Fluid Dynamics for Astrophysics
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Lecture - 44
Spherical blast waves: Bomb explosion and supernova explosion

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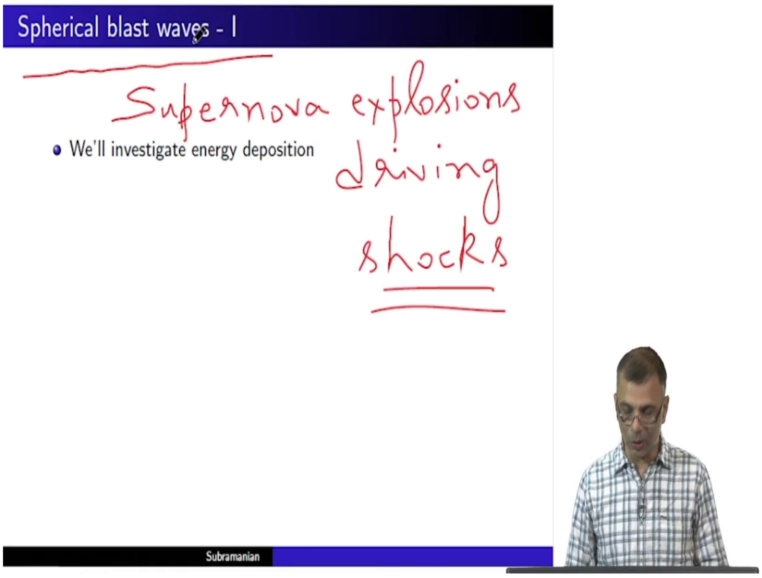

So, having discussed the practical utility of shocks in astrophysical situations and remember shocks are essentially important in astrophysical situations, because they serve as sites for particle acceleration right. What kind of particle acceleration? High energy particles right. So, the high energy particles are not part of the general background fluid flow as we have emphasized over and over again, but these high energy particles are the ones which emit photons often high energy photons.

But not necessarily sometimes optical, sometimes radio photons, which are considerably low energy. But the point is that most often its not the background fluid that is observable, its really these high energy accelerated particles that are observable, that are essentially the tracers for the observations that we make of astrophysical sources. And many times we are puzzled as to the origin of these high energy particles, how did these high energy particles come about.

So, this is the question one asks quite often and shocks in astrophysical situations often provide the answer ok. They serve as agents to accelerate such high energy particles and as we discussed, we discussed the concept of Fermi acceleration using a shock and just to recap one there are 2 basic ingredients in this entire mechanism.

One is the concept of scattering centers magnetic scattering centers, which are also not part of the background fluid, but which are embedded in the background fluid and these scattering centers are can be magnetic irregularities or something else right. And so these high energy particles bounce off of the scattering centers, the scattering centers serve to in the way we discussed it the last time.

They serve to reflect this high energy particles ok, and these scattering centers simply go along with the bulk flow, whatever the bulk flow does they also do ok. And the other important thing is that the name is diffusive shock acceleration right. So, its very important for diffusion to happen in the vicinity of the shock, which enables these high energy particles to sample both sides of the shock, both the upstream and downstream side of the shock.

And therefore, they can undergo approaching collisions on both sides and gain energy very very fast ok, and this kind of acceleration is called first order Fermi acceleration. The other thing about diffusive acceleration is that just like they are able to you know diffuse on both sides of the shock, fairly close by they can also diffuse far away. So, they can escape from the accelerating region.

So, both these ingredients are needed acceleration as well as escape ok. So, this was a very quick recap, a quick run through of why and how shocks are important for our purposes in astrophysics in astrophysical situations. Now, we will turn our attention to one such astrophysical situation, where shocks are known to form that of a supernova explosions ok.

And in particular we will approach supernova explosions from the point of view of spherical blast waves. So, just to emphasize we are really talking about driving shocks. What kind of shocks? These kind of spherical blast wave sorts of shocks ok. So, this is the physical situation we are investigating.

As we will find out later its even more restricted than this, in that we will be investigating only one phase of the evolution of these blast waves, which is the phase where the shock is known to expand self similarly. So, its our analysis is actually quite restricted, but it has the advantage of simplicity and it has the advantage of predictability and historically this was one of the first sort of stepping stones in understanding the formation of shocks in astrophysical situations.

