Astrophysics & Cosmology
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Lecture - 04
The Solar System (Contd.)

We have been discussing the motion of 2 bodies which interact with each other through gravity and in the last class, we discussed, towards the end of the last class, we discussed some very general features of motion in some potential. Today, we will discuss another very general feature that is very important in astrophysics. It goes by the name of the Virial theorem.

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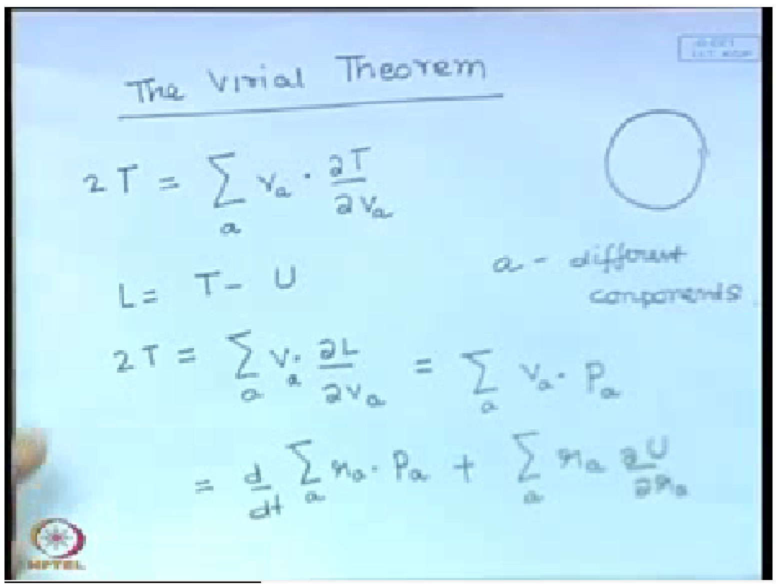

So let us consider some motion which is bound in a region of space. So let us say that the motion is bound within certain region, let us say within this region in space, okay and now the kinetic energy 2T, so we will use T to denote the kinetic energy, twice the kinetic energy is, this is mV square. We know that the kinetic energy, let me just write it here, is, we know that the kinetic energies 1/2mV square.

So this can be written as sum over aVa.del T del V where the system that we are considering may have many particles and these are labeled by a and the V are vectors, the V is shown over here, okay. So by this derivative with a dot products here, so we have to differentiate with respect to different components. I am using some very short notation, okay. A refers to different components of my system, okay.

So T we know is 1/2mV square, so if you differentiate it with respect to velocity and multiply with velocity and add over all the components, there may be many particles, all having XYZ components, etc. So for each particle, you will have a different value of a, then you will recover back the twice the kinetic energy, okay and the Lagrangian is T-U, where U just depends on the coordinates. So we can write this as 2T= sum over aV.del L del V, right.

U is the potential between the different particles in my system or it may be an external potential, okay. Now we also know that del L del V, okay, so this del L del V is the momentum, that is the definition of the momentum, right. That is the momentum conjugate to or we could have written it straightaway. This is not required but anyway, this is = Va.Pa. So those of you who are not very familiar with classical mechanics, this is quite straightforward that if you differentiate the kinetic energy with respect to velocity, you will get MV which is the momentum, okay.

So this essentially is the velocity into the momentum, summed over different components, that is twice the kinetic energy, okay and this can be written as a sum of 2 terms now. We can write it as d/dt, so I can differentiate r, I will get back this term. If I differentiate P, I will get an extra term which I have to subtract out, so I have to subtract out a term which is r sum over a and then I have ra, and the time derivative of the momentum, we know is the force and the force can be written as - the gradient of a potential.

So this term can essentially be written as +del/del raU, right, that is just the force. So P. is the rate of change of momentum which is the force. The force can be written as the - of a gradient of the potential. So that is what we have used. So there are 2 - signs which gives you a plus sign over here, okay. So this is the result. Now the Virial theorem tells us something about the time average of these quantities. So let me define what we mean by the time average.

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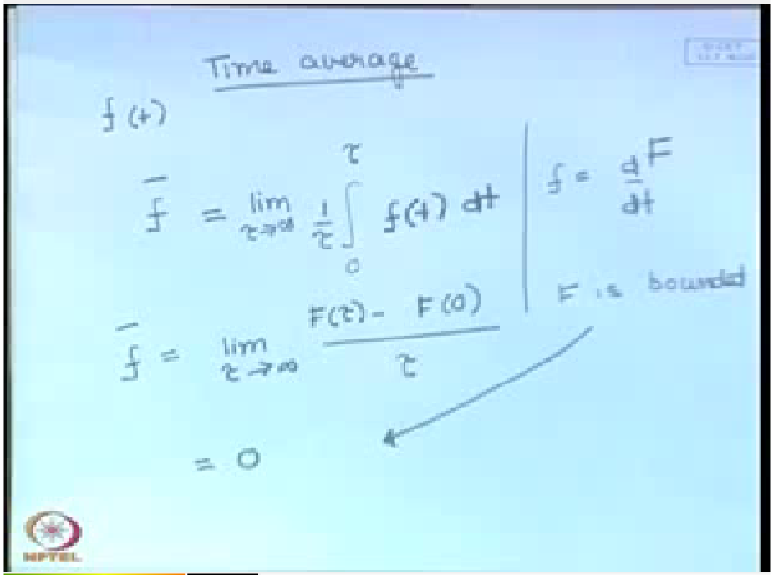

So if there is some quantity f which varies with time, its average f bar is defined as follows: you average this over some time interval tau, so you average f over the time interval tau. So 0 to tau ftdt, you do this integral and then you divide by tau and we are interested in the limit where tau goes to infinity, right very large time. So it is a time average over a very large time, okay. So this is how we define the time average.

And if f, the quantity whose time average we are interested in, is the derivative of some other quantity. If this is true, then we can put this derivative in here and do the integral, what we get is that the time average of f=limit tau go *infinity, 1/tau f tau-f0, right. It is the derivative, so I plugged this in here, I will just get the values at the endpoints and then I have this 1/tau over here. So this time average can be written like this.

If this f is a total derivative of some quantity and if this quantity over here f is bounded. So if we assume that f is bounded, its value does not blow up or it does not become - infinity, its value is bounded, finite and bounded, then this limit you can guess will be 0. If this quantity is bounded then the limit is going to be 0 because this is a finite number, this is a finite number, the difference is a finite number, divide by tau and take the limit where tau goes to infinity, it will give you 0, okay.

So the time average of any quantity which is a derivative of something that is bounded is going to be 0. So here we are interested in calculating the time average of the kinetic energy of twice the kinetic energy to be precise. So we would like to calculate this, 2T bar, okay. Now let us look at these 2 terms. There are 2 terms over here. Now this term is the total time derivative of this quantity which is r*P which is called the Virial, sum over r*P over all the components that make up my system.

So I may have many particles, okay. So I have to calculate this quantity r*P for all of these particles and then sum over it and then I have to take the time derivative of that, so I have to now find the time average of this. Now the quantity r*P, if the system is bounded, is also going to be bounded, okay.

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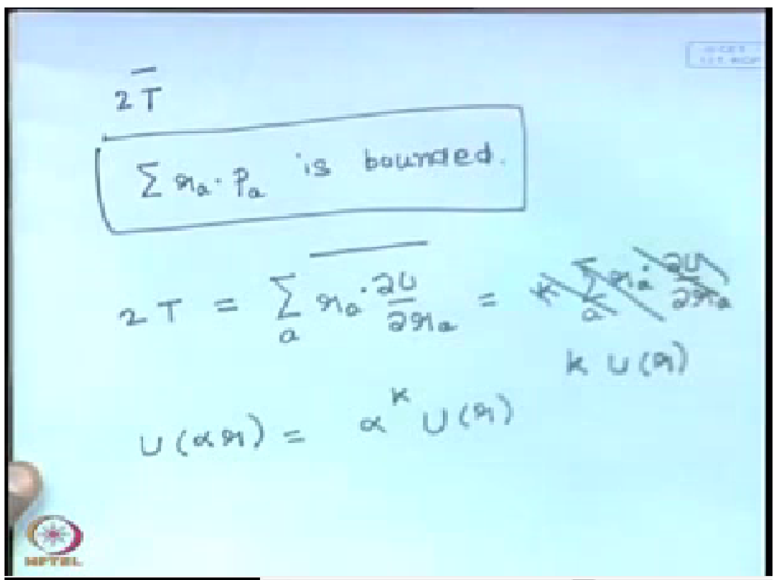

So this quantity is going to be bounded and if this quantity r*P, so if my system is bounded, this quantity is also going to be bounded and if this is true, then we can see straightaway that by the discussion that we just had, that twice the average kinetic energy, so twice the average kinetic energy is going to be = the time average of this quantity over here. So it is going to be =, and in the last class, we were discussing what happens when the potential is homogenous.

