Rocket Propulsion

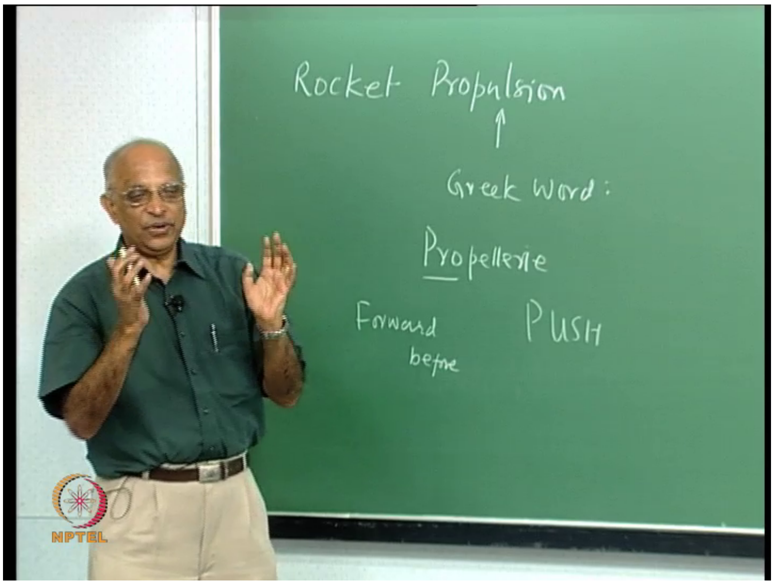
Prof. K. Ramamurthi
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture No. # 01 .

Introduction

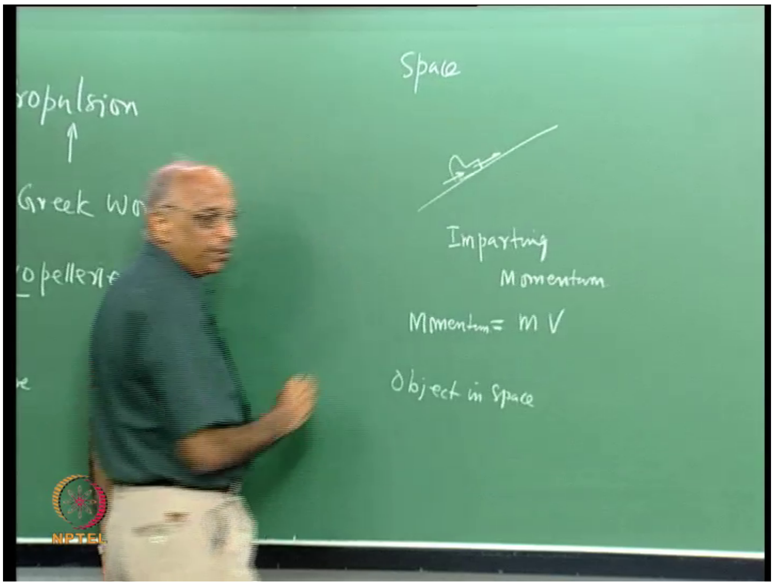
Good morning. This will be our first class on rocket propulsion and in this class we will look at what is this subject on rocket propulsion; how it differs from other propulsion subjects. We will go through the course contents and then see the books that we must be referring to. May be the introductory part will take some something like ten fifteen minutes and then we will get started with the course.

(Refer Slide Time: 00:51)



Let us first take a look on what this subject on Rocket propulsion is about. The word propulsion comes from the word pro pellerie. The word pellerie in Greek means push, therefore we are talking of something pushing. Pro, as you know, means something like forward or before, therefore the word propulsion means push forward and therefore, whenever we talk of any subject on propulsion, what we mean pushing forward.

(Refer Slide Time: 01:54)



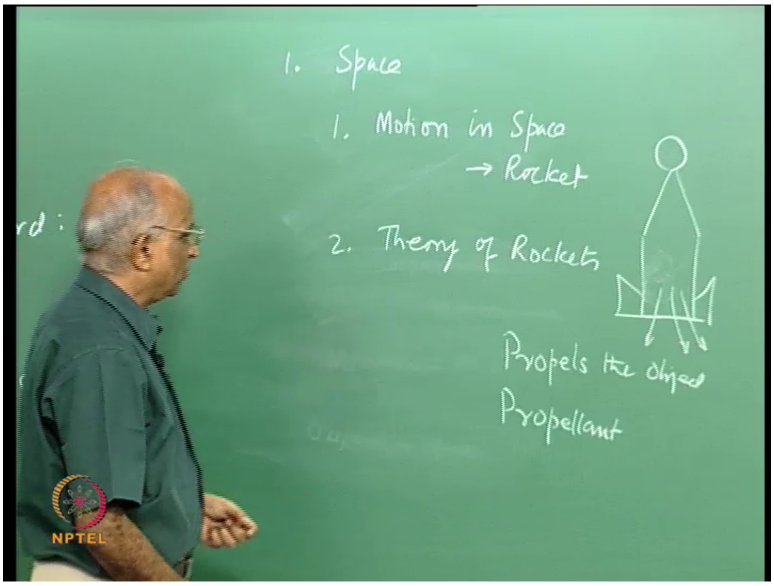
Let us take the simple example of say, a car which has to climb up a hill, up an inclined plane. The engine of the car pushes it forward; and by pushing you are changing the velocity of the car or you are imparting a momentum to the car. What is momentum?

We say the car has a velocity v, it has the mass, if you say mass into velocity is what is momentum and if you want to change the momentum, you have to change the velocity of the car since the mass of the car is about a constant.

You give some velocity and you have what we call as change of momentum. Now you know in deep space, we do not have atmosphere and therefore, the act of imparting momentum to the object in space is what we deal with rocket propulsion. I will again repeat: propulsion means pushing objects and when we say rocket propulsion, we are dealing with pushing objects in space.

Space means anything beyond us, may be up there. Therefore, may be first we must get an idea on what space is about. But before getting more into defining space, let us quickly get some idea on what this whole course is on and how we are going to organize ourselves in the next thirty six classes.

(Refer Slide Time: 04:14)



May be in the first class starting today, we will look at what we meet by the word space, what constitutes space, in what way motion in space is going to be different than motion on the ground. That means, we talk about motion in space and once we know how motion takes place in space; may be, we will able to find out what is the exact requirements of a rocket.

To be able to make a rocket -- a rocket could be something very small or it could be huge -- I must know what is the requirement of motion of a rocket in space? So the first chapter will deal with motion in space and how we go about converting this motion in space to the requirement of a rocket. Once the requirement of a rocket is clear to us, the second chapter will deal with let us say, the theory of rockets.

You know, I would like to ask you a question: why should a theory of rocket be different from a theory of a car or let us say, theory of a gun? I fire a gun - the bullet leaves the gun. In what way is rocket different from a bullet? What is your thinking on it?

