Fluid Dynamics for Astrophysics
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Lecture - 64
Solar eruptions: Coronal Mass Ejections (CMEs) and Solar flares

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So, we will restart from this very pretty movie that we saw yesterday. As I said this is a movie of a flare. The flare is simply this brightening of this region that you saw. So, this is real data captured from the sun, from the solar corona and this image is at a wavelength of 195 angstrom which is an extreme ultraviolet part of the spectrum and this represents roughly a few million degree Kelvin plasma which can be found only in the upper reaches of the atmosphere which is the corona.

So, this brightening is the flare. So, this is a the this is a sudden brightening in 195 angstroms, but experience tells us that this such large flares are brightening's observed all across the electromagnetic spectrum ok.

And these little white dots that you see on the screen these are signatures of accelerated particles, massive particles not photons, particles with mass such as you know alpha particles, protons, things like this right. So, and just to sort of give you a context this is really a very-very small part of the solar surface.

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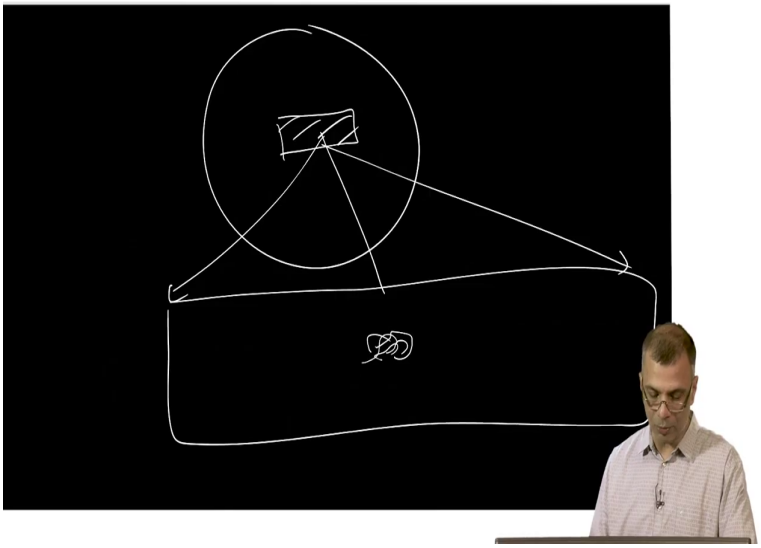

It would be something like if this is the solar surface, you know you are really seeing a blow up of just this ok this is what you are really seeing like that. So, you are you just seeing a blow up of a very small part of the solar surface and what you are really seeing is this you can kind of make out, but it is not very evident.

What you are really seeing is a sequence of very-very twisted loops and so on, so forth and something is happening to those loops which causes you know, you can see some of these

loops something is happening there which causes the onset of this flare and as we have suspected many times, it is really at the heart of this violent energy release and also smaller energy releases.

Some examples of which we have seen before is the process of reconnection; which is essentially a process of facilitating restructuring of magnetic field lines, of magnetic field lines that were stressed and they like to relax.

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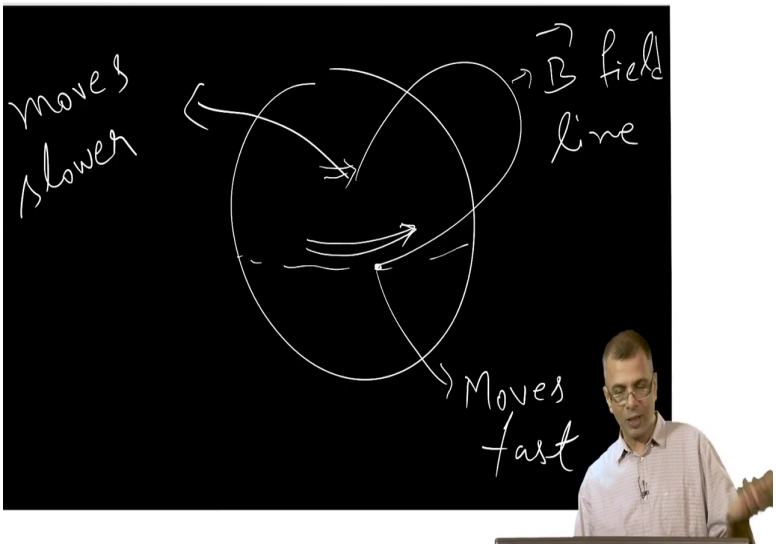

Why are they stressed? As we said yesterday, it is most likely, because of differential rotation. You know you have magnetic field lines embedded in the solar corona say a magnetic field line like this. Now, the problem here is that you know the higher latitude say suppose, this was the equator ok, lower latitudes move faster than higher latitudes.

So, this leg moves fast and this leg moves slower ok. So, naturally you can imagine that this this loop, this is a magnetic field line loop right. So, this loop will not remain like this simply, because of the fact that one leg is moving faster than the other, it starts getting twisted and

when it starts getting twisted it acquires, it is it has more energy as in it no as in the amount of energy that is stored in the twisted magnetic field loop is larger than the amount of energy in this lower energy configuration.