So let us again assume that the potential is homogenous. So U alpha r, if I scale all the r/a value alpha, we will assume we will go to alpha to the power K U to the Ur. So in this situation, if I differentiate it with respect to r and multiply with r again, so I am going to differentiate this U with respect to r and multiply with r again, then this will be K times the same quantity. You can easily verify this by taking a power law, right. Power law, so if U is r to the power K, then this holds and if you differentiate it with respect to r and multiply with r again, you will just pick up a factor of K outside, okay.

So this is a homogenous function of order K. Sorry, this is going to just be K times Ur, okay. This is just going to be K times Ur. You can check this very easily, just take a power law, okay.

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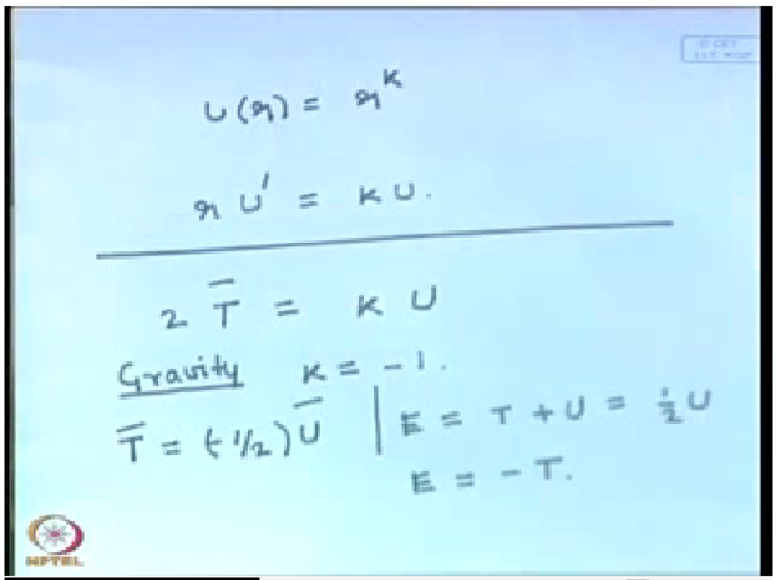

Let me just give you an example, suppose U is, now if you differentiate it with respect to r and multiply with r, so U prime*r, you can see that it is K*U, okay. So what we get from this is that twice the kinetic energy essentially or twice the average kinetic energy is K times the potential energy where the potential energy, potential is homogenous of order K, degree K, okay in the variable r. So let us now apply this to gravity.

We know for gravity, K = what is the value of K for gravity, the potential goes is -1/r, so K has a value -1, right. So, what we see is that for a system which is gravitationally bound, it is bounded, right, so it is a gravitationally bound system, okay. There the kinetic energy will be = -1/2 of the potential energy, the potential energy is negative, so the kinetic energy is going to be positive and the absolute values of the kinetic energy is going to be half that of the potential energy, okay.

This is very important relation for any gravitationally bound object and it is also true for the orbits that we just saw, okay, the planetary orbits. So if you calculate the average kinetic energy, this is average, okay it is not true instantaneously, it is for the average. So if you calculate the average kinetic energy and the average potential energy in those orbits, you will find that this relation holds.

The average kinetic energy is 1/2 the average potential energy though in modulus, okay. The total energy also can be calculated, the total energy which is a conserved quantities, so the time average is not important. The total energy is T+U. So the total energy is, T is -1/2U, so this is = 1/2 the potential energy, right or the total energy = - the kinetic energy for bound orbits, okay. So these are true for gravitationally bound systems, for any system that is bound gravitationally, right this is true.

And it is a very important thing in astrophysics because gravity is the most dominant interaction and we are quite often interested in gravitationally bound objects, okay. So with this background about motions in general and the 2-body problem, let us now move on to a discussion of the solar system which is a gravitationally bound system, okay.

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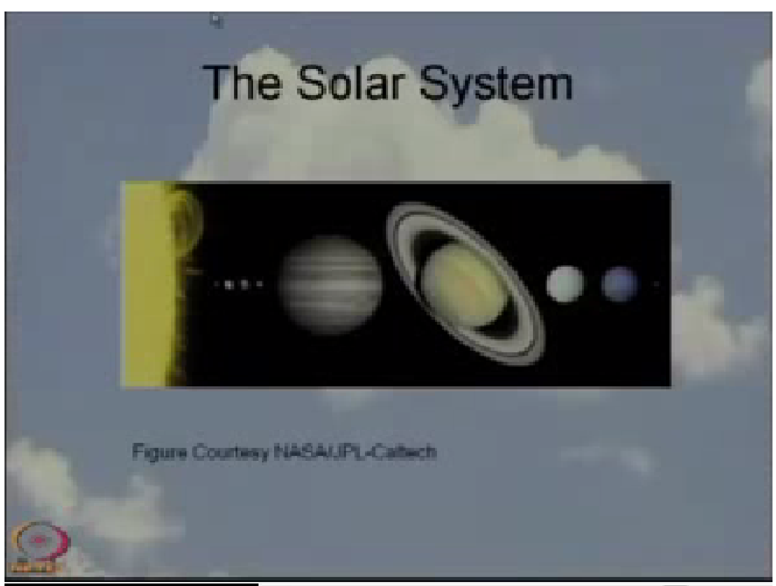

So this picture shows you the solar system, the different components of the solar system, okay. Now the figure is that I am going to use are mainly courtesy of NASA JPL and Caltech. There is one website which they run on solar system dynamics, okay. So the pictures are courtesy of this website of these organizations and much of the data is also from them, okay. If I have taken it from elsewhere, I shall give the due credit as we go along, okay.

So this picture shows you the different components, the planets and the Sun which makeup the large part of the solar system. Now the sizes are to scale, the distances are not, okay. Now what do we see. So what we see here is that the Sun by far is the largest component in the solar system, you cannot even see the whole of the Sun in this picture, okay. So the Sun by far is the largest component in the solar system and then we have these planets.

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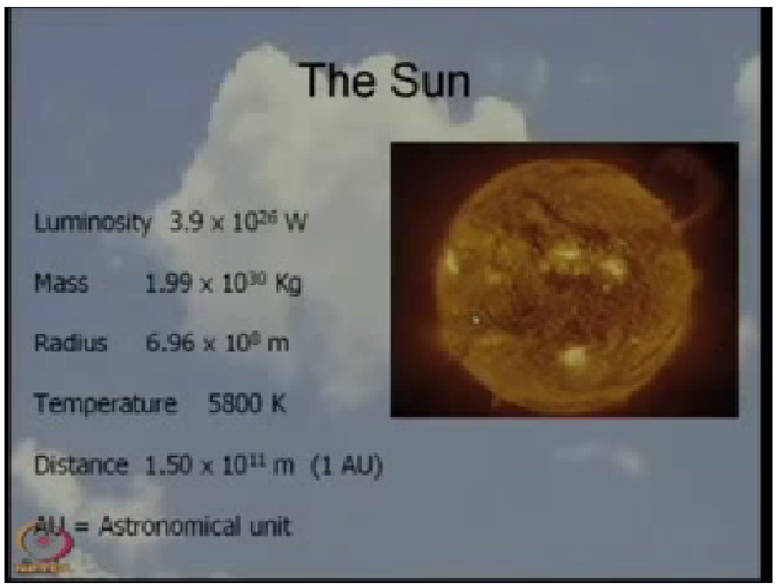

So we shall come to a discussion of the planets a little later, let us first discuss the Sun, okay. So the Sun is the most dominant component of the solar system and the planets essentially all revolve around the Sun. The Sun is a star. It is predominantly hydrogen and some amounts of helium. We shall come to the details of stars later on, okay. To give you just a few physical parameters which are important, its luminosity, the amount of light it emits per second, okay, it is like a bulb a 100-watt bulb emits 100 joules per second, okay.