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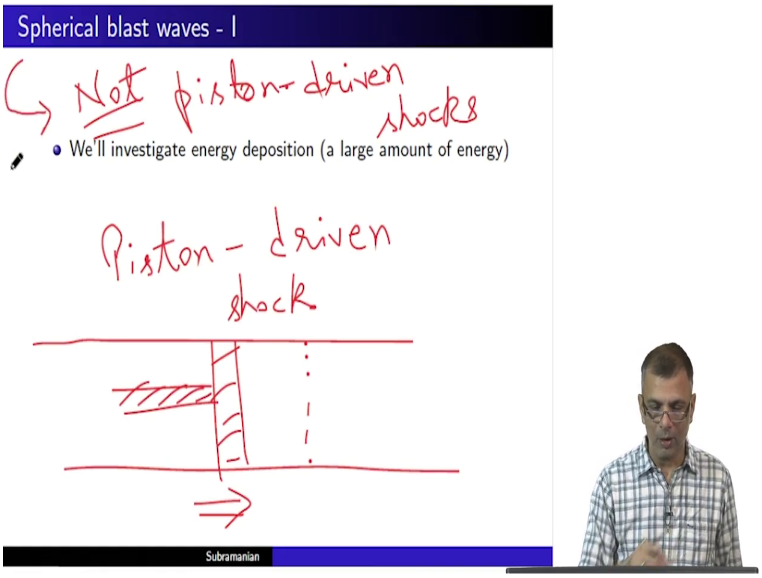

So, it is important for us to go through this right. So, unlike the situations the lab kinds of situations which we have encountered, where you might have you know a tube and a piston right and the piston you know. So, this would be a tube, an air tight tube and this would be a piston and the piston will be going forward and when this when the speed of the piston exceeds the speed of sound, it drives a shock wave in front of it ok.

So, this would be an example of a piston driven shock ok. And. So, this kind of thing would be important in lab situations and also in some astrophysical situations, such as the case of a coronal mass ejection from the solar corona ok. So, the coronal mass ejection is essentially a blob of plasma which is plowing through the heliosphere. And so that blob of plasma plays a role of a piston ok and so, that is pushing material and once it gets supersonic, it drives a shock in front of it.

However, the kind of shock we are talking about is not a piston driven shock ok. This these are not piston driven shocks these.

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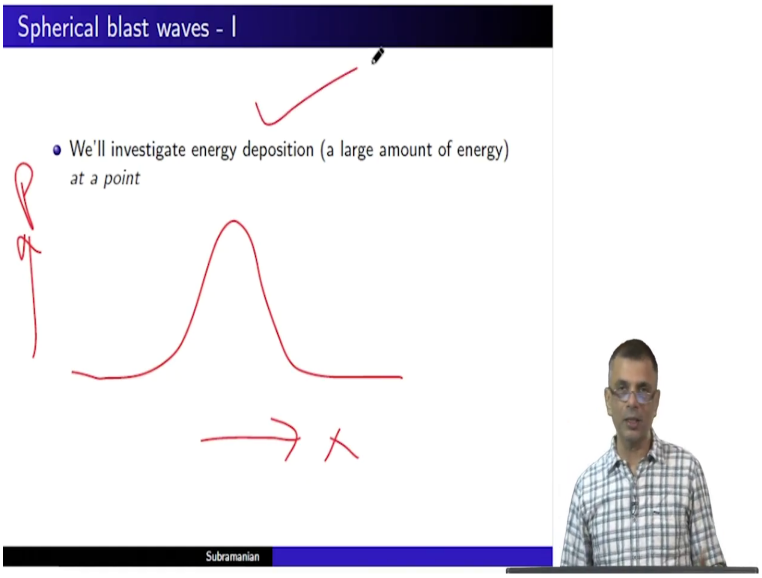

On the contrary these are due to a large amount of energy being deposited at a point, why is why does this also produce the shock you see, you remember a shock is essentially produced due to a pressure pulse ok. A pressure pulse which you know a pressure pulse like this, this would be X and this would be P right.

And the fact that you know the peak of the pressure pulse has a different sound speed, because the Y axis is so large, the pressure pulse is so large, that the peak of the pressure pulse has a different sound speed from the leading edge of the pressure pulse, and therefore the peak tends to overtake the leading edge and leading to shock formation.

So, now this kind of pressure pulse can be produced due to a large amount of energy deposition at a point, a localized kind of energy deposition like this. Like what we are talking about here ok and this essentially happens during a blast, ok.