This is this would be almost a potential field configuration and the process of reconnection helps this, these stress fields relax and in reality of course, the field that the field lines are not as simple as this they are considerably more complicated ok, right. So, now let us take a step back and we I also told you that, the these kinds of flares are often accompanied by bodily ejections of plasma which are called coronal mass ejections we will come to that.

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But before that let us talk a little bit about why we should care about, why should we care why should we care about solar eruptions? Well, one of the reasons is of course, it is a very nice lab, it is an excellent astrophysical lab to study you know fluid dynamics and plasma physics and the these processes of magnetic reconnection are happening at a at a grand scale.

So, simply from a scientific curiosity point of view it is pretty cool, but there is a practical aspect to it also and I thought I would spend a little bit of time talking about these practical aspects, name which is generally called the Sun Earth connection and so, let us do that right now.

Now, as I said earlier we are really well immersed in the extended solar corona, not our atmosphere per say, but because our the magnetosphere shields us. As we know the Earth has a magnetosphere and charged particles which is what the solar wind comprises of do not like to cross magnetic fields.

So, in a sense the Earth is surrounded by a magnetic shield and so our atmosphere the air we breathe is well below the magnetosphere, but nonetheless you know at the Earth as a whole, the earth system as a whole including the magnetosphere is very much immersed in the extended solar corona ok.

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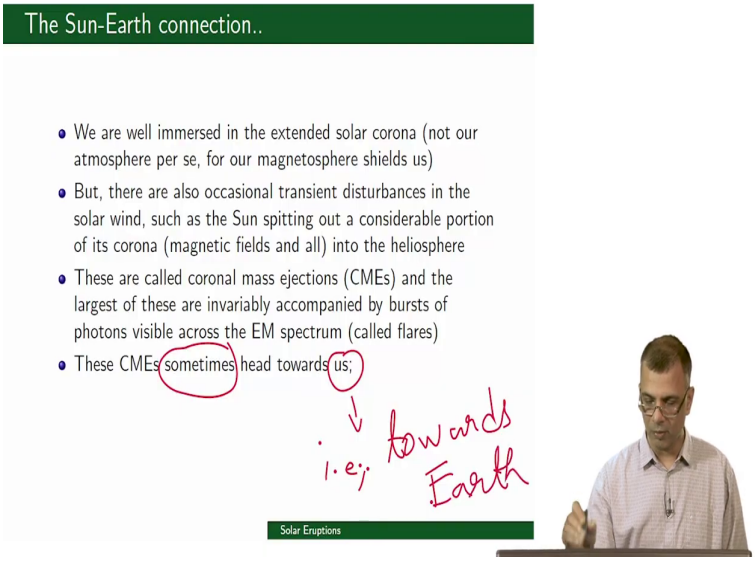

Now, but it is not as if the solar wind is nice and steady all the time although, those were the equations that we solved ok. There are occasional transient disturbances in the solar wind. The word transient means you know some something that is not steady state that is not you know it is blobby ok.

So, there are transient disturbances of the solar wind, such as the Sun spitting out a considerable portion of its corona ok. It is as if it takes some of its upper atmosphere and throws it out, it spits it out along with the magnetic fields and plasma and everything out into the general heliosphere.

And of course, not it is not every time that these ejections reach the earth the and these kinds of things are called Coronal Mass Ejection's CMEs for the C here and the M here and the E here ok. And the largest of the CMEs are invariably accompanied by bursts of photons which are visible across the electromagnetic spectrum. We just saw a very beautiful example and they are called flares right.

And these coronal mass ejections sometimes head towards us, not always ok, it depends upon the geometry, but some of these coronal mass ejections can head towards us. I mean towards earth, this is what I mean ok.

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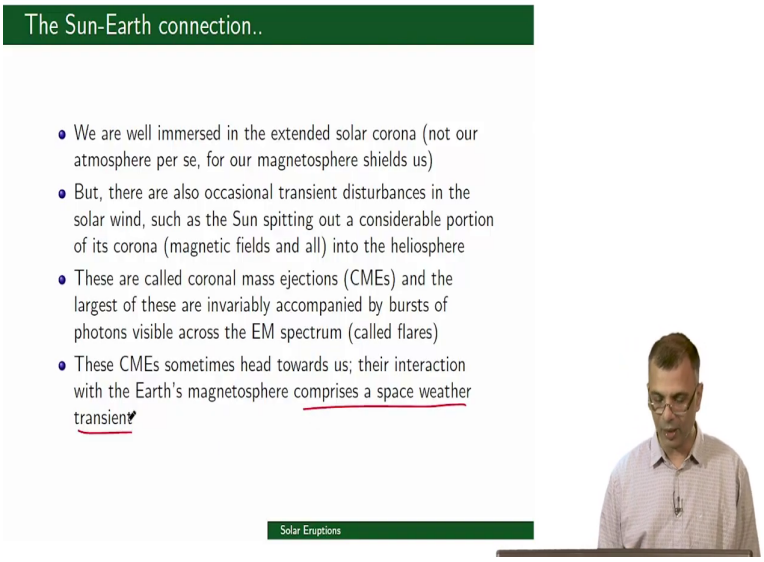

And these coronal mass ejections they are magnetized ok and they carry magnetic fields with them and the earth also has a magnetic field shielding it the magnetosphere and so the interaction between these two magnetic field lines, if they are oppositely directed we now know that oppositely directed magnetic fields when they come very close together they can reconnect.