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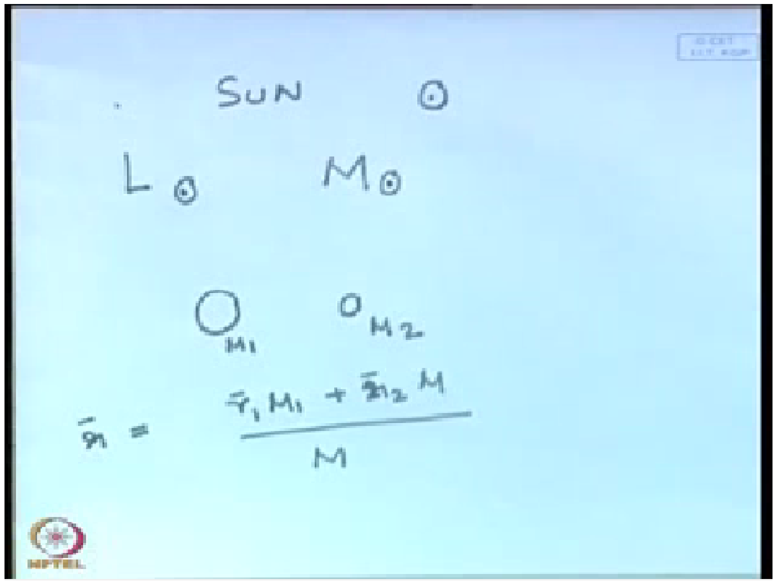

So the Sun has luminosity which is denoted by L. So anything with reference to the Sun is denoted by this, a circle with a dot in the centre, okay and the luminosity of the Sun, the solar luminosity is denoted by this, okay and it is very commonly used in astrophysics and cosmology, so I requested to bear this in mind, okay. Similarly, the solar mass is and it is quite common to denote the luminosity and masses of other objects, other astronomical objects in terms of these luminosities and masses.

So it is very important to get the values clear. So the luminosity of the Sun is 3.9*10 to the power 26 watts, the mass of the Sun is 1.99 10 to the power 30 kilos, okay. So these are the energy scale, the energy that comes out and the mass of the Sun. The radius of the Sun is 6.96 10 to the power 8 meters. So it takes around 2 seconds for light to travel from the centre of the Sun to the edge if it were able to propagate freely, okay. That is the radius of the Sun.

The surface temperature of the Sun, average surface temperature is around 5800 Kelvin, so it is extremely hot and the distance from the Earth to the Sun, the average distance, again this is an important number, it is 1.50*10 to the power 11 meters, okay and it is common practice when discussing the solar system, planets, etc. to use this unit. It is called 1 astronomical unit, AU, okay. So AU is an astronomical unit.

Now when we move outside the solar system, there is another length scale that we shall use, but within the solar system, this is what is commonly used, okay. Now you just take a look at the Sun. Now this is something that we cannot see with the naked eye because the Sun is extremely bright, but if you look at the Sun, you will see that it is not a uniform sphere with temperature 5800 Kelvin.

There are all kinds of features on the Sun and there is a large variety of activity going on. So this is a solar flare that has come out from the Sun. So this is material that is ejected from the Sun, it is a solar flare, okay and there is all kind of such activity that goes on in and around the Sun.

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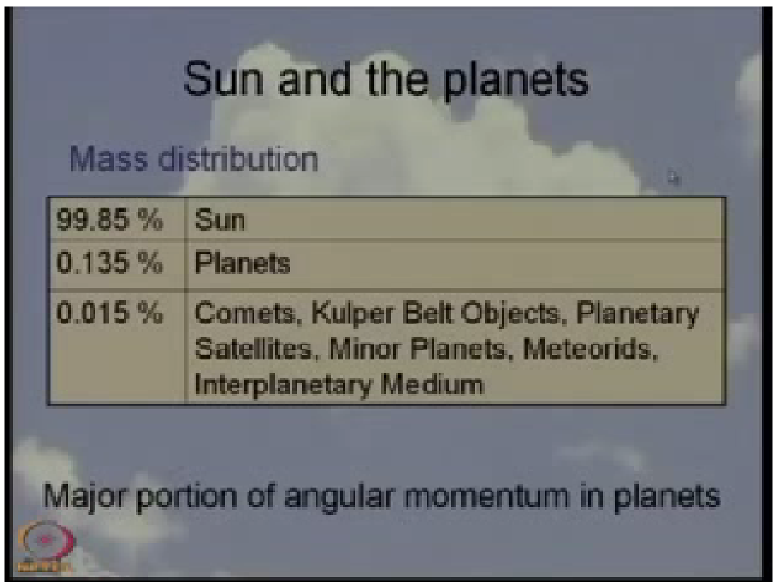

Now let us look at the Sun relative to the other planets, okay. Let us first look at the mass distribution in the solar system, where does the mass of the solar system lie. Now let us look at this table, you see that more than 99% of the mass lies with the Sun which is at the centre of the solar system. The planets have a little more than 1% of the mass and 0.01, 0.02 approximately percent of the mass of the solar system is in comets, Kulper Belt Objects, Planetary Satellites, Minor Planets, Meteoroids, Interplanetary Medium, etc.

These are very small things that also are there in the solar system other then planets, okay. So the mass predominately lies in the Sun. So when we are discussing the 2-body problem, when we discussed the 2-body problem, the centre of mass is the, let us just go back to the 2-body problem, we have 2 masses, let us just consider the Earth and the Sun as 2 masses, forget about everything else.

The centre of mass is at the weighted, so this is M1, this is M2, the centre of mass is r1M1+r2 M2, these are vectors/the total mass, M. So it is quite obvious that the centre of mass of the solar system is quite within the Sun, okay. So you can think of it as singly being the Sun, okay. Now if you consider the angular momentum though, and ask the question, where is the angular momentum of the solar system, how is it distributed, the angular momentum does not predominately lie in the sun, okay.

The Sun rotates around its own axis, around a month I think is the time rotation period, but the angular momentum is largely, major part of the angular momentum is in the planets, okay. So although the mass resides in the Sun, the momentum is distributed among the planets, okay.

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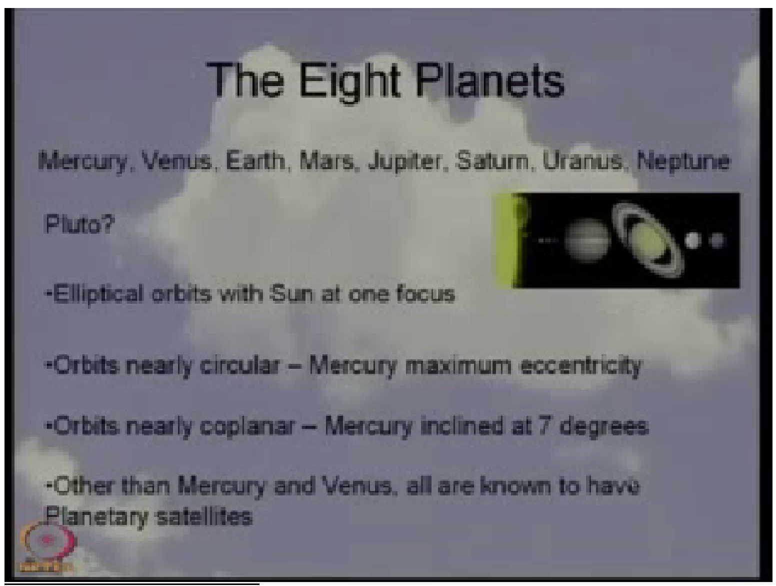

So let us now move on to the planets, the 8 planets, okay. I have listed the 8 planets here. We have Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune, okay. So these are the 8 planets. Mercury, that is the closest and then we have Venus, Earth and Mars, okay. Then we have Jupiter, Saturn, Uranus, Neptune. Now what about Pluto, it is no longer a planet. We shall come back to this at the end, little later, okay.