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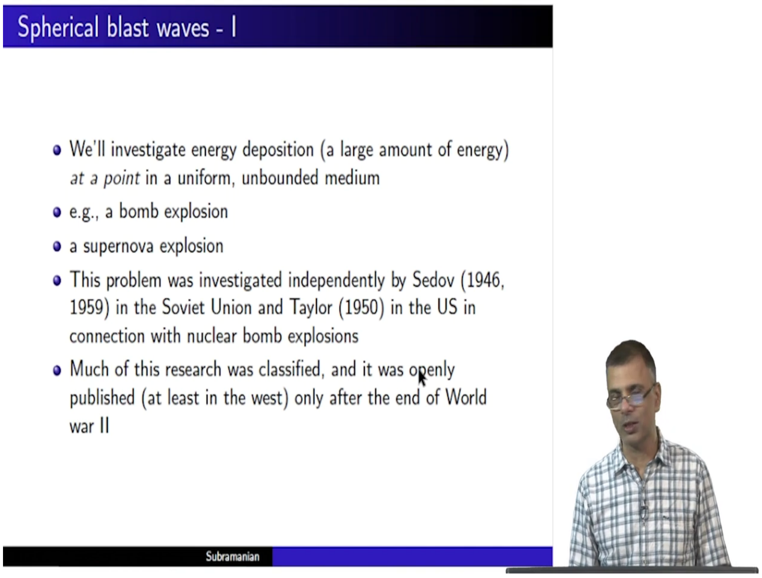

So, the other assumption is that, this entire thing is happening in a uniform unbounded medium ok. You deposit a large amount of energy at a point and the medium itself is uniform and unbounded, the there are no boundaries ok. So, just to simplify things. For instance a bomb explosion this is the prototypical example of energy deposition at a point in a uniform unbounded medium. A bomb explosion and so you can immediately or a supernova explosion ok.

Turns out that the physics in both these cases is very similar, this problem was investigated independently by Sedov, you know the early 1946 and 1959, you can see that there is a large gap in between 1946 and 1959. So, Sedov in the Soviet Union and Taylor in the US, in connection with nuclear bomb explosions.

So, really this is what drove much of this kind of research ok, research into nuclear bombs. So, the people who understood bomb explosions also recognized that, supernova explosions would probably you know involve the same kind of physics. It also in that just like a bomb explosion which deposits a large amount of energy at a point or in a very small, you know area which can be idealized as a point.

Just like that a supernova also when the thermonuclear flash happens at the center of the supernova it is it also deposits a whole a large amount of energy in a very limited region, and therefore it can also drive a blast wave, more specifically a spherical kind of a blast wave in a manner very akin to bomb explosion.

So, the physics was very similar and as you can also imagine a little bit of history about this, as you can imagine since you know research on nuclear weapons and everything was a big deal during those days. Much of this research was classified and, so it was not published in the open literature.

Which is why between 1946, which kind of explains this large gap between 1946 and 1959 ok, although this research was mostly theoretical and nonetheless, it the application was to bomb explosions. And therefore it was openly published at least in the west, only after the end of World War II and World War II ended around 1945 right. So, you can see that the publication took place in 1950 ok.

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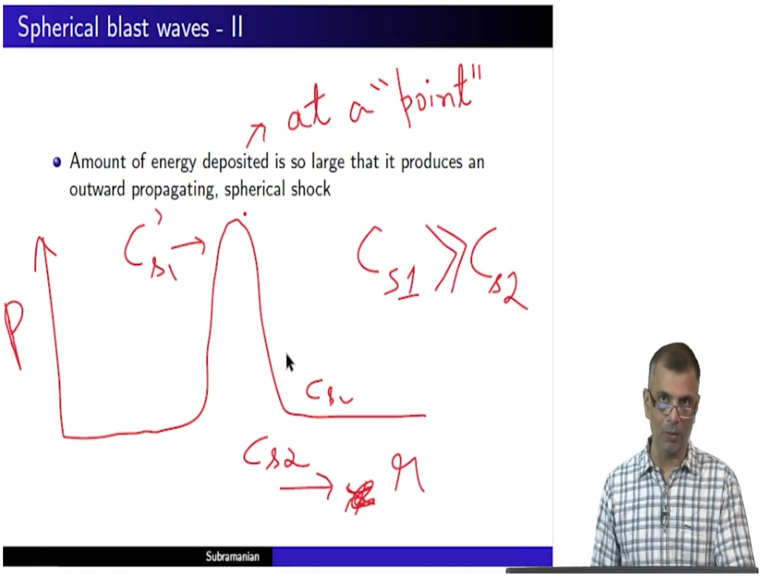

So, this is a little bit of history right, coming down to the physics. So, what are the central characteristics? Well the amount of energy deposited at a point I must say a point or in a very localized region. It is so large that it propagates an outward, propagating spherical shock. Its what it does is it just produces a pressure pulse that is very large like this.