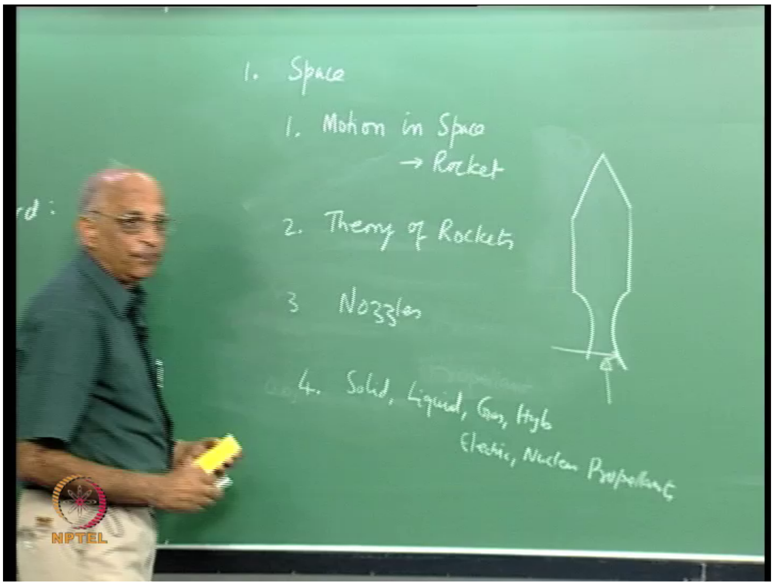
You say it is a non air breathing system. So what, we will get into some details of air breathing, non-air breathing later. Let us say, I have a gun, I fire a bullet from a gun and the bullet leaves the gun at high velocity.

Let us assume a rocket is like this. There is some mass which is available in the rocket. The mass which is available in a rocket, must be able to push it forward. That means, it propels the object and what is the object, you have something like a space capsule which it pushes forward. The mass in the rocket is what propels and we call it as a propellant.

By propellant in a rocket, you mean the substance used for pushing up the rocket or propelling the rocket. Now in the case of a rocket, the propellant is continuingly getting exhausted, it leaves the rocket and therefore, the weight of the rocket keeps coming down, and therefore compared to a car in which I carry something like ten litres of petrol or something near it, I carry tons and tons of propellant which is ejected out and therefore, the theory of a rocket is different from a car or a bullet.

And therefore, we have to look at the theory of rockets which will be the second chapter. After finishing the second chapter, since we need to give change of momentum and therefore,

(Refer Slide Time: 07:37)



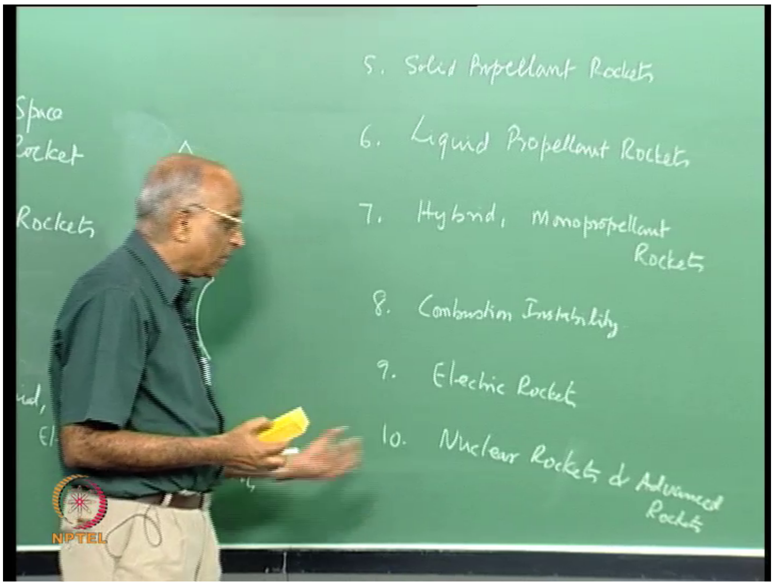
we will go into nozzles which produce high velocity and help us to achieve a large change or impart a large change of momentum to the object in space. You all have studied nozzles in your gas dynamics course. If necessary, we will start from the basics, go through the basics of nozzles, advances in nozzles but it is an involved chapter.

If you have a rocket something like this: may be the internal configuration. I have something like a nozzle here. The flow must run full otherwise if some portion does not run full, I could get something like a side force in addition getting a force in this direction. Therefore, the theory of nozzles is quite involved and the third chapter we should be doing is on nozzles.

In the fourth chapter, we will get back into the propellants or what is used for propelling. It could either be a solid propellant, could be a liquid propellant, could be a gaseous propellant, could be a hybrid a combination of these things, could be electricity itself, could be nuclear, could be anything. And therefore, in the fourth chapter we will study about the different propellants.

What are the characteristics required to make a good rocket and towards this we will study about propellant solid, liquid, gas, hybrid, electric may be nuclear propellants. Once we are clear about the propellants, we can go into the details of the rockets

(Refer Slide Time: 09:24)



The fifth chapter would be solid propellant rockets. And this type of rockets has been used very extensively in India both for GSLV, PSLV and we will have to look at it, look at the design considerations of a solid propellant rocket.

The sixth chapter, would be on liquid propellant rockets. They are more versatile and in this chapter, we will basically look at what are the cycles of operation, in what way it differs from a gas turbine combustor, may be an IC engine and what are the modelling features. The liquid propellant rocket is continuously evolving and when we talk of cryogenic propellants, it is again a form of liquid propellant.

Having studied solid and liquid propellant rockets, in the seventh chapter, we study about hybrid rockets and some rockets which use a single propellant, what we call as mono propellant rocket. This would finish the different type of rockets, how to make them, what are their features and what are the problem areas in rockets. And once we are clear about it, we go to an advanced subject which is combustion instability.

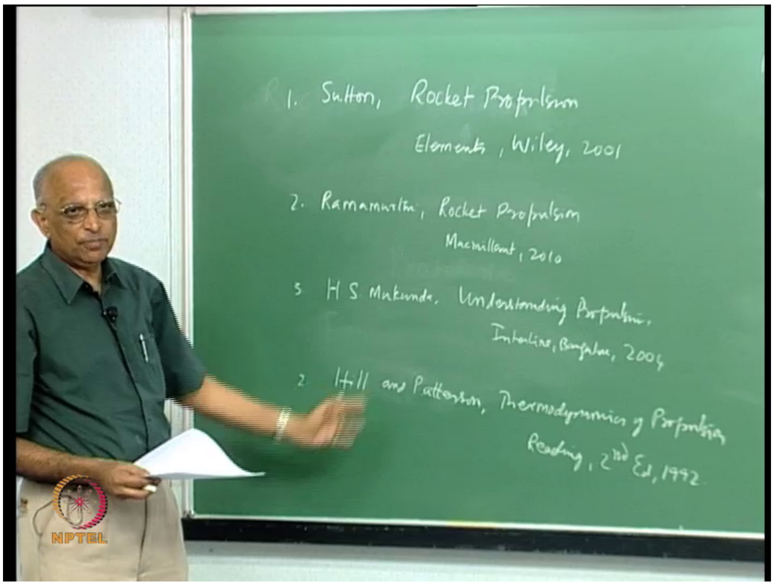
This chapter on unstable combustion on instability is particularly important for PG and research students. Since, we are going to look at what causes unstable or oscillatory thrust or movement instead of having a steady and uniform operation and burning steadily, we will address if it will explode under some conditions or lead to failure.