And so, if that happens their interaction with the Earth's magnetosphere it does a lot of things to the steady state configuration of the magnetosphere system. It is fairly complicated what happens, but by and large this interaction of the CME with the Earth's magnetosphere comprises what is called a space weather transient ok.

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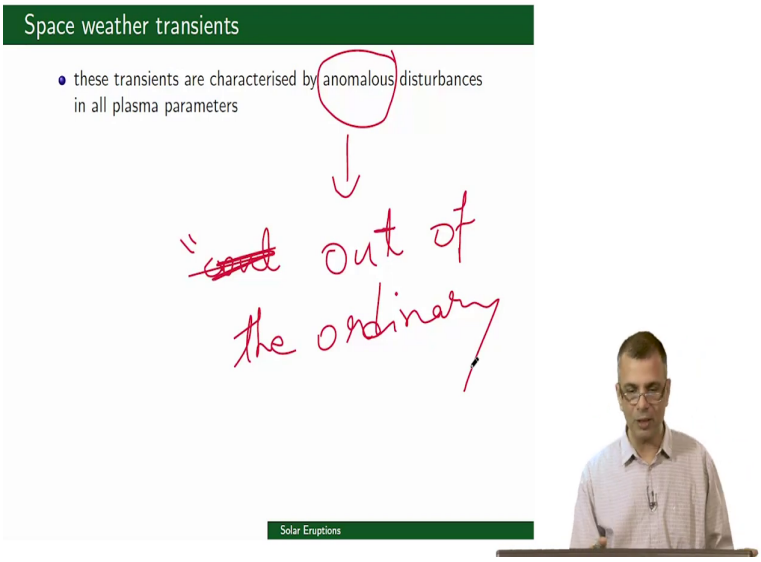

And what is it? Well, these transients so, what are these space weather transients? Well, these transients are essentially characterized by anomalous. I emphasize the word anomalous as in anomalous meaning uut of the ordinary that the I mean as in the plasma in the immediate vicinity of the earth you know just above our atmosphere say the ionosphere upwards.

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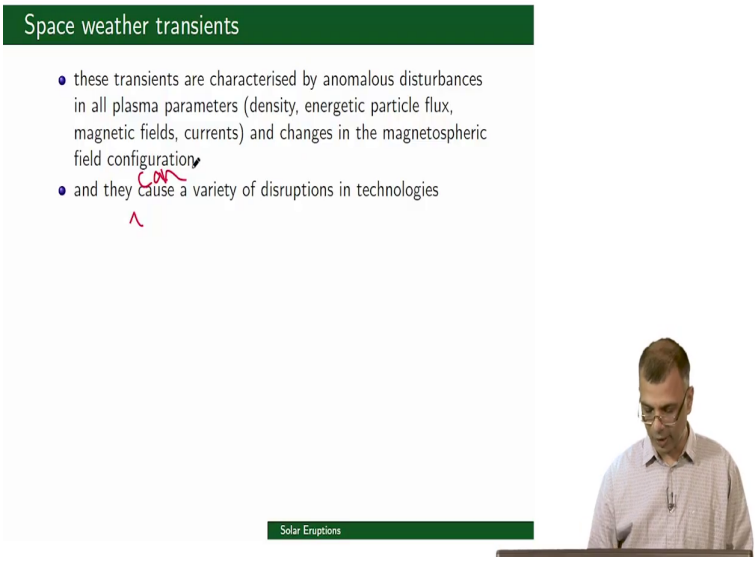

It has a certain steady state configuration ok and when these coronal mass ejections interact with the Earth's magnetosphere things happen and there are out of the ordinary disturbances in all plasma parameters such as you know the plasma density, the energetic particle flux, magnetic fields, currents so on so forth lots of things ok and also changes in the magnetospheric field configuration and they can cause ok. So, they can cause a variety of disruptions in technologies.