So, or if you wish let us not call this X, let us call this r in spherical coordinates. And so the pressure pulse produced by the amount of energy deposited is so large. That it propagates or produces an outward propagating spherical shock. Why? Because you know the sound speed here this C s here C s 1 say and if the sound speed here is C s 2 like this, C s 1 is greater in fact much greater than C s 2.

This amplitude is so large C s 1 is much larger than C s 2. So, this guy overtakes at the leading edge and it leads to a steepening of this front and it eventually leads to the formation of a shock ok.

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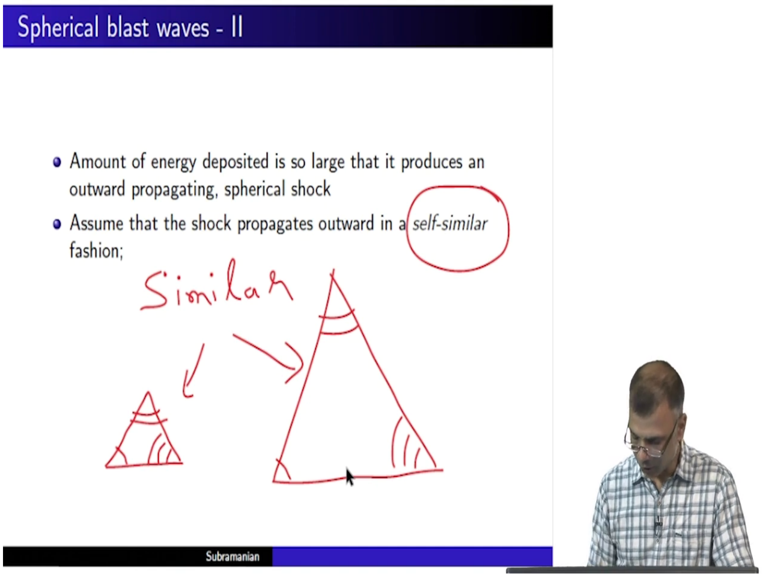

The other principal assumption is that the shock propagates outwards in a self similar fashion and this is a very important word it is important to understand what this means. What self similarity means you are already familiar with the concept of self similarity in fact, consider 2 similar triangles ok say 2 equilateral triangles; one equilateral triangle is small and the other equilateral triangle is large, but they are similar in that, the angles are the same.

So, this is simply a larger copy of this ok. So, these are similar in what sense in that this is simply an enlarged blown up copy of this the angles are the same right.

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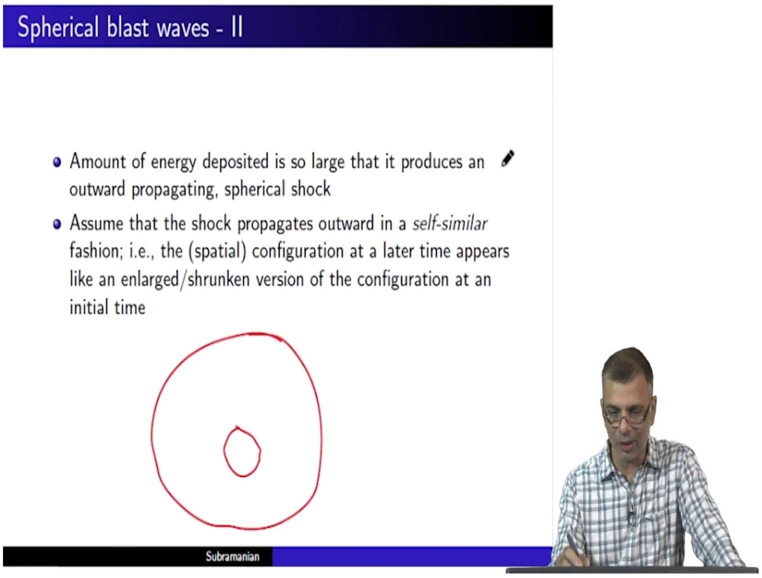

So, it is the same concept for self similar shocks, in that the spatial configuration at a later time appears like in this case it is an enlarged version, it can also be a shrunken version. But in this case since we are considering an outwardly propagating shock, it is really an enlarged version.

