed and that seems to be kind of I mean the Petscheck kind of geometry seems to satisfy this as long as the macroscopic dimension, the quote unquote microscopic dimension is almost of the order of the microscopic one of the thickness of the length current sheet.

In other words, if this thickness here is about the same as this, ok. Now, that is quite a demand really ok that is also little unrealistic, but at any rate you know if this can happen the reconnection rate can approach Alfven speed. So, this is one you know this is one thing to consider. Unfortunately, although this is a elegant solution this is not thought to be the case this is not thought to occur for various reasons, ok.

Because you know at least in simulations one cannot even in lab experiments it is very difficult to actually image the reconnection region, but one can do very detailed computer simulations. And, in simulations it is often observed that you know the geometry of reconnection is more like Sweet-Parker is more you know there is a very small dimension and there is a large dimension. It is not so much like Petscheck where both the dimensions are about the same you see.

In order for V i to be approximately equal to V A i the small l has to be about the same as L star. In other words, the two dimension you know need to be about comparable and that is often observed to be not the case. Although, this is one elegant easy you know way out unfortunately it just remains as that and that is not observe to the case, although I must say that the last word has not been said about this. This is still a very active ongoing area of research ok.

(Refer Slide Time: 19:51)



So, now let us move on to more practical issues. So, why are we interested in reconnection at all is because of the energy released in reconnection because reconnection is a means of extracting magnetic energy as we said in small busts in small episodes ok.

So, the energy released due to reconfiguration of magnetic fields is conceptually appealing the excess energy over and above the minimum energy or minimum or potential energy configuration as we have said that is stored in the twisted fields is released during the reconfiguration.

And, this kind of energy release is held responsible for a variety of phenomena – for a solar coronal mass ejections to solar flares, when we meet next I will show you nice pictures of solar flares in and also of coronal mass ejections, ok. So, this will give you a good real feel for the astrophysical context of this energy release. Also to all the way to flares in active galactic nuclei not just the solar coronal, but extragalactic situations ok.

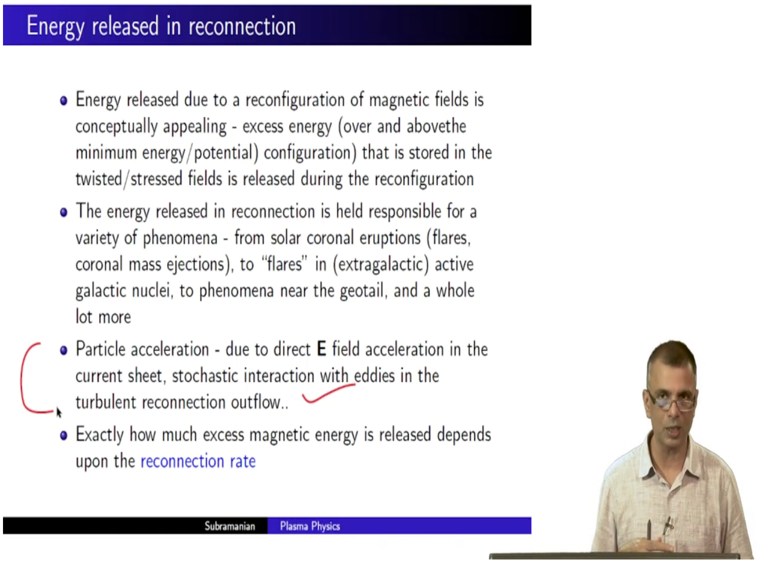
The phenomena near the geotail, on the night side of the earth where you know you know the whole point is the earth is continuously being impacted by the solar wind and so, this reconnection happening in the front on the day side as well as a night side and this energy released there and in these reconnection regions and what is called the geotail and this has been measured in great detail by a near earth space craft.

So, reconnection is held responsible for this wide variety of phenomena ok and the thing is you know because you have these electric fields anywhere whether you are talking about Sweet-Parker reconnection or this reconnection there is an electric failure that is unavoidable when you have got a oppositely directed magnetic fields coming together you will have an electric field induced, ok. And, that electric field accelerates particles right you have got an electric field in the electric field well accelerate particles, ok.

And, we are talking particles because by the time you are down to length scale that are small enough as small as a reconnection region the fluid approximation almost breaks down and then and so, you are really holding a magnifying lengths to the what is going on and you are almost or of observing the particles so to speak ok.

The dimensions of the reconnection region are so small that they you know what is in there you cannot use the fluid approximation any more. So, you are justifying starting to talk about particles and these particles can be accelerated due to direct electric field acceleration in the current sheet. You know the force in a particle is just you know this from elementary electrodynamics wherever you have an electric field there is a force, right and so, there is a force on the charged particle and so, the force causes the particles reaccelerate it.