The ninth chapter, will deal with electrical rockets. What do you mean by electrical rockets? We told ourselves for any rocket, we need to push an object in space. We will try to see how we can generate electrical forces. Different forms of generating electrical forces using electrostatics and electromagnetics.

The tenth chapter would on be nuclear rockets and other advanced rockets. What do we mean by nuclear; I could use nuclear energy to generate a force. I could also use space time curvature like relativity to generate a force. And some of these things will consider as the last segment of this course.

Let me now briefly talk about one or two books which I will be following: A good book for this particular course.

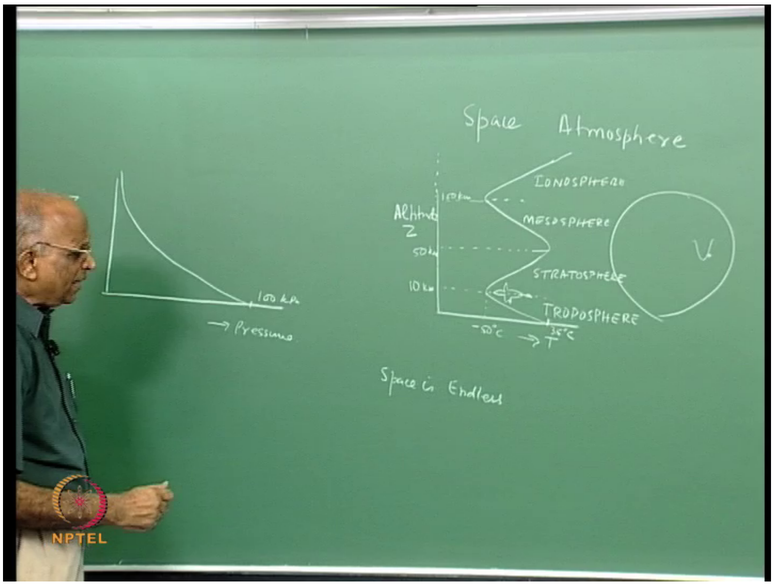
(Refer Slide Time: 13:04)



is by Sutton; it is on Rocket Propulsion Elements. I think the publisher is Wiley, year of publication is 2001. This book gives a very good description of rockets but the mathematics of rockets is somewhat missing and I have published a book, the name of which is Rocket Propulsion. It was published by Macmillan, in 2010. This was based on my teaching of the course over the last 6 to 7 years.

The third book which gives the good description about the different rockets is by H S Mukunda; the name of the book is Understanding Aerospace Propulsion and is published by Interline, Bangalore in 2004. One important book which I should have said at the beginning is a book by Hill and Patterson, the name of the book is Thermodynamics of Propulsion, the publisher being Reading. It is an old book; it was first published, I think in 1970 or so but the second edition is published in 1992. We have copies of these books in the library. This book deals with the thermodynamics of propulsion, including many of the propulsion elements. I will introduce more books on specific subjects as we go along.

(Refer Slide Time: 16:13)



Let us now get started. What do we mean by motion in space? Anybody would like to guess in what way it will be different than motion on ground.

We need to first define what is space: Is anything above us: space? Say, we go on up and up or we go sideways go to infinity. Is it space? We talk of space capsules, we talk of planets, we talk of galaxies. How would you define space? You are telling me that anything outside the atmosphere is space.

What really is space about and what do you mean by atmosphere? We are here, in Chennai. Chennai is normally a hot place and let us try to plot the temperature in the air or in the atmosphere above Chennai as a function or let us say altitude z. We know since the sun is heating the earth, earth tends to get hot.

May be the temperature at the surface of the earth is around 35 to 40 degree Centigrade. As we go higher and higher up, that means as we increase the altitude, the temperature decreases until at an altitude of around, let us say around 10 to 11 kilometres, the temperature is around minus 50 degree Centigrade. These are notional numbers. Thereafter the temperature begins to increase again. That means, temperature drops to minus 50 degree Centigrade at an altitude of around 10 kilometres and then begins to increase again.

Why does the temperature decrease? The Earth receives radiation from the Sun and gets heated and the surface of the Earth is relatively warmer and as you proceed away from the surface, the temperature drops and this zone where in the temperature drops is known as troposphere.

A jet aircraft flies at an altitude of around between 8 to 10 kilometres. Let us say, this is where the jet aircraft flies and it flies where the ambient temperature is between minus 40 to minus 50 degrees Centigrade. You would have heard this announcement while flying in an aeroplane that your aircraft is cruising at an altitude of around 10 kilometres where in the ambient temperature is of the order of minus 45 degree centigrade or minus 50 degrees Centigrade.

If you go up still further after the temperature drop, the temperature increases, the increase in temperature is because in this area you have lot of ozone available. The ozone sort of gets heated by the solar radiation, it absorbs the solar radiation and decomposes; the temperature increases and this increase manifests for another 40 to 50 kilometres.

Let us say upto 50 kilometres we have the region of the increasing temperature; this region is what we call as the stratosphere but when we go to still higher altitude let us say higher than 50 kilometres, the pressure in air is so small or the molecules of air are so small that they are unable to absorb any significant radiation from the Sun.

Therefore, the temperature again drops with further increase of altitude from around 100 kilometres. But if you go to still higher altitudes you have the molecular oxygen reacting with other molecules and you have the temperature going up.

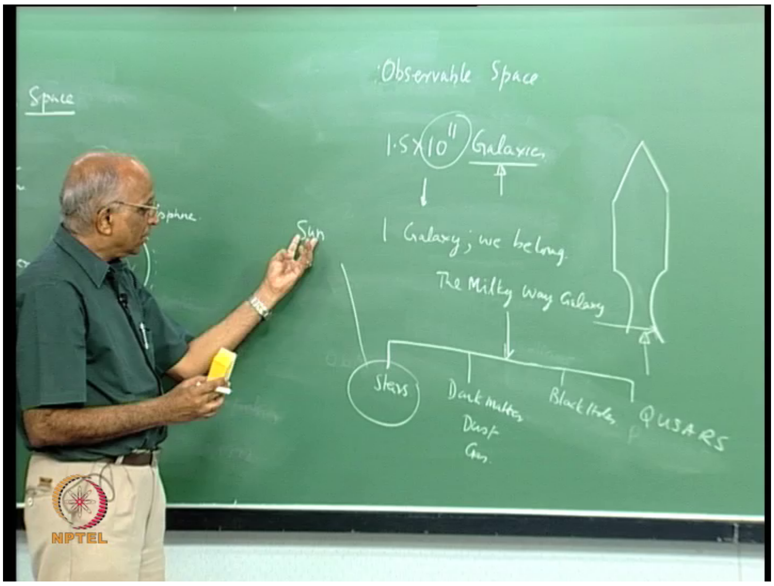
The region wherein the temperature drops again is what we call as a mesosphere and the region of temperature increase because the individual atoms and molecules are getting heated by reacting with each other to increase its temperature is what we call as the ionosphere. This continues for something like another 100 to 200 kilometres.