So, it looks like an enlarged version of the configuration at an initial time. So, in other words if the spherical shock front was somewhat like this at an initial time, later on it would appear suppose, this was how it appeared at an initial time, later on it would appear like this. Whatever this is we if we are sketching pressure contours or density contours or so on so forth ok. So, this is one of the central assumptions that we will adopt.

And there are 2 reasons for adopting this assumption; number 1 it leads to a drastic simplification in the mathematics you really do not have to consider partial differential equations, the partial differential equations reduce to ordinary differential equations. So, this is one advantage the other advantage is that it is quite motivated by observations. So, observations strongly suggest this kind of self similarity ok, alright.

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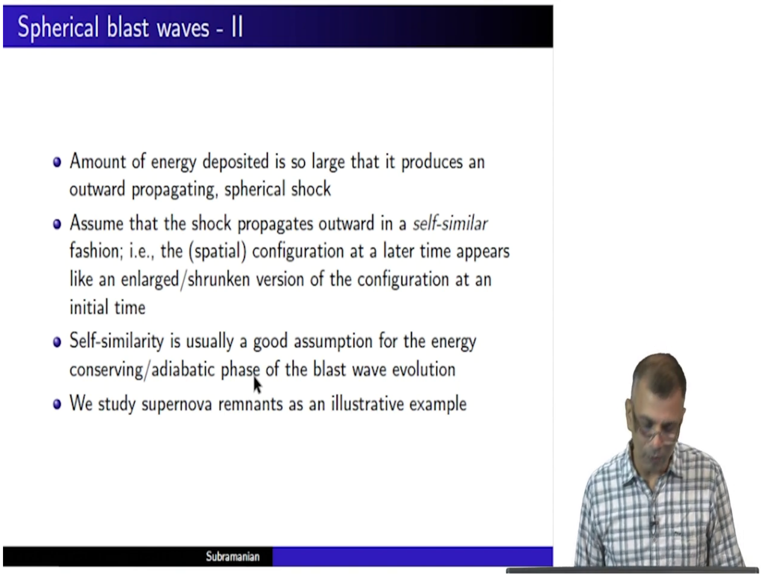

So, for the time being let us proceed ahead and noting that these are the central assumptions, one of the central assumptions is that the amount of energy deposited is so large, that it leads to shock formation it leads to the formation of an outward propagating spherical shock.

The other assumption is that the shock propagates outward in a self similar fashion and self similarity is usually a good assumption at least for the energy conserving adiabatic or what is often called the adiabatic phase of blast wave evolution and this adiabatic phase is the only phase that, we will consider in our analysis. We will not bother about the other snow plowing phase or so on so forth ok.

It makes analysis a little restricted, but that is ok, alright we can at least be complete in our analysis and in draw number of very useful conclusions, right. So, we will study supernova remnants as an illustrative example, supernovae to give you some as to astral background.

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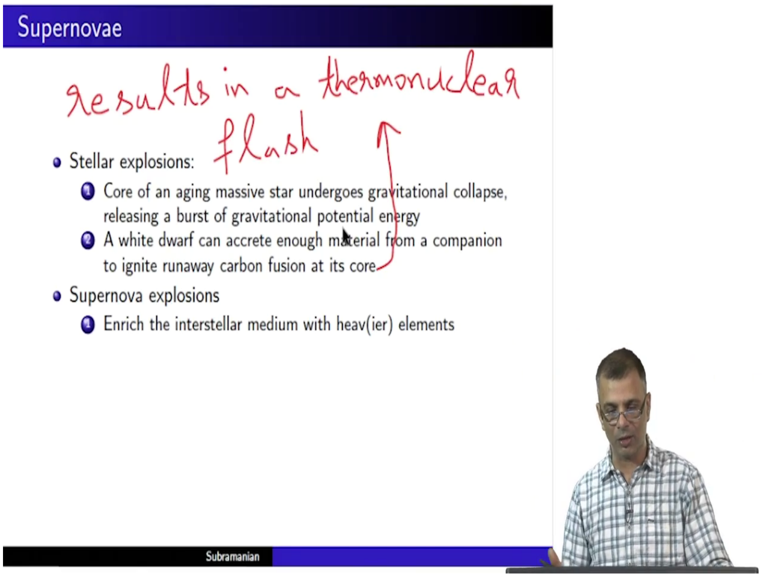

Supernovae are essentially stellar explosions ok, and this happens when the core of an aging massive star undergoes gravitational collapse. So, you see a star the surface of a star is held in equilibrium due to a balance between several forces. You have the core pulling the outer layers of the star inwards ok and so that is the gravitational attraction.