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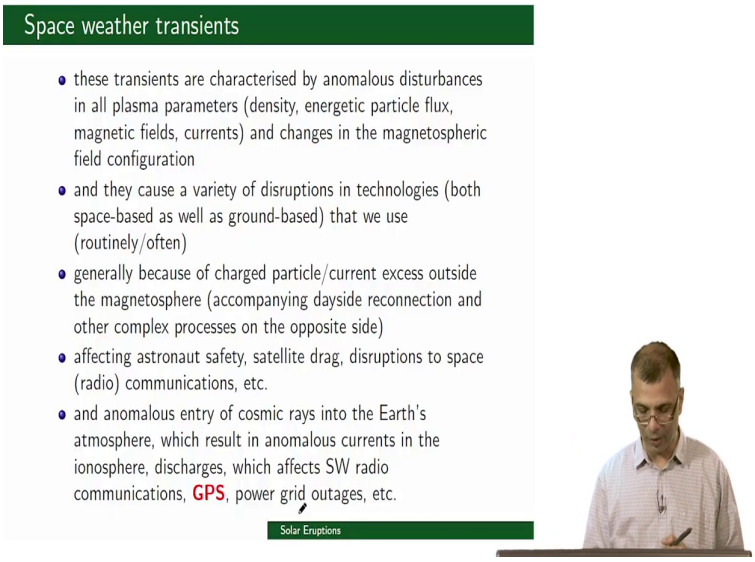

Both space based as well as ground based that we know, we are very dependent on space based technologies these days such as you know the cell phone that we use, Dish TV, it communicates with satellites Earth orbiting satellites. So, if the atmosphere in which the satellite is operating, if the density, magnetic fields currents, and so on so forth and that in that atmosphere changes suddenly, the operations of that satellite will be hampered greatly ok.

And these things are generally, because of charged particle or current excess outside of the magnetosphere accompanying dayside reconnection dayside meaning the side of the Earth that is facing the Sun and fairly complex processes on the opposite side on the night side ok.

So, these things these space weather transients have a variety of effect. It affects astronaut safety. For instance if you were conducting you know a human space flight or for instance you were conducting a spacewalk or something say you know on the international space station, you needed to send a, send an astronaut out to repair something or something you know you need to be very-very conscious about their safety.

They are wearing these safety suits, but nonetheless if there is an expectation there is there is going to be a large space weather event then you know this is so to speak bad weather for the

astronaut ok, this is almost certainly fatal. So, you should be very you know cognizant of that (Refer Time: 10:58) changes in the density or energetic particle flux or some so on, so forth. Around the satellite it affects the drag experienced by the satellite and most of the time it enhances the drag and so it reduces its life so on, so forth.

These space weather transients can cause disruptions to space communications. For instance if you are communicating to with a satellite from the ground, like you know the Dish TV that you use or so many other you know instances GPS, for instance GPS signals are transmitted from the ground to the satellite and the satellite you know sends us back.

So, so these communications can be disrupted due to space weather transients and of course, anomalous entry of charged particles of cosmic rays into the Earth's atmosphere which result in anomalous currents in the atmosphere discharges which so on, so forth. Lots and lots and GPS I have outlined this in red, because it is very-very important to us in everyday life these days ok.

The global positioning system is something that is of importance not only you know, for instance if you are using Google maps or something, but also to guide you know aircraft navigation, when an aircraft is landing you need the GPS, you rely heavily on the GPS so on, so forth. It also often causes power grid outages and these things of course, power grid outages and things like this are especially more severe at higher latitudes that are closer to the pole.

The purpose of this slide was not to explain the space weather transients in any great detail, because it is a very complex subject somewhat outside the purview of the course, but just to give you know a bit of a birds overview of the kinds of effects that transients in the solar corona, in other words solar eruptions can have on our everyday lives ok.

So, this is these are some practical reasons to wonder about what is causing these solar transients and how these solar transients propagate and things like this. So, apart from a basic physics viewpoint where you know it is really curiosity based and itis cool to study them it is very nice to understand them.

Apart from that there are also practical reasons to understand them so that we can predict and we can mitigate the effects of these space weather transients better. If we understand them better naturally well be able to mitigate their effects better right.

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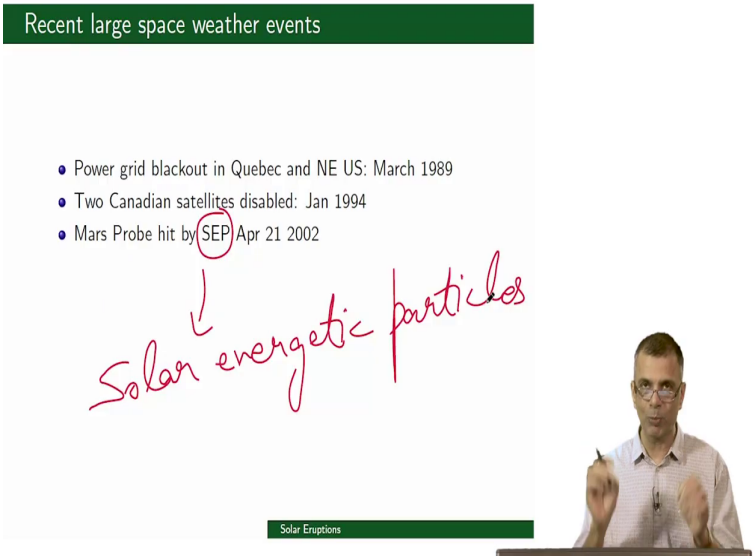

So, here are some examples of recent large space weather events there was a power grid blackout in Quebec in Canada and a large parts of the North-Eastern United States in March 1989. Two Canadian satellites were disabled in January 1994, because of you know space weather transients and then mind you each satellite is really really expensive ok. These are like go up to millions of dollars.