If I were to plot the pressure of air, may be as a function of an altitude z in let us say in kilometres. At the surface of the Earth, the pressure is around 100 kiloPascal and the pressure monotonically drops, keeps on falling until maybe at the ionosphere, you hardly have any air left. This is where we said that the temperature increases.

The concept of temperature fails in this region of ionosphere because there is no continuum. And it is the individual molecules of some of these gases which tend to get heated to high value. Now the question is what do we define as space? Is it anything above the surface of the Earth going through the troposphere, stratosphere, mesosphere, and ionosphere and beyond?

That means, space is sort of endless. It keeps on going till infinity. Not being able to define space precisely in terms of extent, let us examine what is there in space?

(Refer Slide Time: 22:39)



We cannot define something which is endless. We have to look on what constitutes it?

And if you go back and see what is there in space; you see that there are something like 10^{11} galaxies not in total space but in the space which we can observe. In the observable space, we say we have something 10^{11} galaxies. That means, space is still beyond but what I can see is only this.

What are galaxies? Gravitationally bounded system of stars and each galaxy has a system of stars and lot of may be some dark matter, something like gas, dust, etc., in it.

Let us consider one galaxy to which we belong, which is the Milky Way galaxy. Therefore, what we have said is, space is endless, in the near observable space, we have something like 10^{11} galaxies and our attention has now come to the galaxy which we belong to or in which we live, which is called as the Milky Way galaxy.

Why the Milky Way? It comes from the some Roman or Greek mythology, which says that the colour is something like milk and there are some stories around it. We will not get into those details but just say when we talk of number like 10^{11}, we are talking of a very large number. At the beach you have lot of sand particles and I go to all the beaches around the world and collect all the sand particles, then we are nearing a value of 10^{11} . One particle among all of them corresponds to our Galaxy out of all the galaxies. Therefore, we have shrunk ourselves and you can see, you how small we are in relation to space.

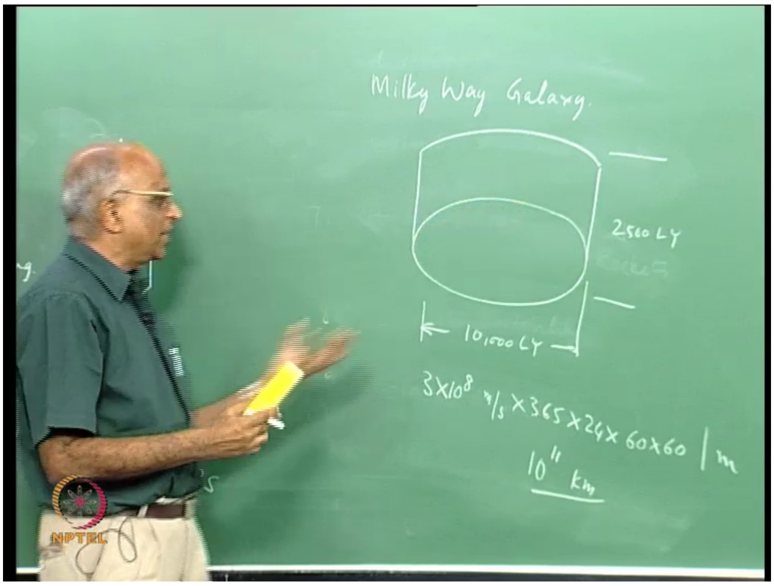
If now you really see what constitutes the Milky Way galaxy: well you have a large number of stars in it. And what are stars? Massive objects in which nuclear reactions are taking place. They emit light and heat. Then you could also have something like dark matter between the stars, you could have some gas and stellar dust or dust: could have gas, you could also have lot of different things in it.

You would have heard of black holes; what are they? You could have it in in our Milky Way galaxy. You know what happens is that sometimes the stars shrink to very small size after their life time is over. Therefore, you have infinite mass concentrated in a very small volume and when we have large mass concentrated in a small volume, it is capable of attracting, that is the gravitational pull will be large.

We will get into the gravitational pull towards the end of this class and therefore, what we say is we have black holes, we could also have other objects like quasars. What do you mean by quasar: Quasi stellar radio sources. These quasars are objects which are again travelling at near about the speed of light itself.

Therefore, you have lot of things in our Milky Way galaxy and out of all the stars in it, let us figure out one star which we call as the Sun. And therefore, we focus ourselves maybe from a large number of stars to one star. We note that we have come to one galaxy out of all the galaxies and now we talk of the Sun which is a single star and it is about this which we will be basically interested in for the present discussion.

(Refer Slide Time: 27:38)

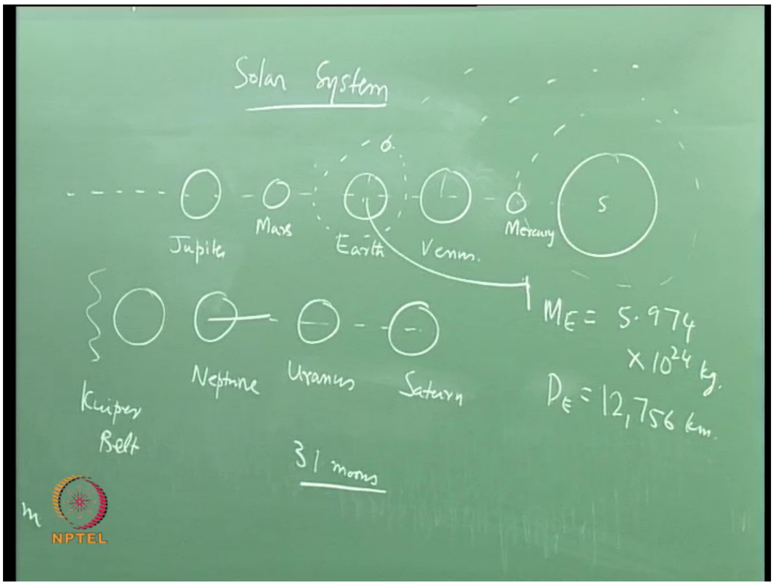


Let us put this together with some dimensions. If you look at the Milky Way galaxy, let us see the extent of this; it somewhat cylindrical in shape. The diameter is around 10,000 light years. Why do I say light year and not say kilometres because it so huge. And what is the magnitude of a light year? The distance travelled by light in one year.

The speed of light as you know is 3 into 10 to the power of 8 meters per second. In 1 year have 365 days multiplied by 24 hours multiplied by 60 per minute, 60 per second. And therefore, one light year will therefore correspond to so many meters which should be around $9.5\text{x}10^{11}$ kilometres or so.