And then there is energy produced in the core and that produces photons and photons, you know have radiation pressure of their own and they have they exert outward radiation pressure and also the overall material is hot ok. So, there is thermal pressure. So, the gravitational inward attraction due to the fact that the core is massive the inward attraction is balanced by these the outward action of these pressures, and the star is in equilibrium.

Often what happens is the during the course of stellar evolution, the core becomes so massive that one force, the gravitational attraction predominates over the tendency of the pressures to resist this gravitational attraction and so during such a phase and this can happen only under certain very specific conditions, for certain very specific initial masses of the stars.

But it happens quite often and so what happens is it undergoes gravitational collapse ok. So, the core cannot resist gravitational collapse and it collapses ok. And it in the process of collapse it releases a burst of gravitational potential energy ok, and in what way for instance a white dwarf can ignite enough material from a companion to ignite, a can accrete beg your pardon can accrete enough material from a companion to ignite runaway carbon fusion at its core.

So, what happens is once the core collapses beyond a certain critical density during what is called the main sequence of stellar evolution, like for instance our sun. What is happening in our sun right now is that hydrogen is being fused to you know to produce helium ok.

But that is because those are the I mean the density and temperature at the core of the sun is conducive only for that particular fusion reaction to happen; however, if the density at the core of the sun increase beyond a certain critical threshold, then it could ignite runaway carbon fusion ok. So, heavier elements will be will start getting fused this is never going to happen in our sun.

Simply because of the initial mass that the sun the proto sun started out with, but in other kinds of in other kinds of compact objects, such as a white dwarf the density at the core can often become so high, that heavier elements, such as carbon can start getting fused at its core ok.

And the density becomes so high because of gravitational collapse ok. So, this is the sequence of events. The white dwarf starts accreting material and then the material accumulates at the core and beyond a point the core becomes so massive, that it cannot withstand gravitational collapse the material collapses.

And once the material collapses at the very core the density becomes so high, that it ignites carbon fusion which is the next sequence after helium, carbon starts getting fused ok. And what is more the carbon fusion is run away its unstable ok. And so it results in a thermonuclear flash and that is a supernova explosion.

So, what happens is that at the very core the you know the runaway carbon fusion ignites a thermonuclear flash and that is essentially the bomb like explosion that we are talking about. So, this results in a thermal nuclear flash, this is essentially the explosion we are talking about ok. This is the bomb. So, to speak this thermonuclear flash is the bomb ok.

From now on, we will study the evolution of the blast wave driven by this thermo by this quote unquote bomb explosion at the center of our supernova, which is which happens due to these two reasons ok. There are some very interesting things about supernova explosions. They enrich this interstellar medium with heavier elements.

Otherwise, you see the interstellar medium contains mostly just ionized hydrogen, maybe a little bit of helium. But that is about it no other heavier elements could have existed ok. So, what happens is because of the fusion of heavy elements at its core, in the core you know the heavier elements are cooked in the core, and when the core explodes this cooked heavy element heavier elements are you know thrown into the interstellar medium ok.

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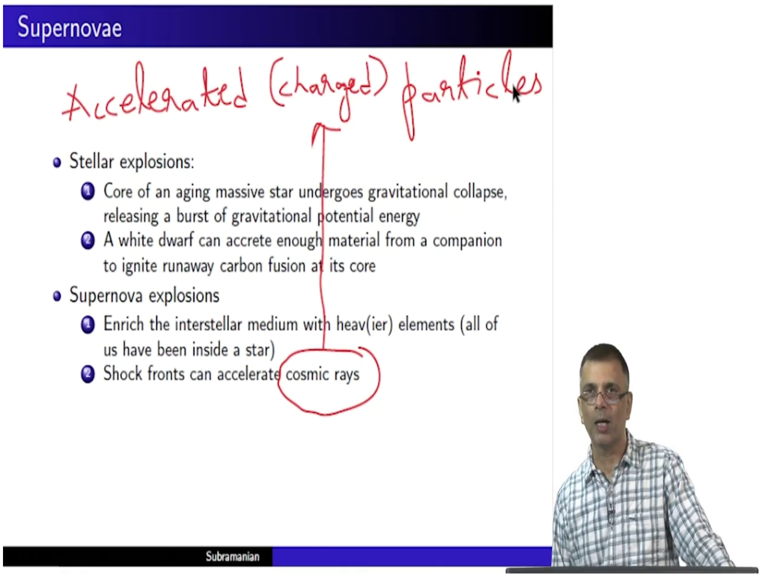

So, in some sense all of us we are made of heavier elements, we are not simply made of hydrogen and helium, we have all kinds of other elements in us right. And where did it come from? It came from inside of a star ok. That is the only way I mean you know the interstellar medium could have gotten, quote unquote polluted with heavier elements.