So, it happens that Canadian satellites were disabled, but you know satellites launched by any country they are in outer space. Outer space simply means you know outside of the immediate Earth's atmosphere. They are still pretty close to the Earth, these things called geomagnetic storms very much affect earth orbiting satellites ok.

So, two entire satellites disabled this is a serious loss ok and the mars probe was hit by solar and energetic particles. These are the, this is a; this is a short form for solar energetic particles, particles that were emitted during the course of one of these eruptions like we saw in the movie, the these white specks. So, these are called solar energetic particles.

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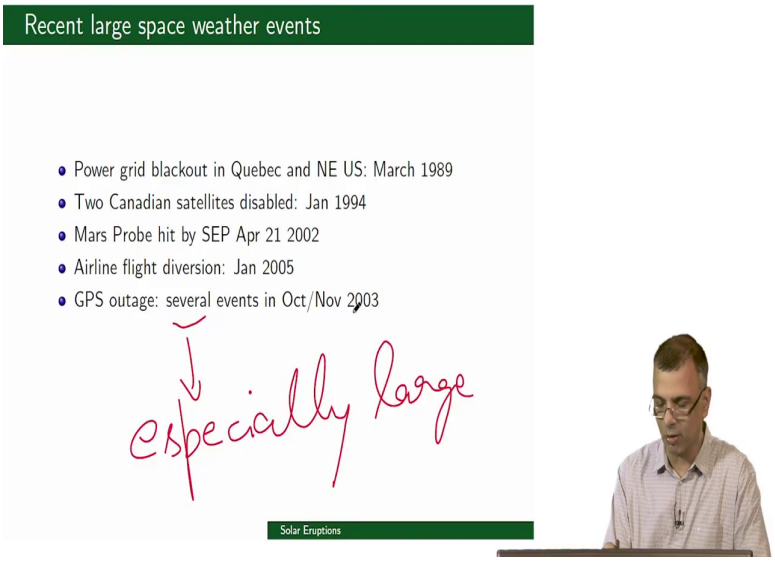

Because of you know a rather large geomagnetic storm in January, 2005 lots of airline paths had especially the ones which are flying over the North Pole. These paths have had to be diverted. So, regular airline paths have to be; have to be rerouted and this is a major thing you know you have to have lots of coordination, it causes considerable changes in schedules and also you know it is a big business decision, because you know it impacts the profitability.

I mean you change an airline path, you make it longer, it consumes more fuel and so on so forth and so, the flight is costlier that is that is what it is. So, and there were several outages of GPS and the global positioning system due to a series of especially large events, several especially large events in October and November 2003.

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And historically, perhaps one of the largest flair kernel mass ejection event happened in August and September 1859 and interestingly, the geomagnetic observatory in Alibaug near Bombay, this recorded, this was one of the few observatories which recorded this event called the Carrington event.

There were also very large events recorded in 1882, May 1921, August 1972, these are so to speak you know record breakers. So, to speak, ok record setting events, just to say that these are examples of large space weather events.

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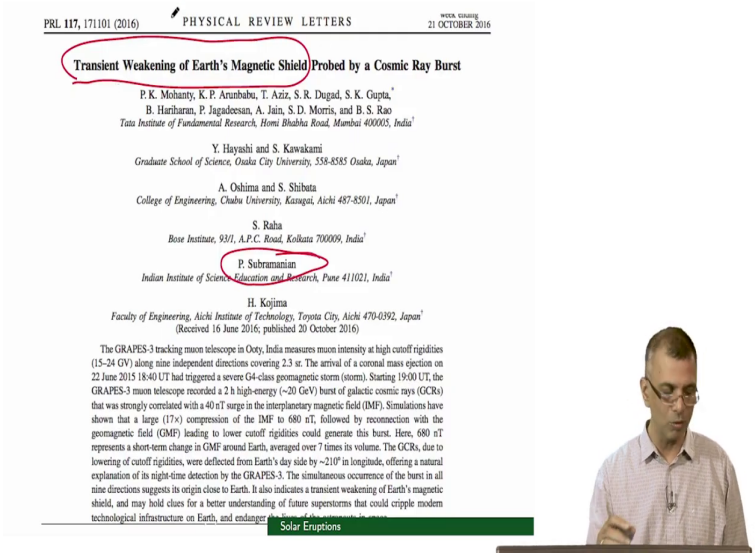

And here is a paper that I was part of that is me here and this tells you how due to a space weather event and there was a transient weakening of the Earth's magnetic shield. So, there was a chink in the in Earth's magnetosphere. So, to speak and this weakening was probed by a cosmic ray instrument situated in Ooty and so, this was published in the physical review letters in 2016, just an instance ok.