Now the planets all move in elliptic orbits with the Sun as one focus, okay. So the centre of mass that is what we learnt. So if you have 2 bodies, they move around in ellipses. The relative distance between these 2 bodies traces out an ellipse. Now in this case, the Sun is essentially the centre of mass lies at the Sun and the relative distances, the distance you can think of it as the distance from the Sun to the planet, so that traces an ellipse and one of the focus will be the Sun, okay.

These orbits are nearly circular, they have very small eccentricity. Mercury has the maximum eccentricity of all the planets, okay. The orbits are also nearly coplanar, approximately in the same plane except for Mercury which has the maximum inclination, which is 7 degrees amongst the planets. This is a not directly related to this. Other than Mercury and Venus, all the known planets have planetary satellites, okay.

So whatever we have learnt about the 2-body problem, you can straightaway apply to the orbits of these planets around the Sun, okay. They will move in ellipses; in the orbit, they cover equal area in equal time with respect to the Sun and the time period we saw, how it scales with the size of the orbit with the energy of the orbit, okay. So these are things that we have already learnt and all of these can straightforward be applied to the planetary motion.

Actually this was a verification, the planetary motion was a verification of Newton's laws of motion and Newton's law of gravity, okay. They were derived, they were arrived at by looking at planetary motions and one can actually verify whether they are correct or not by looking at this planetary motions, okay.

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Orbit Parameters (J2000)

Planet	Major axis (au)	Eccentricity e	Inclination
Mercury	0.38709927	0.20563593	7.00497902
Venus	0.72333566	0.00677672	3.39467605
EM Binary	1.00000261	0.01671123	-0.00001531
Mars	1.52371034	0.09339410	1.84969142
Jupiter	5.20288700	0.04838624	1.30439695
Saturn	9.53667594	0.05386179	2.48599187
Uranus	19.18916464	0.04725744	0.77263783
Neptune	30.06992276	0.00859048	1.77004347

So let me show you the data. This table summarizes the orbital parameters, okay. As of 2000, so these parameters are not supposed to change. If I had just 2 bodies interacting with each other through gravity, the major axis, the semi-major axis, or the eccentricity, would remain fixed, okay but here there are other planets. So when I considered the Sun and the earth, there are other planets whose effect will cause the semi-major axis and the eccentricity to change slowly.

The changes will be small, but they will be there, okay. There will be a slow change in the ellipse but it is a slow change, okay. So to a great approximation, we can think of it as a 2-body problem, okay. So this shows you the size of the orbits, this shows you the eccentricity and this shows you the inclination of the orbits. Now the size of the orbits as you can see increases as you go further and further away, that is obvious.

The point to note here is that the outer parts of the solar system are largely very sparsely populated. There are large gaps between these planets, between say Jupiter and Saturn, Mars and Jupiter, right the gap between Earth and Mars is, this is the Earth-Moon system, binary system. The distances are relatively small. Whereas once you go out, the distances between the orbits are pretty large. So there are large gaps between them, okay.

The eccentricity, if you look at it, Mercury has the largest eccentricity, it is around 0.2. The other planets have very small eccentricity, the orbits. So the first place beyond the decimal point are all

0, okay. So they have extremely small eccentricities. They are very close to circular and this shows you the inclination to the ecliptic plane. The ecliptic is the plane of the Earth's orbit, okay and this shows you the inclination of the orbits of different planets with respect to the ecliptic.

And you can see that Mercury has the largest inclination, Venus has a somewhat large inclination and the rest of them are around are much smaller, okay.

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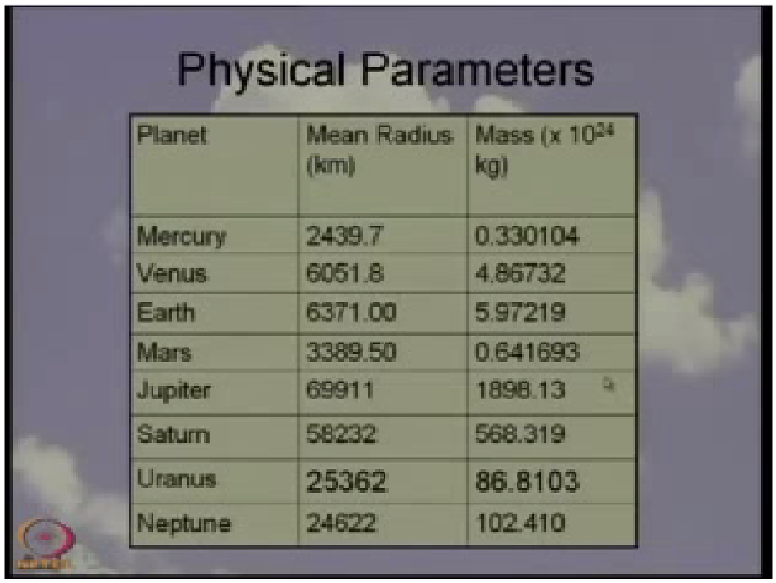

Planet	Mean Radius (km)	Mass ($\times 10^{24}$ kg)
Mercury	2439.7	0.330104
Venus	6051.8	4.86732
Earth	6371.00	5.97219
Mars	3389.50	0.641693
Jupiter	69911	1898.13
Saturn	58232	568.319
Uranus	25362	86.8103
Neptune	24622	102.410

Some more parameters about the planets and their orbits. So let us just look at this. These are some physical parameters, the mass and the radius, okay. The mean radius and the mass. The radius can change along the equator and the poles. So this is the mean radius of the planets and this is the mass, the radius are in kilometer, the radii and the mass in 10 to the power 24 kg. Again note that the radius and the mass, both of them, here they are of the order of few thousand kilometers and there is a drastic jump once you go to Jupiter.

Similarly, the mass here, these are around of the order unity, whereas here suddenly, there is a big jump, it becomes thousand, okay and the values here are much larger. This shows you the period, okay the period of the planetary rotation and the orbital period, okay. These periods are Sidereal Orbital Period and the Sidereal Rotation Period. What we mean by Sidereal is with respect to the fix stars, okay.

So Earth's Sidereal day is the time the Earth takes to complete 1 rotation with respect to the fixed stars. It is not the time from sunrise to sunset, sorry not sunrise to sunset, the time that Sun takes to go around the sky once. This is because in addition to rotation, the Earth also moves around the Sun, rotates around the Sun, okay and that changes the time, the Sun takes to go around the sky once, okay.

So there is a difference. You should bear this in mind. So these are Sidereal Rotation Periods and these are the Sidereal Orbital Periods. The orbits, you can see, increases as you go further away and we have seen how the orbits are expected to increase with the size of the orbit. That is the Kepler's law, we derive that in the last class.