There are some other things about you know the heaviest and beyond a certain element in the periodic table, even supernova explosions could not have cooked these elements. But that is a slightly different matter, but most heavier elements have been synthesized inside a star and. So, in some sense this is all of us have been inside a star in some sense all life not just us, but the rocks and the inanimate objects everything that we see around us.

Now, at some point we were inside a star that is where we all began ok. So, this is a bit of a philosophical you know detour. Now, the other thing of course, is that the reason we are discussing this in a fluid dynamics course is that, these supernova explosions they you know they drive shock fronts ok. And these shock fronts accelerate cosmic rays, cosmic rays are simply accelerated also charged particles.

And it turns out that these charged accelerated charge particles permeate us all over. Cosmic rays are ubiquitous they are everywhere ok, as we speak we are based in a the earth is based in a shower of cosmic rays and cosmic ray detectors on the earth, detect them all the time. There is a constant rain of cosmic rays on us.

So, it is always been you know very interesting question, where did they come from? How did these particles get accelerated? And we know from what we discussed you know in a couple of in the preceding couple of sessions, that shockwaves shock fronts are ideal candidates for accelerating particles such as cosmic rays ok.

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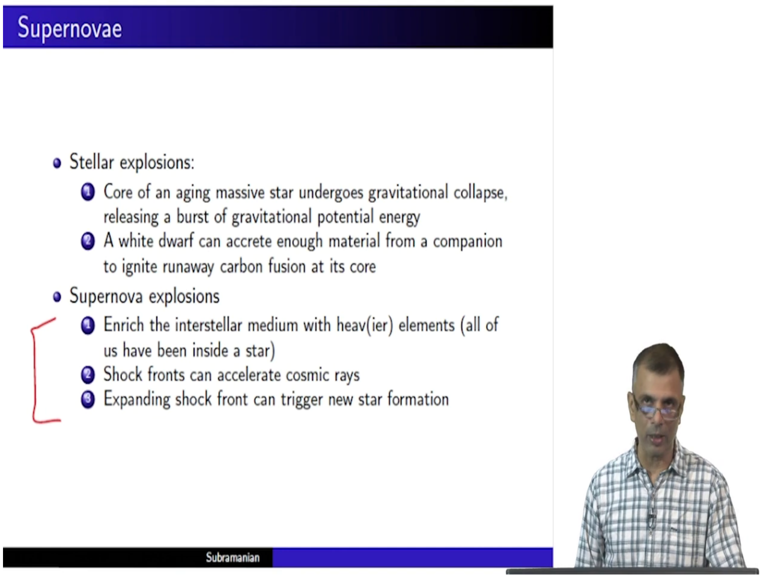

What is more? The expanding a shock front can also trigger new star formation, you see you have the expanding shock front and it as it propagates through the interstellar medium. It snow plows a material in front of it ok. So, material is pied up in front of it. So, in front of the shock, you have excess material, excess density and this excess density sometimes the densities is so large, that you can have smaller episodes of gravitational collapse and it can lead to star formation ok.

It can lead to the formation of new stars, for an astronomer this is what these kinds of reasons are these are the kinds of reasons, why supernova explosions are useful, ok. But for us in this fluid dynamics class we simply want to sort of understand the evolution of the shock front and to a slightly lesser degree try to understand, how the shock fronts result in particle acceleration.