Therefore, we are talking of a large diametrical content of the cylindrical Milky Way galaxy and its height is something like 2500 light years. And in this you have number of stars. We are getting focussed around one particular star called the Sun or the solar system.

(Refer Slide Time: 29:16)



We are concerned with the solar system. From the large number of galaxies in the observable part of endless space and we come down to the solar system.

What does the solar system consists of? It consists of the Sun, a single star out of the large number of stars in our galaxy and you have planets going round the Sun. May be starting from Mercury, then you have Venus little bigger. Then we have the Earth, what is next Mars. What would be the next one, Jupiter. Next one Saturn, two more Uranus and Neptune. Therefore, you have 3 plus 5, 8 planets which are going around. You know previously we had included another planet known as Pluto giving nine planets or "navgraha" but Pluto has been decommissioned as a planet because it is not fully formed. It is something like a loose mass which is still going along with a belt here which known as a Kuiper belt.

I will come back to this belt because it gives inputs regarding some asteroids coming and hitting earth. All what we said is in the solar system, we have something like eight planets going around the sun and this is the part of the space with which we are immediately interested.

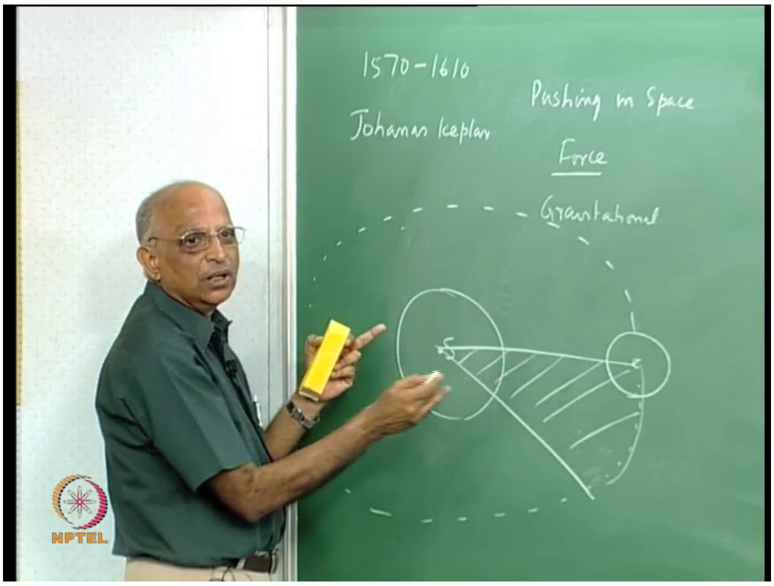
This solar system also consists of something like 31 moons. How do we define a moon? There are certain objects which go around the planets and they go around like satellites around it. There are 31 moons and Earth has a particular moon which is going around the

Earth and this is the moon of the Earth. So also, we will have moon for Saturn, we have moons for Jupiter and there are something like 30 other moons in the Solar system.

When we are dealing with all these eight planets going around the Sun, it is necessary to have some idea of what constitutes these planets; may be Earth, let us put down the mass of the Earth, let us put down the diameter of the Earth. The mass of the Earth is 5.974 into 10^{24} kg, the diameter of the earth is 12,756 kilometres. These numbers are important and I will circulate a table to you giving the mass of the different planets and their diameters. But just to get an idea: mercury is about the smallest planet around one-third the mass and diameter of the earth.

The largest would be something like Jupiter. These planets go around the sun and it is the motion of planets which provided or which prompted Newton to formulate the universal law for gravitation. I think I should repeat this point in a slightly different way after consolidating what is said so far:

(Refer Slide Time: 33:49)

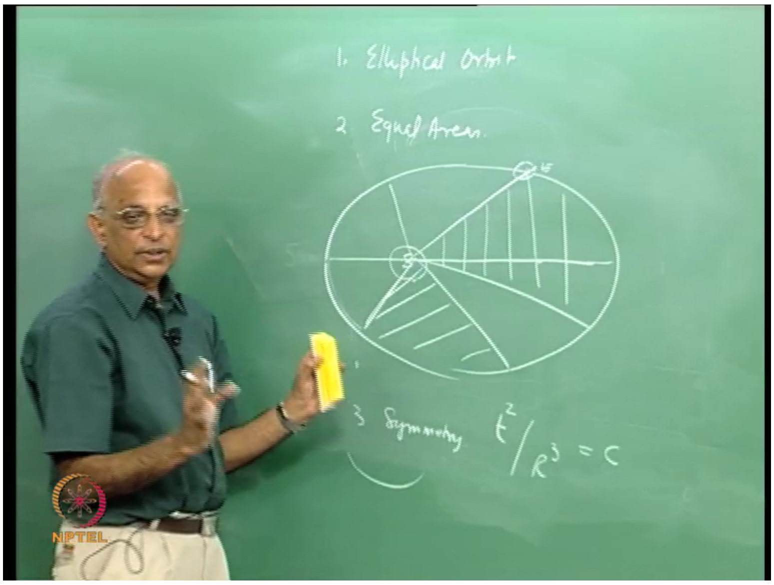


Let us therefore quickly revise through what we have done so far: we said propulsion or rocket propulsion deals with pushing in space. For pushing in space, one of the forces which we could consider is the gravitational force.

Let us start with the gravitational force. It becomes necessary for us to go back into the solar system to understand it. Look at the revolution of the different planets around the sun. Now let us just take one particular case: I take the Earth as shown in this figure and it is going around the sun.

Earth is going around the sun. You know people have been watching the motion of planets around the Sun for years together and around the year between 1570 and 1610, we had a famous person by name, Johanas Keplar. He introduced three laws which govern the motion of planets like Earth around the Sun.

(Refer Slide Time: 35:26)



The three laws were: 1. All planets move in elliptical path, i.e., have elliptical orbits. By orbit, I mean the path of the planet around the Sun. But if you read the newspapers around the month back, there was news that the orbits are not really elliptical but they are wavy orbits something like a wavy elliptic orbit.

As per Johanas Keplar: we have the orbits in an elliptical path which is the first law of orbital motion of planets. The second law was on equal areas. Suppose we join the centre of the sun with the centre of the Earth with a straight line. We find out what is the area swept by this line during the elliptical orbit. We find that the equal areas are swept out in equal times.

Let us put it together: this is the Sun which is at the focus and you have something like an elliptical path. Let say this is the major axis and then you have an elliptical path this is the second foci. This is the Earth going around the Sun. First law says it is an elliptical path, the second law says equal areas are swept out for equal times.