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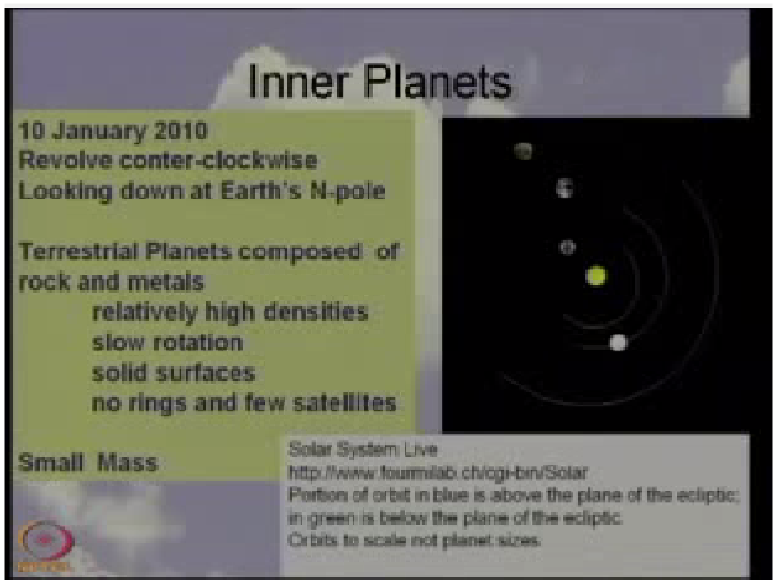

Now the planets have been roughly divided into 2 groups. So we have the inner planets or the inner solar system, okay. So this picture over here shows you the position of the planets on 10th January, 2010 and you can just visit this solar system life. This website whose address is given here, so this figure was made using this solar system life. It is a software web based software which you can at any time, you can see, you can give the time and it will show you the position of the planets at that time, okay.

So let us just look at this figure. So the distances in this figure are to scale, but the size of the planets are not. The Sun is obviously much larger, okay. These are pictures of the planets and the size of the orbits and the ellipses and the position of the planet are all correct, but the size of the planets are not to scale. Orbits are to scale, okay. Now the part of the orbit that is in blue, okay, so you can see that there is a part of the orbit which is in blue, this part of the orbit lies above the ecliptic plane.

The part in green is below the ecliptic plane. So the orbits cut the ecliptic plane, they are slightly inclined and a part of the orbit lies above, a part of the orbit lies below. The ecliptic plane is the motion of the Earth around the Sun or if you sit on the earth, the Sun appears to move along that curve, okay. So the orbits cut it and this shows you which part of the orbit is above, which part is below.

Now in this picture, the whole thing is rotating counterclockwise and we are looking down on the solar system on the Earth North Pole. So, the face of the Earth that you see has a North Pole. Okay, when you look down from the sky towards Earth's North Pole, you will see that the earth is rotating counterclockwise, the whole solar system also rotates counterclockwise. So, all the planets are moving in this direction, all of them. Okay, they are all moving in the same direction.

So, the angular momentum vectors are all oriented. The whole thing is rotating counterclockwise. So, the planets shown over here are Mercury, Venus, Earth, and Mars. These are called the inner planets. You can see that the distances from the sun are comparable and these are also referred to as terrestrial planets. What we mean by that is that the planets are largely composed of solid. They are largely solid, rocks and metals, okay.

So, that is the constitution of these planets, just like Earth. So, they are made up of rocks and metals. They have relatively high densities. They have the slow rotation and the surface of these planets is solid and they have no rings and few satellites. The Earth, for example, has one satellite, the Moon. So, all of these planets have the feature that they are solid, they rotate in slow rotation and they have a few satellites, no rings, okay.

These are also referred to as they have small mass, so these are minor planets. These are also referred not minor, these are the small mass planet. So, they have small mass, all of these planets.

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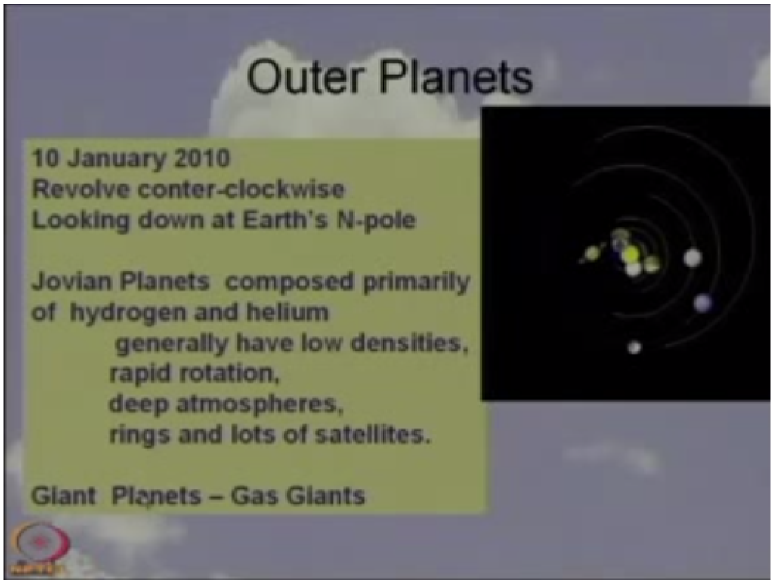

This is a picture of the remaining planets. These are the outer planet. Okay, again this picture is as of 10th January, 2010 and they all rotate clockwise, all the orbits. The orientation is the same. The blue and green has the same interpretation. This picture also shows Pluto which is not a planet. So, this eccentric orbit is Pluto, you can ignore it okay, in this particular discussion. The inner planets are extremely small here. You cannot make them out.

They are very close to the sun. You see that these orbits are at much larger distances and there are big gaps between them, okay. These are also referred to as Jovian planets and these Jovian planets refer to Jupiter-like planets. These are composed primarily of hydrogen and helium gas, okay. So, these are mainly made up of hydrogen and helium gas. Unlike the Earth and the terrestrial planets which are solid. They generally have low densities.

They rotates rapidly and they have deep atmospheres. Okay, the atmospheres are very deep, unlike the Earth's atmosphere. They have rings and lots of satellites and these are giant planets. There masses are much larger than the masses of the inner planets. They are also called Gas Giants, okay. So, these are the outer planets. They are much larger and they are gaseous. There are quite different from the planets like the Earth that we inhabit, okay.

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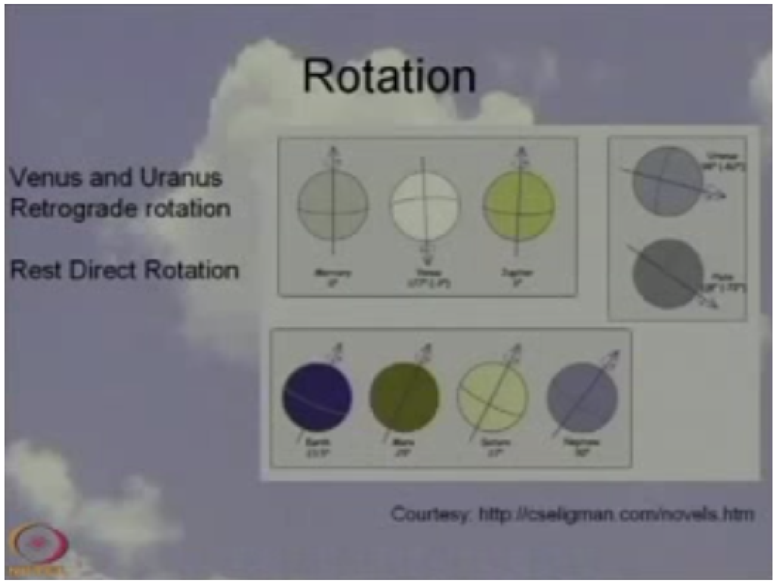

Now, let us take a look at the rotation of these planets. So, this picture, the source is given over here. This picture shows you how the planets rotate. The rotation axis of the Earth, we have seen, is slightly tilted with respect to the vertical of the solar system. You can see it here, okay. So, it makes an angle of 23.5 degree Earth here, it makes an angle of 23.5 degree. The point to note is that nearly all the planets have the rotation axis aligned normal to the ecliptic plane, nearly normal, okay.

They rotate in roughly the same direction in which they are revolving around the sun. If you look from the North Pole, the earth is rotating counterclockwise. It is also revolving in the counterclockwise direction. So, the 2 angular momentum vectors are in the same direction. This is called direct rotation, so the rotation and revolution are in the same direction. It is called direct rotation and most of the planets show this.