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So, from our point of view the this was a very quick run through of you know various effects that can arise due to space weather events which are caused by eruptions on the Sun. Let us sort of consider this in a little more detail what causes these events ok. Most of the time these are due to coronal mass ejections from the Sun and what are these?

As we have mentioned before, these are bodily expulsions of coronal plasma ok and so million degree coronal same thing, coronal plasma is about a million degree hot. It is not like it is uniformly a million degrees, it comprises multi thermal plasma.

Some of the constituents are considerably hotter than a million degrees about tens of million degrees, but nonetheless million degrees plasma is a rough is a good estimate to go by. So, these are expulsions of a million degree plasma and they are quite occasionally accompanied by flares and flares and coronal mass ejections different things ok.

Flares are just bursts of photons whereas, coronal mass ejections are actual bodily expulsions of this coronal plasma and these Coronal Mass Ejections or CMEs are often aimed at the earth ok. So, let me now show you some examples of CMEs.

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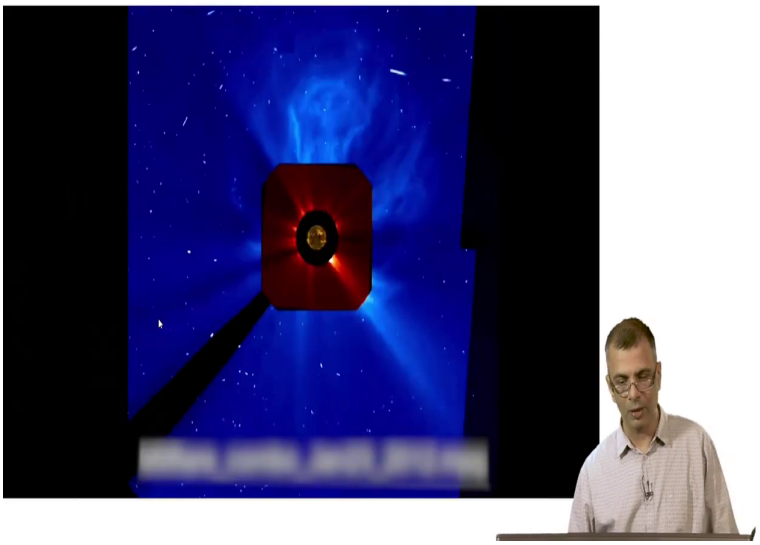

Here is an example. So, what this is I have to; I have to explain this figure a little bit. What this is, you see the Sun this is a series of juxtaposed movies ok. The Sun is in the is in the very centre ok and so this is just an image, this is an extreme ultraviolet image of the Sun that is just artificially superimposed on this picture.

What this is a picture of is really? This black disc that you see, this is what is called an occulter ok. This particular instrument which took this the red image and the blue image, these are what are called occultes ok.

They are they create artificial eclipses. You see an eclipse happens when the moon comes in between the Sun and the Earth and so what happens is the moon blocks the face of the Sun and the face of the Sun is very-very bright which is why you are not able to see the surrounding corona which is much dimmer.

So, what this what this occulter does? This is a space based occulter, it is sitting on a spacecraft and it blocks the face of the Sun somewhat like this ok. So, this is called this instrument is called a coronagraph.

So, you the this black circle is one such occulter ok and so this this occults, the Sun up to a distance of about 2.2 solar radii ok. So, this where my cursor is right now is about 2.2 solar radii and the edge of this red field of view is about 6 solar radii, if I am not mistaken.

So, from 2.2 to 6 solar radii you are able to observe the corona and as the movie runs you can see out here that there is a there is an expulsion of some white bright material which is like going out and this is what is a coronal mass ejection. This white this bright stuff, it means that you have excess density, excess density over and above the surroundings ok.

So,; that means, that there is some excess density of coronal material, because coronal material is what you are seeing right now that is expelled outwards ok. So, this is one coronagraph which is imaging the Sun from about 2.2 solar radii to about 6 solar radii and this blue stuff is yet another chronograph which is imaging the Sun from about 4 solar radii all the way up to this the edge of this field of view is about 30 solar radii.

So, taken together the these two instruments are giving you an uninterrupted view of the Sun. These two chronographs are giving you an uninterrupted view of not the Sun, the solar corona from about 2 odd solar radii all the way up to 30 solar radii and what are you seeing in this movie? You are seeing a coronal mass ejection which is propagating outwards like so and you see it continues in the outer field of view and you can see that the white stuff continues outward.

So, this is an example of a coronal mass ejection and this was also accompanied by a flare.