(Refer Slide Time: 23:08)

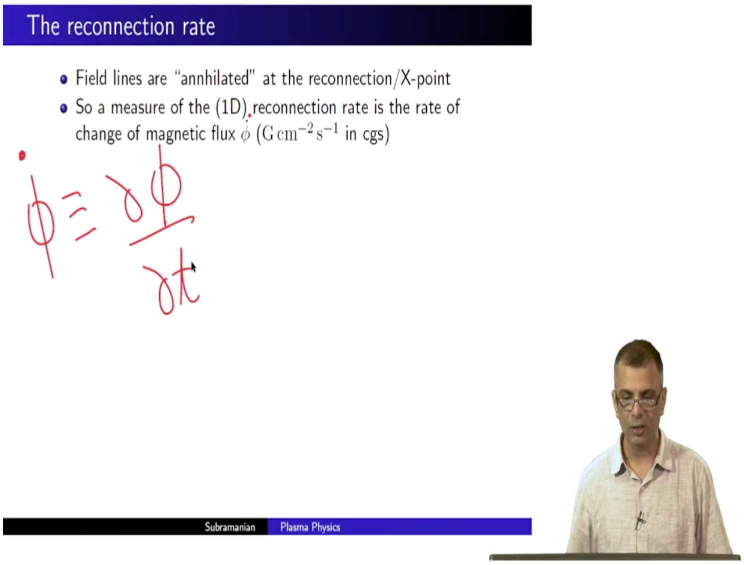


And, accelerated particles they emit radiation. So, there is direct particle acceleration. There is also stochastic interaction with eddies in the turbulent reconnection outflow and ah. So, we will talk about this in a minute in some more detail when we meet next. Let us put this this particular aspect of for the time being..

So, the point is this is the reason reconnection is appealing ok. This plasma heating, there also particle acceleration, but at the end of the day all of this energy is essentially how much energy you can extract from the magnetic field ok. The magnetic field carries excess energy and when it relaxes to lower energy state via cutting and pasting which is reconnection via the process of reconnection so, that excess energy is released.

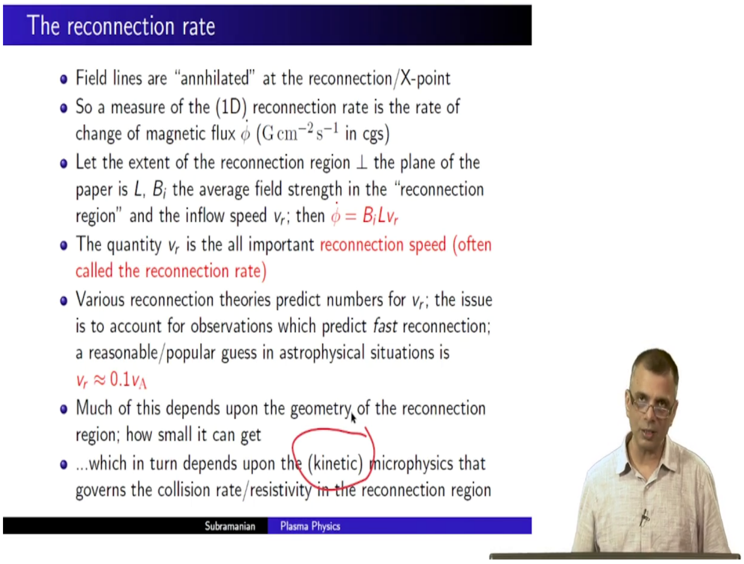
And, how much of that excess energy is pumped into various avenues it depends ok and these are the avenues that are of interest to us. Now, exactly how much excess magnetic energy is released of course, depends upon the reconnection rate, right.

(Refer Slide Time: 24:18)



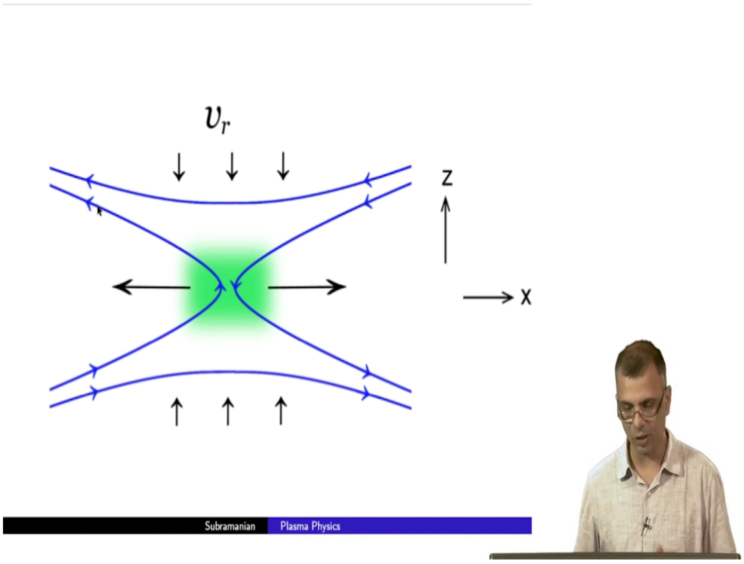
So, let us talk a little bit about the reconnection rate. You see field lines are annihilated or they are eaten up at the X-point in the reconnection region. So, at least in one dimension measure of the reconnection rate is simply the rate of change of magnetic flux phi dot, ok. So, we say and this phi dot is just phi dot is essentially short hand for d phi d t ok you know this gauss per centimeter square per second at least in cgs, ok.