There are 2 exceptions; one of them is Venous here whose rotation axis is in the opposite direction. So, the rotation axis of Venous is in the opposite direction, but the rotation period is extremely large. So, it rotates very slowly.

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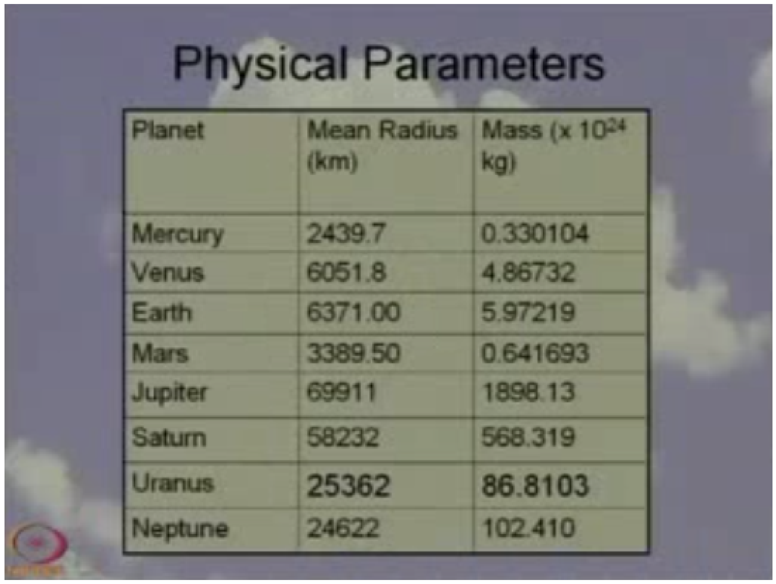

Physical Parameters

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Jupiter	69911	1898.13
Saturn	58232	568.319
Uranus	25362	86.8103
Neptune	24622	102.410

You can see that here. So, the rotation period of Venous is 243 days, okay whereas for Earth it is close to 1 day. Mercury also has a very interesting thing. It is rotation period is comparable.

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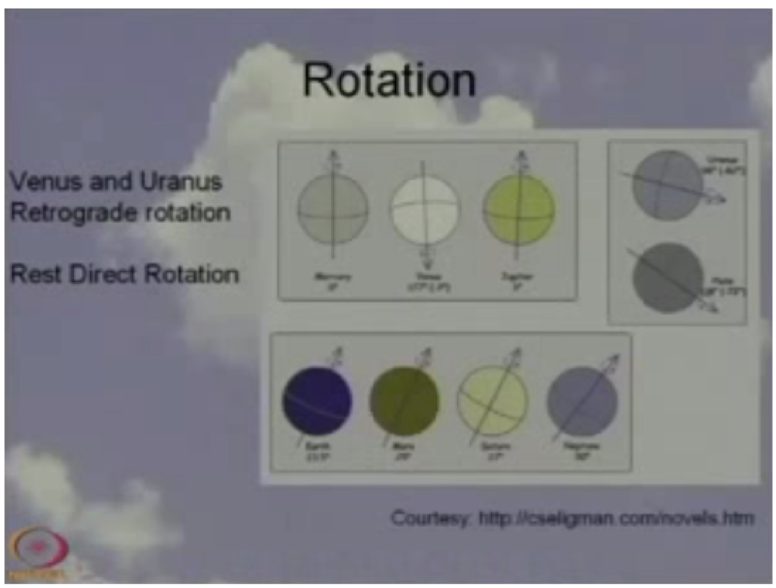

Now, the other exception, Venous is one of them is Uranus whose rotation angle neither is it aligned nor is it opposite, it is perpendicular to the revolution axis. So, the direction along which it rotates is roughly in the plane of the orbit, okay Uranus. Now both Venous and Uranus they rotate in directions opposite to which they revolve around the sun. This is called retrograde rotation.

So, the rotation is in one direction and it revolves around the sun in the opposite. This is called retrograde rotation. The angles given here are perpendicular to the orbital plane of the particular planet. They are very close. It is a very small difference. For Mercury, it is 7 degree right. So, this is with respect to the orbital plane.

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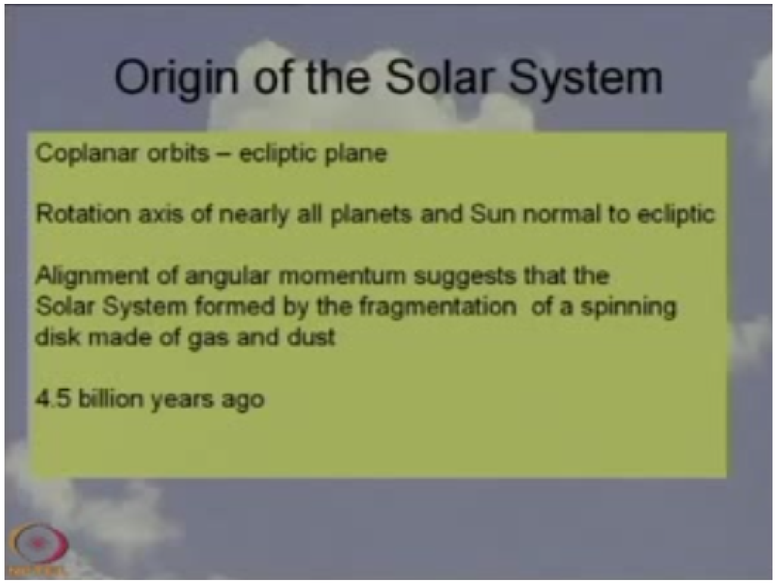

Now, let us look at the origin of the Solar System. So, where we see that there are these planets in the Solar System. Let us just briefly address the question how did Solar System originate, okay. So, we see that the orbits are coplanar that is one of information. So, they all revolve in the same plane and the direction of the orbital angular momentum are all the same. All the planets have the same orbital plane and the direction of the angular momentum vector are the same right.

Second thing, the rotation axis of nearly all the planets and the sun are normal to the ecliptic plane. So, on average they also rotate in the same direction in which they are revolving. So, the angular momentums are aligned, okay. So, it seems that most of the objects in the Solar System, the planets and the sun, have their angular momentum vectors alike.

There are a few exceptions, so this alignment of the angular momentum vectors suggests that the Solar System was formed by the fragmentation of a spinning disk made up of gas and dust, okay. So, there was a disk which is spinning, the whole disk is rotating made of gas and dust that fragments, then you can get these stars, planets, everything with the same angular momentum vector, right.

The angular momentum of the original disc will be conserved and it will be there in these objects also and the age of the solar system is estimated to be around 4.5 billion years. So, the whole thing took place around 4.5 billion years ago, okay.

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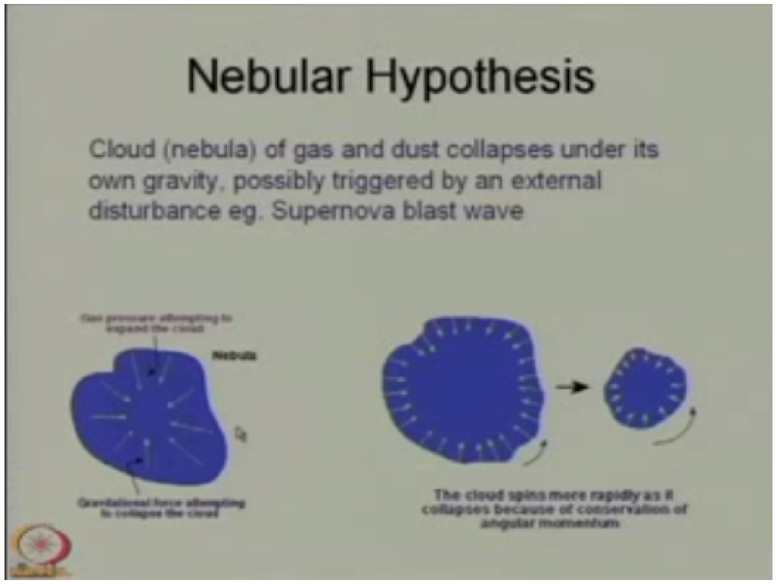

So, this is a commonly accepted picture, but the details of this picture are still not very clear. So, it is not 100% accepted and verified, etc., it is a commonly accepted picture. Okay, so the picture is referred to as a Nebular Hypothesis. It is pretty old. It is more than hundred years old 19th century. The picture is as follows. You have a cloud of gas and dust and this cloud and dust collapses under its own gravity, okay.