A flare would be brightening somewhere here that you are not able to see that, but you know trust me it did happen and the telltale signatures of that flare are these white streaks that you see, these are massive particles as in particles with finite mass like protons, alpha particles, and so on, so forth which were accelerated in the flare, which were hit which are now, hitting the detectors and you are seeing these streaks, the these are essentially ionization streaks on

the detector which is observing these coronal mass ejection. So, this is one very nice example of a coronal mass ejection.

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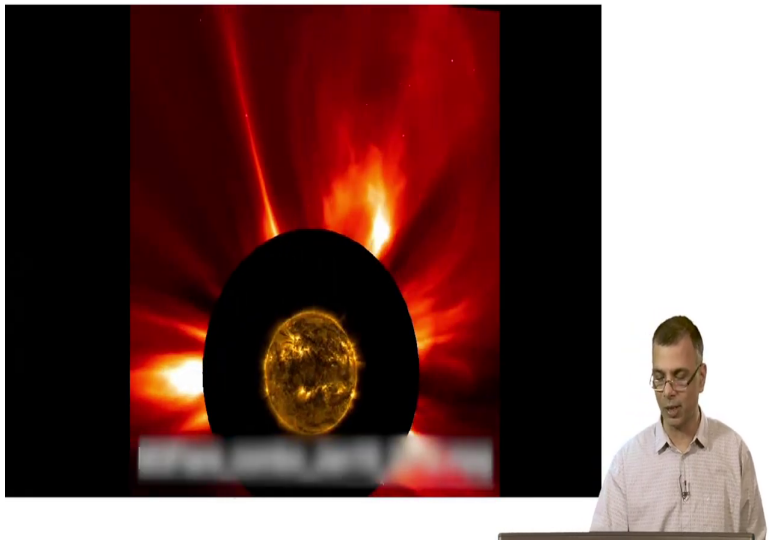

And here is yet another example you see. This this particular thing only has this is only this is a bit of a close up and it is showing the field of view is only from about 2.2 solar radii which is the edge of this which is the edge of this occulter up to about 6 solar radii and here too you can see that there is there is bright stuff.

Yeah, you see this bright stuff here and actually these are 2 3 coronal mass ejection. There was one going off that way, there was one going off this way and there is one going off here also and this happened on January 19th of to 2012 ok. So, several coronal mass ejections happening all at once and I will save the best for the last. Here is another truly spectacular movie of a coronal mass ejection.

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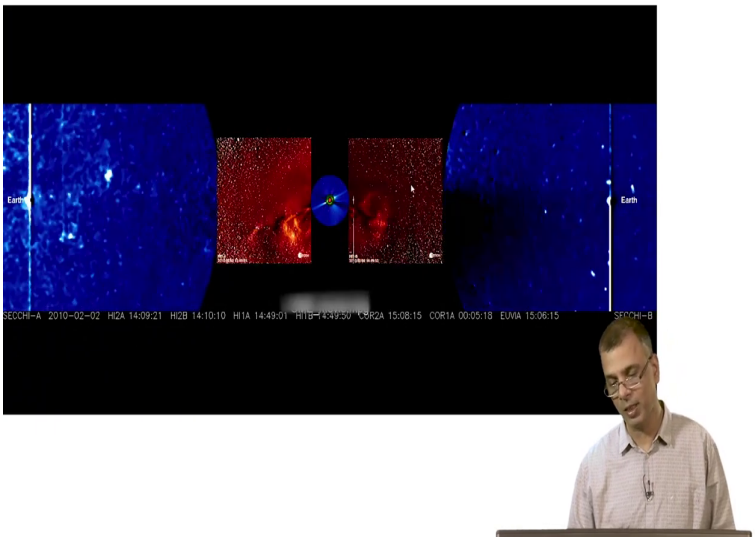

Now, let me explain this a little bit these are two spacecraft ok. These are images from two spacecraft; one here and one here ok. There is one spacecraft which is obtaining these images, there is one spacecraft which is obtaining this image and this image and there is another spacecraft that is obtaining the right pair this image and this image.

So, the pair of spacecraft that are obtaining this and this and this and this these two spacecraft are what are called the NASA STEREO spacecraft for obvious reasons. Two spacecraft imaging the Sun, Earth the heliosphere in tandem just like our two eyes which always see in STEREO ok.

The way this image is structured is that you know whatever is being seen by the left spacecraft and the right spacecraft is folded out and laid on a two dimensional piece of paper that is why you see the Earth here as well as here.

If we were able to see this with two eyes what this would actually happen is that that the brain processes it and it folds up the left image and the right image into a three-dimensional image. Here, this 3-dimensional image is projected onto a 2-dimensional plane.

So, now, what is this showing us, this is showing us a coronal mass ejection which is going all the way from about this is about 30 solar radii, this is I suppose about 50 solar radii and this is 215 solar radii that is Sun Earth distance and we see a coronal mass ejection which is propagating like so, all the way and you can even trace it although it becomes dimmer and dimmer and dimmer and therefore, it is progressively more difficult for the instruments to detect it.

