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8.01 Physics I: Classical Mechanics, Fall 1999
Transcript – Lecture 20

We're now entering the part of 8.01 which is the most difficult for students and faculty alike.

We are going to enter the domain of angular momentum and torques.

It is extremely nonintuitive.

The good news, however, is that we will stay with this concept for at least four or five lectures.

Today I will introduce both torque and angular momentum.

What is angular momentum? If an object has a mass m and it has a velocity v, then clearly it has a momentum p.

That's very well defined in your reference frame, the product of m and v.

Angular momentum I can take relative to any point I choose.

I choose this point Q arbitrarily.

This now is the position vector, which I call r of Q.

Let this angle be theta.

And angular momentum relative to that point Q--

it's a vector--

is the position vector relative to that point Q cross p.

So it is r of Q cross v, and then times m.

The magnitude of the angular momentum, relative to point Q, is, of course, rmv, but then I have to take the sine of the angle theta, so let's say it is mv r sine theta and this I often call, shorthand notation, r perpendicular.

That r perpendicular is this distance, relative to point C.

What you just saw may have confused you and for good reason, because I changed my index "Q" to "C," and there is no C.

The indexes should all be Q, of course.

So this r is the length of this vector.

It is the magnitude of this vector.

So this should have a "Q." And r of Q sine theta, which I call r perpendicular, must have an index Q, and that is this part here.

This angle is 90 degrees and this here is r of Q perpendicular.

No Cs at all, only Qs--

I'm sorry for that.

The direction of the angular momentum is easy.

You know how to do a cross product.

So in this case, r cross v would be perpendicular to the blackboard and the magnitude is also easy to calculate.

Now comes the difficult problem with angular momentum.

If I chose any point on this line, say point C, then the angular momentum relative to point C is zero.

Very obvious, because the position vector, r, and the velocity vector, in this case, are in the same direction.

So theta is zero, so the sine of theta is zero.

So you immediately see that angular momentum is not an intrinsic property of a moving object, unlike momentum, which is an intrinsic property.

If you sit there in 26.100, you see an object moving with a certain velocity, it has a certain mass, you know its momentum.

What the angular momentum is depends on the point that you choose, on your point of origin.

If you had chosen this point D, then the angular momentum would even be this way, because when you put here the position vector in there you see r cross v is now coming out of the blackboard.

And this is why angular momentum is such a difficult concept.

But we will massage it in a way that it will be very useful.

Suppose I throw up an object in 26.100 and at time t equals zero, the object is here and at time t, the object is there.

So this, then, is the position vector at time t.

The object starts off with a certain velocity v and a little later, here, say, the velocity is like so.

And there is, of course, a force on it, mg, which makes this curve.

What is the angular momentum relative to point C at time zero? The angular momentum is clearly zero, because the point itself, the mass itself, is at point C.

So the position vector has no length, so it's clear that it's zero.

What is the angular momentum at time t when the object is here? Well, that angular momentum is clearly not zero, because you see here position vector and you see the velocity, so clearly the angular momentum was changing.

Now you will say, "Of course it was changing--

big deal." Because angular momentum has a velocity vector in it.

And here the velocity vector is changing all the time, so, obviously, you would say the angular momentum is changing.

Well, yes, that is not a bad argument, but I will now show you a case where the velocity is changing all the time, but where angular momentum is not changing.

I choose the Earth going around the Sun.

Here's the Earth, with mass m.

At point C here is the Sun.

This is the position vector r of C and the Earth has a certain tangential velocity and the speed never changes, but the velocity does change.

So this is the position vector at a later point in time.

What now is the angular momentum of the Earth going around the Sun, relative to point C? I pick C now.

Well, that angular momentum...

If I take the magnitude of the angular momentum, because the direction is immediately obvious...

If the object is going around like this--

this is the position vector--

then the direction will be pointing out of the blackboard.

That's easy.

So I'm only worried now about the magnitude.

So the magnitude is the mass of the Earth times the magnitude of the cross product between these two vectors.

And notice the angle is 90 degrees.

So I can forget about the cross, the sine of theta is one, and so I simply get mrv, v now being the speed.

This is the case when the object is here, but when the object is here, the situation has not changed.

Again, r cross v, the magnitude, is exactly the same, because the sine of the angle hasn't changed.

And so you see here a case whereby the velocity is changing all the time but your angular momentum relative to point C is not changing.

Suppose I had chosen point Q.

Is angular momentum changing relative to point Q? You'd better believe it.

There is a time that the object will go through point Q.

Well, then the angular momentum is clearly zero because the position vector is zero.

If the object is here and you take the angular momentum relative to point Q, for sure the angular momentum is not zero.

You have a position vector and you have a velocity.

So only relative to point C--

it's a very special case now--

is angular momentum not changing.

So angular momentum is conserved in this special case, but only about point C.

And I want to address that in a little bit more general way.