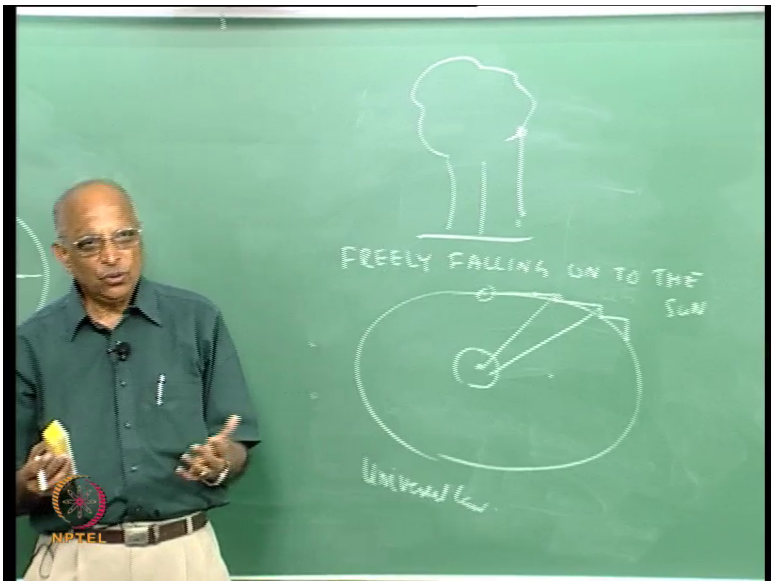
If this is the time taken for this area is swept out by the imaginary line joining the centre of the earth with the centre of the sun. And similarly in an equal area will be swept out during the motion from here to her for the same timee. All the second law tells is, if I come to this particular path in which the minor axis, it'll travel a longer path here compared to a shorter path along the major axis.

The third law is one which deals about symmetry of orbits. All what it tells is you have the Earth, you have Mercury, you have Neptune far away. It tells that the time for 1 revolution divided by the radius, is such that the orbital time t square divided by the distance cube is a constant (t^2/R^3 is a constant).

That is the distance from the Sun to the different planets divided by the time of orbit of the particular planet is the particular constant. These are the three laws of the orbital motion as formulated by Johanas Keplar.

Why are we getting into orbital motion? We want to understand something about gravitation. And Newton comes out with the Universal Law of Gravitation based on these laws of orbital motion of planets. What does Newton find?

(Refer Slide Time: 38:43)



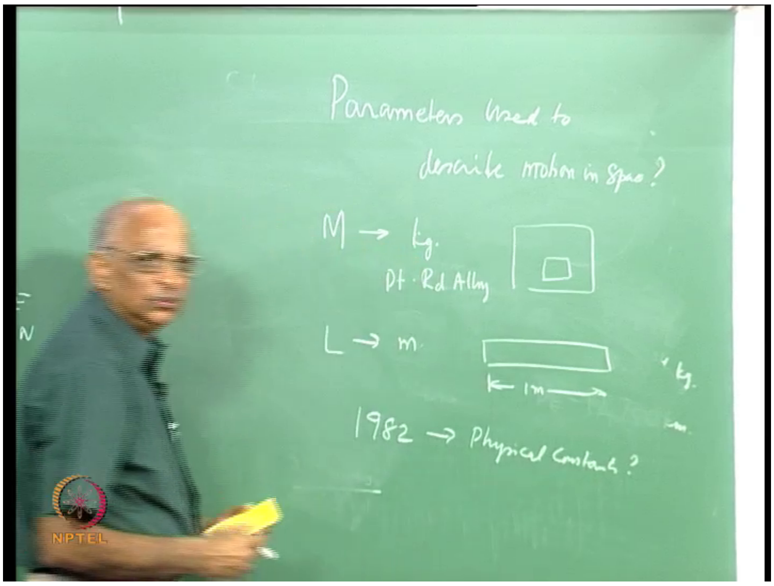
Well. The story goes like this. He watches an apple fall on the ground from a tree. He immediately connects the apple falling from a tree to the elliptical orbits or orbital motion of the different planets around the sun. What is the commonality? How can we identify what is the common factor between these two. Let us take another look at the planetary motion that we were dealing with it. This is the Earth as it is going around the sun in an elliptic orbit.

May be the Earth as it is travelling some distance like this, it falls through some distance because the trajectory is elliptical. Again the Earth let us say, it would had a horizontal velocity it will go like this but in the process of going horizontally, it falls through some particular distance. Again it goes through some it comes over here, again it comes like this. In another words, if I had given a horizontal velocity to the earth, it keeps on falling towards the Sun at each instant of time as it progresses at constant horizontal velocity. If the Earth were to go horizontally at a given velocity, it falls by a certain distance as it travels.

That means, we have a constant linear velocity and it keeps falling on to the Sun. It looks as if the Earth is freely and continuously falling. It is no different from an apple which falls on to the ground from the apple tree. Actually, if we look at ourselves today all of us are freely falling towards the Sun. Just in the same way, as a fruit or a stone is falling. Therefore, Newton is able to relate the commonality between an apple falling to the ground and the planets falling towards the Sun and it becomes the Universal Law.

Newton did not do the experiments himself. He did nothing to really say that, I derive the gravitational law like this, or that. He based it on observations of Johanas Keplar and others who preceded him like Galileo Galilee who as you know dropped a piece of a feather and an iron ball and found that in vacuum both of them will take the same time to come to the ground. Just based on the observations, he was able to formulate the Universal Law for Gravitation. But before I get into the gravitational law, its necessary for me to go into some more details like how do you measure forces, distances and velocities and their units. We need to be clear on what are the parameters and the units.

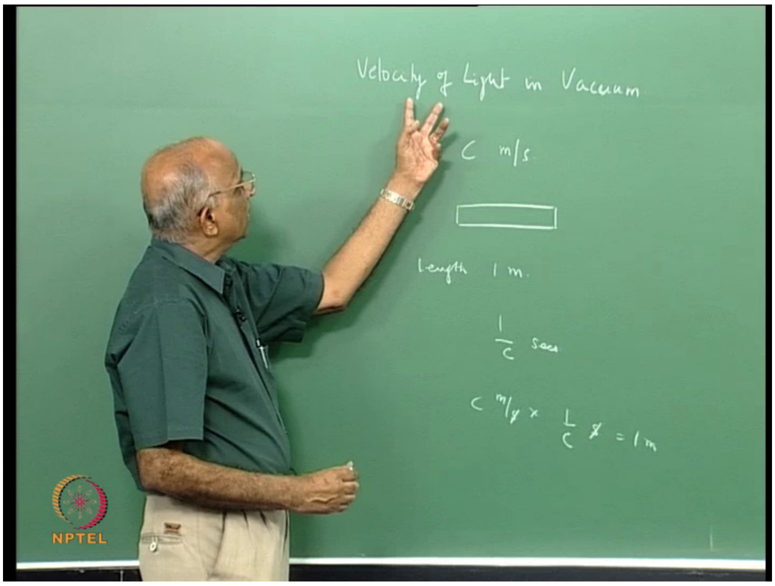
(Refer Slide Time: 41:50)



We wanted to describe motion in space. I think we must be very clear because a time has come when I need to put some numbers, like to apply or derive equations. We can say we are all engineers, we know about mass, length and time. I can use these three fundamental quantities and describe motion in space. How will you describe mass? Quantity of matter, unit is kilogram. But what is a kilogram. It is some reference kept in a lab near in Severs near Paris since let say, 1819 or so. Some standard is kept which we call as kilogram. It is kept very carefully, you know in a desiccator under very controlled condition such that it will not get worn out nor will form scales on it.