(Refer Slide Time: 25:00)



So, let the extent of the reconnection region perpendicular do the plane of the paper B given by L in this case replace paper by screen, ok. Let B sub i be the average fields strength in the quote unquote reconnection region.

(Refer Slide Time: 25:20)



And, let the inflow speed be v r like this like this, ok. Now, we are you know changing notations a little bit do not worry about that, ok. So, then if that is the case then this phi dot is B i times L times v r and you can figure this out just from dimensional considerations as well, alright. What about it?

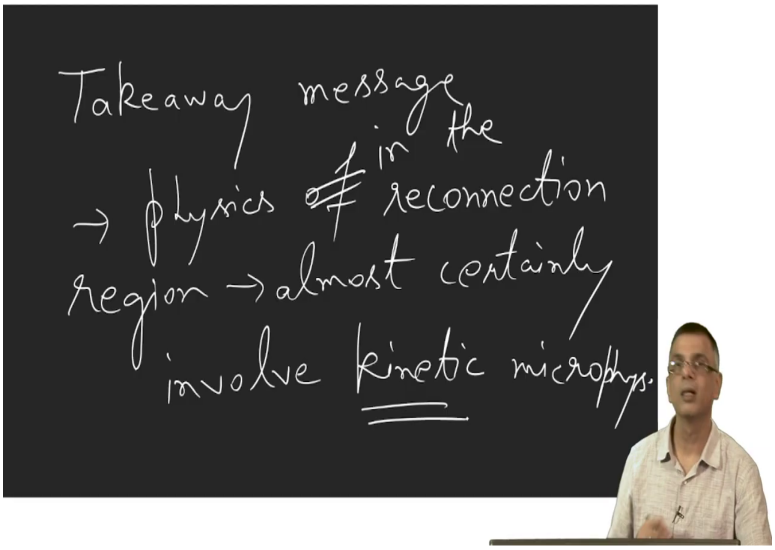
So, now, the quantity v r is what we were discussing about for the most part in this lecture and that is the all important reconnection speed. How much of a fraction of the Alfven speed is it that is what we were worrying about. Whatever it is it is ok it is all important reconnection speed ok often called the reconnection rate it is a bit of a misnomer at any rate.

Now, various reconnection theories predict numbers for v r and the issue is to account for observations which predict fast reconnection. Reconnection rates they are close enough to the Alfven speed reconnection speed they are close enough to the Alfven speed ok. That is what called fast reconnection and I would say a reasonable popular guess in astrophysical situations is this, ok. The reconnection speed is something like 10 th of the Alfven speed.

If your theory is able to account for this I would say most people would agree that your theory is a reasonably successful one, ok, right. Much of this of course, depends upon the geometry of the reconnection region; as we saw if the geometry is more like Petscheck than like Sweet-Parker, then you have a good chance of doing this it all depends upon the geometry and the geometry is really not clear astrophysical situations ok. It is only from simulations that one can make some guesses about the geometry, ok.

Now, the geometry of the reconnection region also depends upon the kinetic microphysics, ok. Why do I say kinetic because by the time like we said by the time you come down to you know length scales that are small enough as small as a reconnection region and the fluid approximation breaks down and you really need to start worrying about kinetic effects, ok. So, this is the thing.

(Refer Slide Time: 27:41)



And, so, the takeaway message is that the takeaway message is that the physics of the reconnection region if you will are not of may be in in the reconnection region almost certainly involves kinetic microphysics kinetic microphysics ok involves particles ok either particles explicitly or distribution functions, ok. It almost certainly does.

So, reconnection is the yet another one of those things where you are forced to you know you know side step between fluids, between the microscopic fluid theory and kinetic microphysics ok. So, when we meet next we will take up some observational examples of reconnection. I will show you some spectacular movies of solar flares and of coronal mass ejections. These are spectacular eruptive phenomena which are thought to be enabled by reconnection. So, that is it for now.

Thank you.