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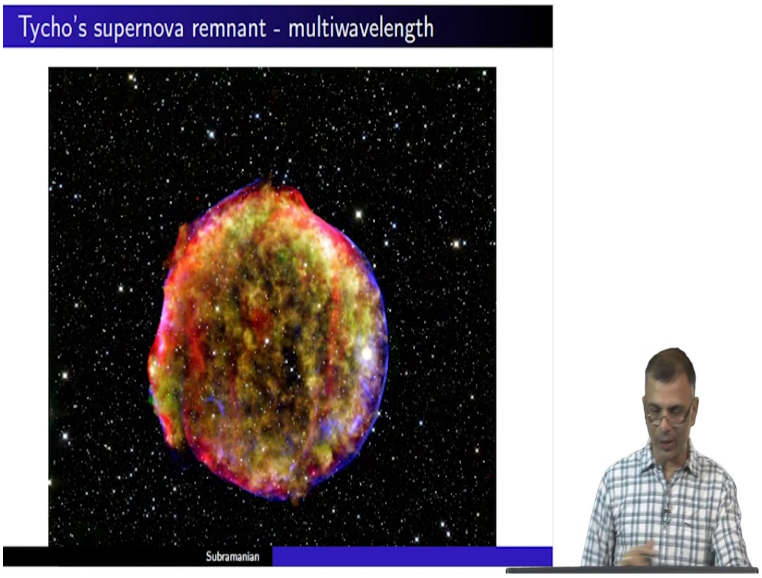

And here are some pretty pictures of this, this is not all just you know speculations this is one particular supernova remnant called Tycho’s supernova remnant. And this is a multi wavelength picture of it, multi wavelength meaning its a montage of say X-ray, radio and optical wavelengths and all each of these wavelengths is assigned a different color ok.

So, these different colors represent different wavelengths, not necessarily visual not necessarily wavelengths that are that can be observed by our eyes ok. But the one thing to observe here is the incredible spherical, this is a real image by the way ok in taken at different wavelengths and these different wavelengths are superposed with each other.

So, that you get a panoramic view of this supernova remnant it is truly astounding one of the prettiest pictures in all of astrophysics, the thing I wish to draw your attention to is the incredible near spherical symmetry of this entire object ok. This is why we are well justified in thinking or talking about a spherically expanding blast wave ok, this is the reason. So, its not simply mathematical convenience as we will discover later, its also you know physical evidence such as this.

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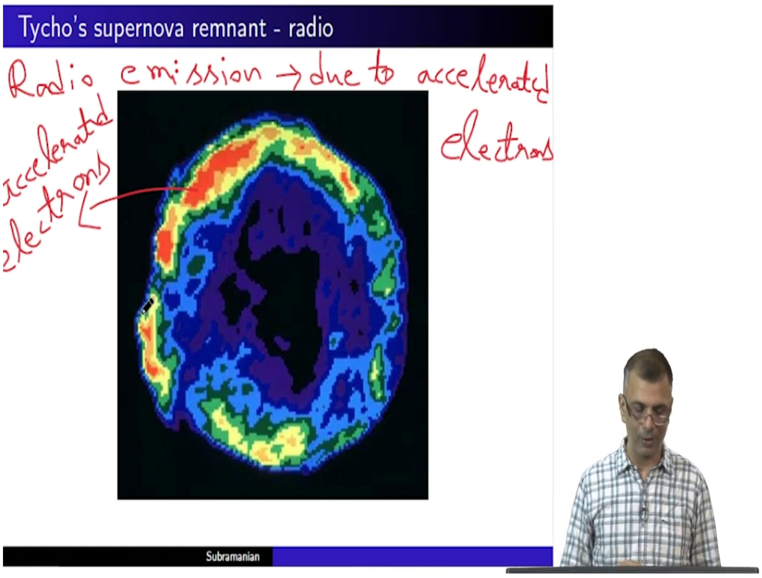

And here is another very nice picture of the same object, the same object Tycho's supernova remnant, except this is only in radio ok. Now, the color scale is such that red represents highest intensity, yellow represents the next kind of next lower level of intensity and blue and black represent lower intensity. So, what this is saying is that at radial wavelengths this Tycho's supernova remnant is brightest at the rims ok.

And we know that this emission radio emission is produced emission is due to accelerated electrons ok or non thermal electrons. And we know we can clearly see from this image, that the radio emission is highly concentrated at the rim. So, all over here these are essentially telltale signatures of accelerated or non thermal electrons ok.

And we know what are good agents for accelerating electrons shocks, hence our whole basis for discussing this, this is most likely this is the this is a very strong you know piece of evidence to conjecture that, this is most likely I mean the spherical front essentially is in outwardly is a spherical shock ok, is an expanding spherical shock.

Why? Because we are seeing signatures of accelerated electrons observable in the radio only at the spherical front not at the center ok, and therefore this sphericals front is most likely an expanding shock. And when we meet next we will study the time evolution of this shock front. So, that is what we will study from now on. So, that is all for the time being.

Thank you.