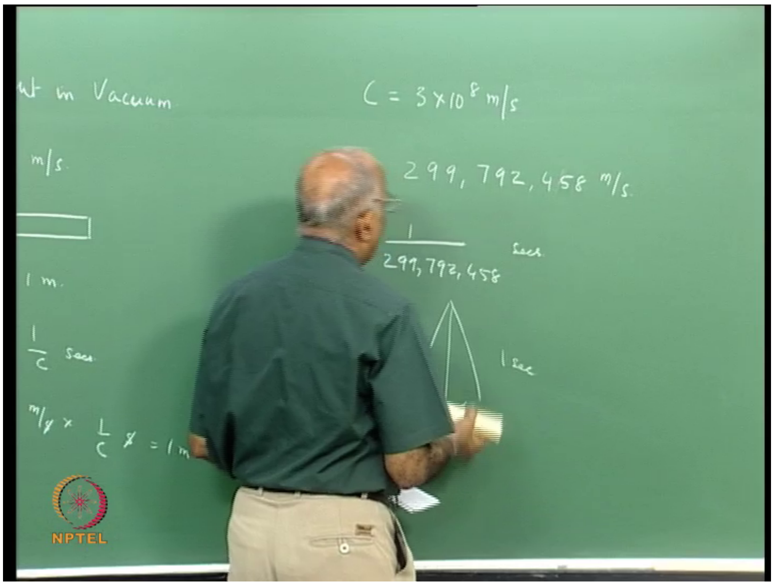
It is a platinum rhodium alloy which has a mass of 1 kg and it has been duplicated at different places and used as a standard. Well. We say this is 1 kg. So, also when I say length is in metres. What is a meter, again a reference kept at the same lab since may be last 150 years or so. And this is the particular length scale which is given; the length of this standard. It’s again an exotic alloy of platinum rhodium but then there are some problems; though it is stored in the best of conditions and you have some duplicates in some other countries also, it keeps eroding or scales are formed on it. Some changes do take place over a long period of time. Therefore, it is not a good standard and we need a better standard. How will you have a better standard? In the year 1982, i.e., quite recently, scientists suggested to express the length standard through physical constants. What is the physical constant to be used? Whatever happens the length would be the same, it cannot change may be after a million years the meter will still be the same since a physical constant is used.

(Refer Slide Time: 44:35)

C 

The physical constant used for defining the length is velocity of light in vacuum. All of us know that, light is propagated as an electromagnetic wave and the speed at which the light is propagated, we say is C meters per second. The question is can we use this constant to define length? It is a constant because the electromagnetic waves propagate through vacuum at a constant speed. Let us say C meters per second and rather than define the length in terms of a standard like what we considered viz., a standard of length, which is kept near Paris, we would like to define it with respect to this constant velocity of light in vacuum. How do we do it? We say the distance travelled by light is C meters in one second. In 1/C seconds, the distance travelled will be one meter. The duration, we are considering, is one over C (1/C) so many seconds. Second and second get cancelled and we get one meter. Therefore, the more recent definition of length scale is with reference to the velocity of light in vacuum which is C meters per second. The precise value of C is:

(Refer Slide Time: 46:24)

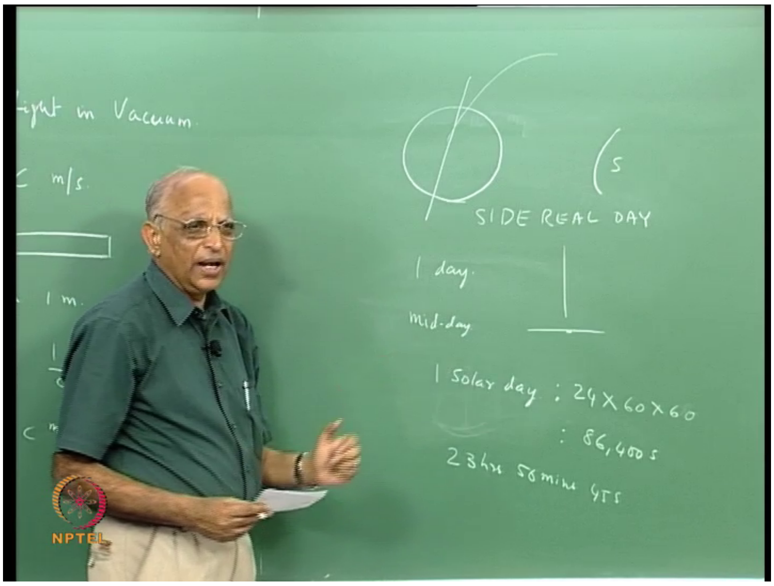


299,792,458 meters per second i.e. about $3x10^8$ m/s. Therefore, the definition of length of one meter is the distance travelled by light in vacuum over the duration of 1/299,792,458 seconds. This is how we define the length scale of a meter.

Therefore, what is it we have done so far? We have considered something like the definition of mass as a standard kilogram, may be length has a standard meter but now we are telling ourselves meter corresponds to the distance travelled by light in vacuum for a duration of one over let us say 299,792,458 seconds. But then, we have still not defined time.

How do we define time? We must be very clear. Time is something related the duration: let us say we have a pendulum; the pendulum goes up and down. The duration of one cycle of the pendulum; pendulum starts here, goes here, comes back here is what we say is a duration of one cycle of this pendulum which we could say as one second. But then, it is difficult to have a period like a standard pendulum being used to describe the time scale and its easier for us to define the time scale based on the duration of an event such as a solar day.

(Refer Slide Time: 48:15)

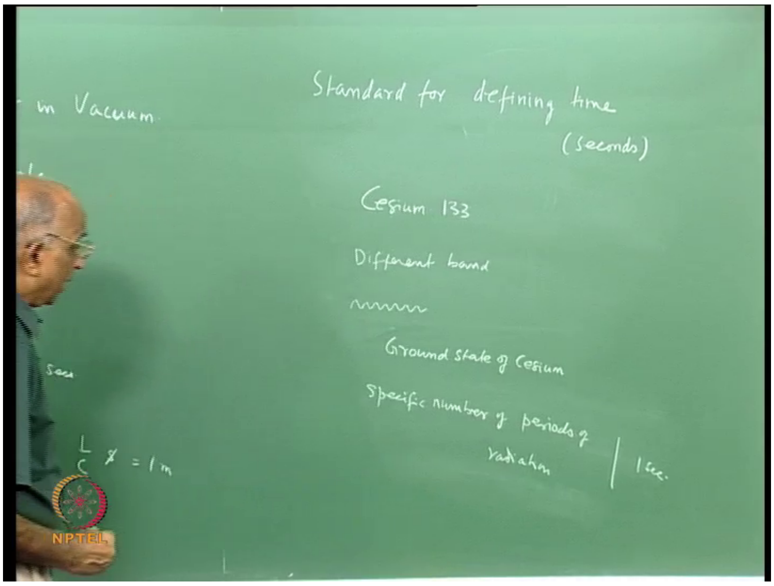


This is the most simplest to describe. We have the Earth, may be rotating on its axis as it revolves around the sun. One revolution of the earth around its axis is what we call as one day. May be we call mid-day (middle of the day) as when sun is vertically above us. When the sun is vertically above a particular part of the Earth, we call it as mid-day at that part of the Earth. And we go to the next mid-day, next time the sun is vertically above at that point and this corresponds to 1 period of rotation and we call it as one solar day . That means, in 1 solar day, a day consists of 24 hours, again each hour consists of 60 minutes and each minute consists 60 seconds.