So, this is a cloud of gas and dust and its own gravitational pull tries to make it collapse. But there is another force which is the pressure gradient, we shall learn about this later on, which tries to prevent this collapse, okay. Now it may happen that the gravitational force wins over this thing collapses and it is quite possible that there is an external disturbance. For example, a Supernova blast wave which would have disturbed the gas cloud to start with and caused this thing to collapse.

Okay, so the picture is there is a gas cloud which is collapsing under its own gravity. Okay, so this shows you the picture. This is the gas cloud and it collapses under its own gravity, okay.

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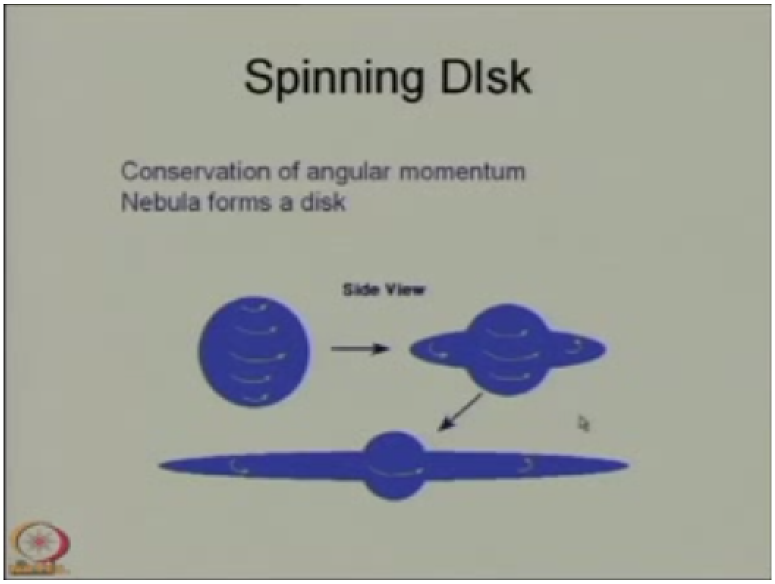

Now this collapsing disk has angular momentum and the angular momentum is conserved, so it cannot collapse in the direction of the angular momentum. So, first of all, when it collapses it starts rotating faster. So, it is rotating this way let us say. So, if this has to collapse any further it will have to spin very rapidly which prevents it from collapsing, but it can collapse easily in the perpendicular direction. So, it is rotating in this way.

It can collapse easily in this direction and it collapses to form a disk like this with a bulge in the centre. So, the gravity attracts more matter in the centre. So, there are 3 force essentially, there is a gravitational attraction, there are the special gradient and there is the rotation which allows it to collapse in one direction and prevents it from collapsing in the other 2 directions. That is a centrifugal force which prevents it from collapsing, okay.

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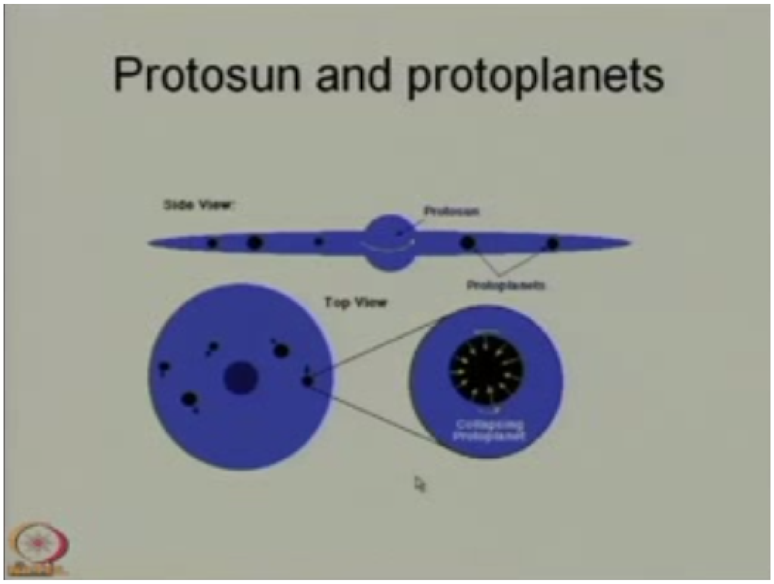

Finally, you end up with something that looks like this and then this disk fragments again due to some instability and you form the protostar over here, you have protoplanets and the Solar System is possibly formed in this way, okay. Now we have been discussing the planets until now, but the planets and the sun, but these are not the only components of the Solar System.

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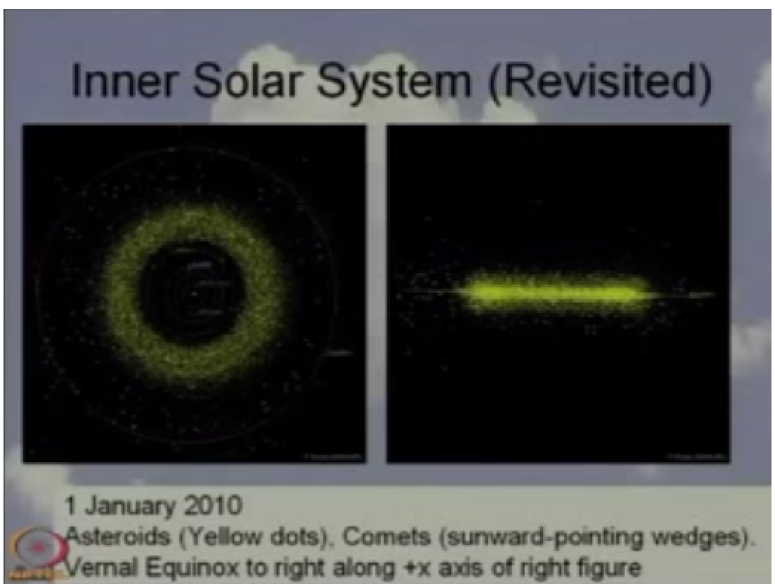

Now, let me show you another picture of the Solar System. So, this picture shows you the positions of the planets and the other components of the Solar System of the inner Solar System, okay. So, this is the Inner Solar System Revisited. This shows a picture of the positions on 1st January, 2010, okay. Now, here this shows you the planets all the way up to Jupiter. Now, notice that in addition to the planets you have this tremendously dense thing over here, right.

You have these many-many yellow dots over here, what are these yellow dots. These are asteroids, so the asteroids are shown in yellow dots over here, okay. These wedges over here which point toward the sun these are the comets, okay. So, in addition to the planets, you also have these asteroids and the comets and you can see that there are a large number of them and there is a large belt of comets between Mars and Jupiter.

You can see it over here and there are all these comets and the comets you can see are not restricted whereas the asteroids are roughly restricted over here, the comets are distributed all over space. This is side picture of the same thing, side view. The Vernal Equinox is over here to the right. Okay, so what we see over here is that in addition to the planets, we also have a large number of asteroids and comets which are there in the solar system.

There is a belt of asteroids, the number of asteroids is very high. The asteroid seems to be concentrated in the region between Mars and Jupiter. There is a belt of asteroids over here, okay between Mars and Jupiter. This is the outer solar system again the same thing. Now, again in addition to the planets we have the asteroids and the comets, also shown over here okay and you can make out that there is this disk of asteroids over here outside beyond Neptune.

So beyond Neptune, you have this belt of asteroids over here. Beyond Neptune, there is a belt of asteroids. Pluto's orbit you can see goes around like this quite far away, okay and the orbits of the comets Haley and Hale-Bopp are also shown over here. So, you can make out the orbits of these orbits that go far away are Hale-Bopp and Haley, okay. There is a comet Haley also which is, yeah this is comet Haley which is shown in this picture, okay.