You can see this coronal mass ejection coming from the Sun and coming all the way to hit the Earth. And you can see the same phenomenon as observed by the other spacecraft and in this case too you can see the coronal mass ejection propagating and coming all the way to the Earth. So, you can be you can rest assured that everything that we have been saying about space weather transients and so on, so forth is not just fiction.

Here is an actual demonstration, this is real data of a coronal mass ejection which is propagating from the Sun comes and reaches all the way to the Earth of course, what this does not show you.

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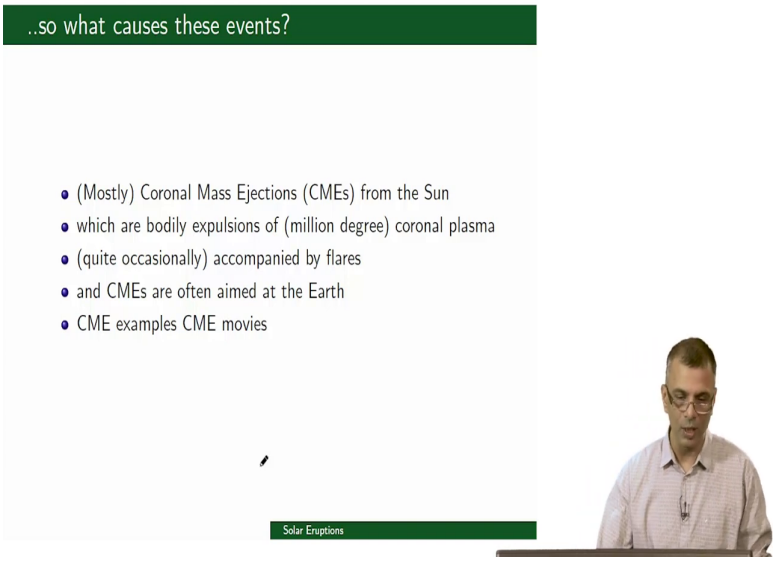

When the coronal mass ejection hits the earth and when it causes geomagnetic storms and so on, so forth well, those are that is what we talked about here. So, to summarize as a grand summary I would say all everything that we have been talking about by way of magnetic reconnection and so on, so forth.

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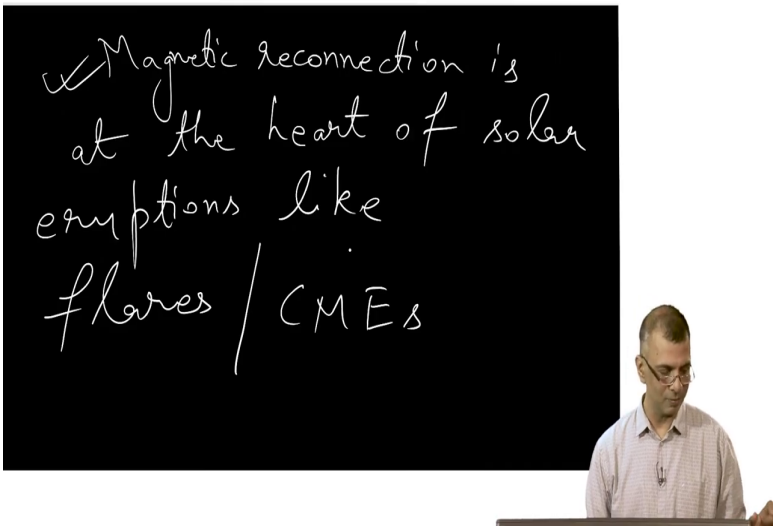

Magnetic reconnection is at the heart of solar eruptions like flares and coronal mass ejections and we have seen why it is important to study flares and coronal mass ejections? Because A; because we can learn something about this this cool process of magnetic reconnection, but B; also, because it has you know considerable practical relevance many of these coronal mass ejections are responsible for large transients in the near Earth space environment which affect range of technologies that we you know depend upon in our daily lives.

And at the heart of all this is this process of magnetic reconnection ok. Of course, there is this also this other thing it is all a fluid phenomenon. Once, the coronal mass ejection gets ejected the manner in which the CME propagates from the Sun to the Earth. This is you know it is a viscous medium the solar wind although, it is a collisionless medium, it is a viscous medium. So, it is subjected to viscous drag.

We have we have talked about viscous drag earlier early on in the course. So, all of these fluid phenomena in particular magneto hydrodynamic phenomena can be brought to bear in study of this at least this one particular astrophysical context which is that of the solar corona.

So, I thought I would go into some detail simply, because it is very immediate and we can appreciate the practical relevance and also you know the solar corona in the Sun in as such is a great lab for studying these fundamental fluid dynamical and plasma physical aspects.

Many of these things can be studied in terrestrial labs on the Earth, but you know these are stages where such processes, can be pictured and invesized in much more grandeur than what is possible in laboratories on the Earth. So, with that we will stop here.

Thank you very much for your attention.