And therefore one solar day consists of something like let us say 86400 seconds and we can therefore define the time. There is one problem in this definition though. We said earlier that the Earth is revolving in an elliptical orbit around the sun and it is also rotating on its axis as it is revolving around the sun. The period of rotation is therefore not exactly 1 day but is slightly shorter because as it is rotating on its axis as it is also revolving. And therefore, the exact period of one rotation on its axis is not exactly 24 hours but it is something like 23 hours 56 minutes and 45 seconds and this duration is what is known as a sidereal day. There is a difference between solar day and the sidereal day.

Therefore, we have complicated the day, instead of having one solar day. We need a side real day which is smaller than 86400 seconds. Now there are perturbations in the rotation and also in the path of the Earth around the Sun. it. And therefore, it is very difficult to really define time absolutely very   accurately in terms of either sidereal day or in terms of solar day.

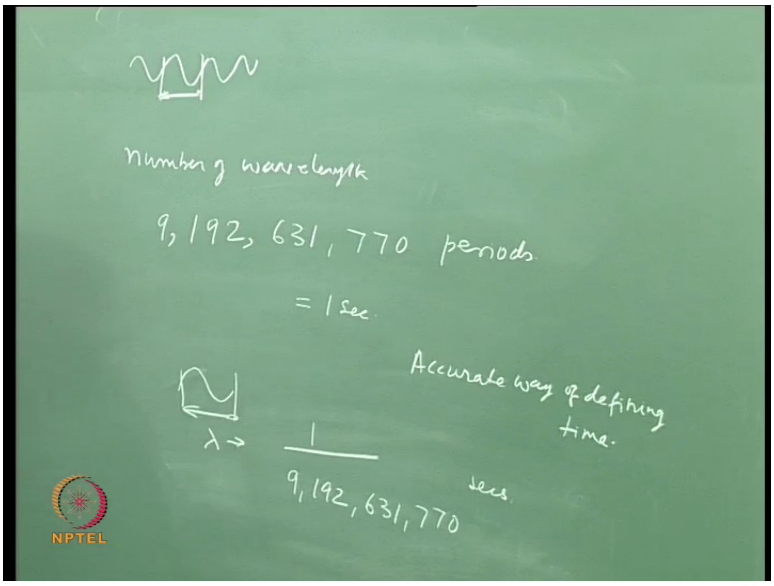
(Refer Slide Time: 51:12)



It becomes necessary to have some other standard for defining time. This is based on the period of a wave. Cesium133 material is an isotope element and it emits radiation. It emits radiation in different bands. What we mean when it emits radiation is that it gives out packets of photons as energy. These radiations are emitted at discrete frequencies i.e., each one having a specific period. So, many periods of radiation are getting emitted.

Therefore, we look at one specific band namely at the ground state of cesium. And at this ground state of cesium, you take one hyper fine level and you say, many number of periods which are emitted. That means, you say specific number of periods of radiation which is emitted at the ground state in this particular hyper fine level is what we will call as one second. Therefore, how can we represent this hyper fine level?

(Refer Slide Time: 52:59)

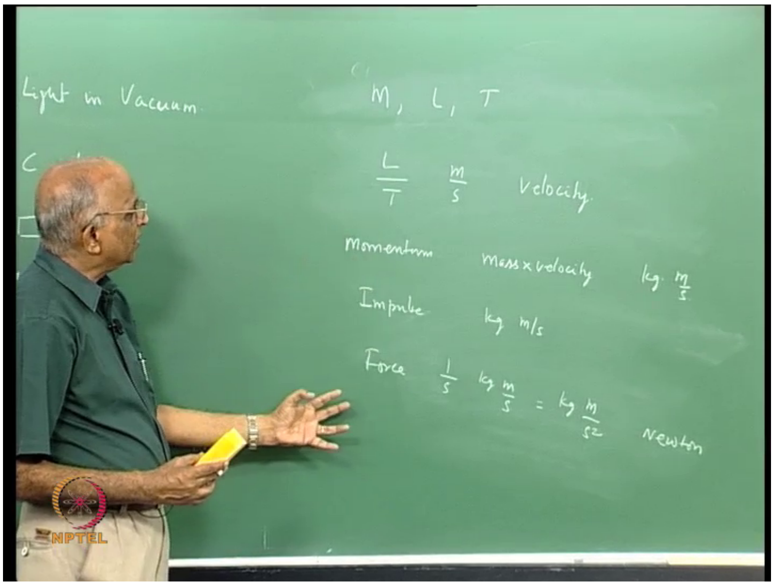


We just said that at this ground state Cesium is emitting radiation. Each wavelength corresponds to a certain time. I count a large number of these wavelengths and the number of periods or the number of wavelengths, amounting to something like 9,192,631,770 periods or wavelengths equals one second. Corresponding to this ground state we have 1 period of radiation or 1 wavelength is 1/ 9,192,631,770 seconds.

And this is how we define time: namely in this ground state 9,192,631,770 periods of radiation emitted is what constitutes 1 second. And this is an accurate way of defining time.

To recap: we have defined mass in kg as a standard, we have defined length as meter as a standard, the standard length being on the basis of the velocity of light. Then we defined time seconds as a standard.

(Refer Slide Time: 55:03)



And now we can derive a set of units, the length or distance divided by time has units meter per second and this is what we call as velocity. When I say distance: it is a vector, and therefore, velocity is a vector. And if, I say momentum, we said mass into velocity or rather the units is equal to kilogram into meter per second is becomes momentum. We say change of momentum is impulse and therefore, impulse will have units to be same as momentum namely kilogram meter per second. We also said rate of change of momentum is what constitutes force or rather the impulse divided by the time is force.

And therefore, force could be defined as rate of change of momentum, that is 1 over second into we have momentum change as kilogram meter per second or rather the units of force becomes kilogram meter per second square (kg m/s^2) which is what we call as Newton. Therefore, we have defined through these three basic definition of mass, length and time, the velocity in meter per second, momentum in kilogram meter per second, impulse again kilogram meter per second and force which is kilogram meter per second square.

Having defined these quantities may be its time to go forward and examine how we can describe using these units the motion in space of the different bodies and this is what we will do in the next class.