The 2 comets Haley and Hale-Bopp are also shown in this picture and this shows you the distant Solar System, okay. So, it shows you all objects which are beyond 6 astronomical units, okay as of 1st January, 2010. In addition to that, it shows the planets, it shows Haley and Hale-Bopp comets and there are these Sedna and Eris. There are 2 more orbits shown those of Sedna and Eris. In addition to Pluto, there are also the orbits of Sedna and Eris which are shown.

You can see them, these are very large orbits, so this is one of them, okay.

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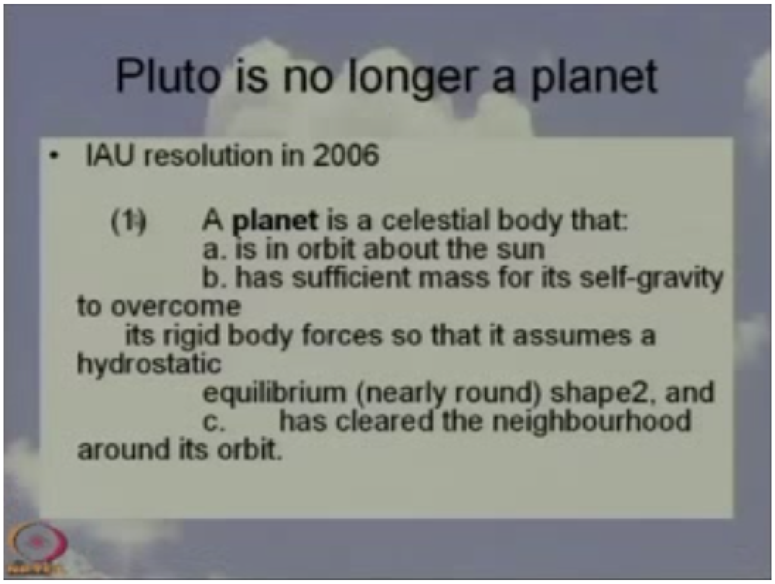

Okay, the point here is once you go beyond Neptune, you find that there are a large number of objects which you have. You have this belt of asteroids and then you have all of these new objects like Sedna and Eris and possibly many more which are there floating around beyond the orbit of Neptune. It is very distant part of the Solar System, okay.

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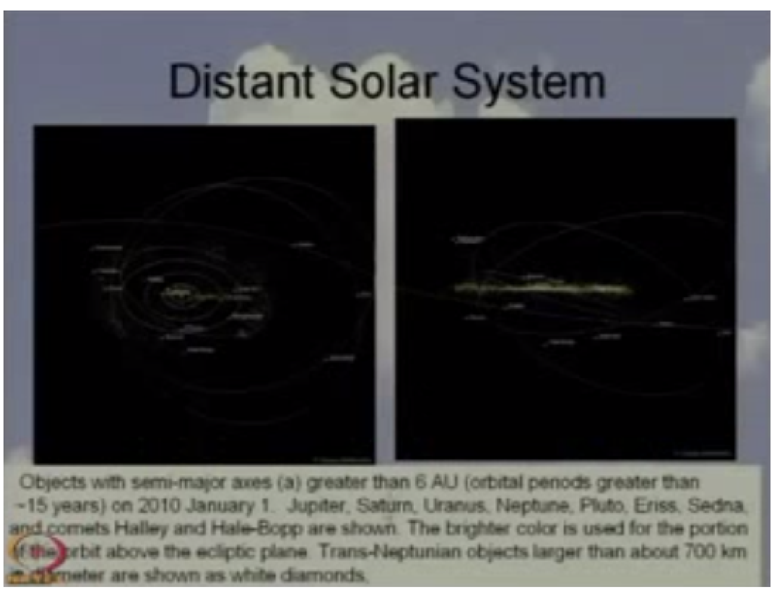

So, this gives you an overall picture of the Solar System. Now let us address the related question as to what happened to Pluto. Why is Pluto no longer a planet, okay. The reason is that there was an IAU resolution (International Astronomical Union) in 2006. It resolved the following. Let me summarise the resolutions of the International Astronomical Union. So, it defined what is a planet.

A planet is a celestial body that (a) is in orbit about the sun, (b) has sufficient mass for its self gravity to overcome the rigid body forces so that it assumes a dynamic equilibrium nearly spherical shape, okay and has cleared the neighbourhood around the orbit, okay. So, it should in orbit around the Sun, it should have enough self gravity to come to hydrostatic equilibrium. So this is in orbit around the Sun, but does not have enough self-gravity to overcome the shape which is held there.

So, atoms here are held together by electromagnetic forces and quantum mechanics, okay, not by gravity. But if it is gravity was sufficiently high, it would then collapse and form spherical. It would come hydrostatic equilibrium, it would form a spherical shape then it would be a planet, okay and further it should also have cleared the neighbourhood around the orbits. So, if you look at the orbit of, let us say, these planets you do not find the orbit littered with asteroids, okay.

The asteroids are there, but they are in between the planetary orbits. The planetary orbits do not cut the region with large number of asteroids. The planets have gravitationally attracted all of them and cleared of the path. So, it defined a new kind of object a dwarf planet. So, the first 2 conditions are the same, but it has not any object that satisfies the same first 2 conditions, but they have not cleared the neighbourhood of its orbit and is not a satellite, any such object.

So, if you have an object that goes around the sun, which looks like a planet. It is spherical. It has overcome the other forces and is in hydrostatic equilibrium under self gravity, but it has not cleared its orbit of other objects, then it is called a dwarf planet. Okay, that is a new nomenclature introduced by IAU and all other objects, except satellites orbiting the Sun shall be referred to collectively as Small Solar System Bodies, okay.

So, everything else that orbits the sun except for planetary satellites shall be referred to as Small Solar System Bodies, okay.

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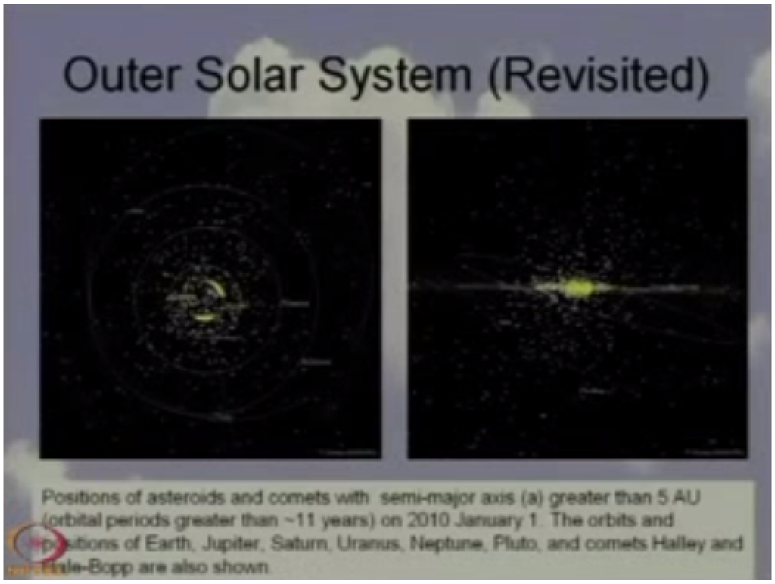

So, if you look at the orbit of Pluto here you can see that it cuts across this tremendous thing of asteroids which are there around Neptune, okay. So, this is one of the reasons why a Pluto was removed from the list of planets. The other reason is that we now have a picture that there are many other objects which are more massive than Pluto, okay. One expects to find in the future and there are already 2 more which are designated planets.

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So, one of them is Ceres which was earlier classified as an asteroid and another one is Eris whose orbit I have shown you. So, all 3 of these designated as dwarf planets, okay and this was done because if you include Pluton, then you have to include these 2 and you have to include many other objects in the Solar System, okay. So, let us stop here for today and we shall continue.