I take the angular momentum and I choose a point Q, and I know that the definition is position vector relative to point Q cross p.

I take the derivative, time derivative dL/dt relative to that point Q.

It's always important that you state which point you have chosen relative to which you take the angular momentum.

That is going to be dr/dt...

excuse me--

cross p plus r of Q cross dp/dt.

This is the way that you take the time derivative of a cross product.

We calculate the angular momentum relative to point Q.

So the index has to be Q throughout the equation.

The position vector, relative to point Q.

And in this equation, you see the correct index Q here.

You see the correct index Q here, but I slipped up here and I put a "C" there.

There is no "C" in this problem, so this is also r of Q.

Sorry for that.

This, here, is the velocity of the object, the velocity vector, which is always in the same direction as p.

So this is zero.

dp/dt--

that is, the force on the object--

we've seen that before in 8.01.

And so now we have that dL/dt, relative to a point Q, equals the position vector r from that point cross F.

And this, now, is what we call torque.

And we write for that the symbol tau... it is a vector.

And I put in that Q again.

And this is one of the most important equations that will stay with us for at least five lectures.

What this is telling you is that if there is a torque on an object, the angular momentum must be changing in time.

If there is no torque on the object, angular momentum will be conserved.

And now you get some insight into this situation that we just discussed.

The force, the attractive force, gravitational force exerted on the Earth is in this direction.

The position vector is in this direction, so r cross F is zero.

There is no torque relative to this point C, because the angle between the two vectors is 180 degrees and so the sine of the angle is zero.

Therefore, no matter where you are on the circle, always r cross F will be zero.

There is no torque relative to point C.

But if you take point Q or you take here some point A, clearly, there is going to be a torque, a changing torque even, and so there you will have a change of angular momentum.

So there's something very special about that point C and I will come back to that, of course.

Now I want to expand the idea of angular momentum from one point object that moves in space to an object like a sphere or like a disk which is rotating about its center of mass.

And I will start with a disk.

Here we have a disk.

The disk has mass M and the disk has radius R, and at this point C is the center of mass of this disk.

It's rotating with angular velocity omega and I want to know what the angular momentum is of this rotating disk.

The direction of the angular momentum is going to be trivial.

If it's rotating like this...

If you take here a little mass element, mass m of i, this is the position vector r of i, relative to that point C, and here you have the velocity, v of i.

And you see immediately that r cross v is coming out of the blackboard so that's easy.

Angular momentum will be in this direction, but what is the magnitude of the disk as a whole? Well, let's first calculate what the angular momentum is of this little mass element about this point.

So L of C for mass element i equals...

Oh, let's just only worry about magnitude because already we know the direction.

So that is m of i and then the cross product between r of i and v of i.

But this angle is 90 degrees so I can forget about the sine of theta.

So I simply get r of i, v of i.

r of i relative to that point C times v of i--

this is the magnitude.

Now, I hate to see v of i in a rotating disk because the velocity will depend on how far you are away from the center.

The velocity here is zero.

However, they all have omega in common.

Every single element that you choose has the same omega.

So I'm always going to replace--

in a case like this--

v by omega R.

And so this then becomes m of i, r of i of C.

I get a square here and I get omega.

So I wrote down v equals omega R, which, of course, holds in general.

It would have been better, perhaps, if I had written down v of i equals omega times r of i, because each element little "i", which has a position vector r of i, has a velocity which is given by v of i equals omega r of i.

But I condensed that, sort of, in one equation--

v equals omega R.

But this is the connection that will make it, perhaps, easier for you to understand what follows.

So that is the angular momentum for this little mass element.

But now I want to know what the entire angular momentum is about that point C as an axis going through the center of the mass, through the center of the disk perpendicular to the blackboard.

And now, of course, I have to do the summation of all these elements i.

I can bring the omega outside, and I would have, then, the summation of m of i r of i relative to that point C squared.

And you see immediately--

I hope that you see immediately--

that this is the moment of inertia for a spin around the center of mass for that point C.

And so I can write for this, I of C times omega.

Now comes the question--

so this is the magnitude--

now comes the question, is this angular momentum different, for instance, for this point A? And your first reaction will be, "Yeah, of course, because it depends on the point you choose." Well, the remarkable thing is that if you have a rotation about the center of mass which I have chosen here, then even if you calculate the angular momentum relative to this point--

or any other point, even this point in space--

you will always find the same answer.

But only in case that there is a rotation about the center of mass, and we call that the spin angular momentum.

The spin angular momentum is an intrinsic property of an object regardless of which point you choose relative to which you calculate the angular momentum.

So in the case that an object is spinning about its center of mass, you no longer have to specify the point that you have chosen, your point of origin.

You can really talk now about the angular momentum.

The Earth is spinning about its center of mass, so the Earth has an intrinsic spin angular momentum.

In addition, it has an orbital angular momentum.

If you want to talk about the orbital angular momentum of the Earth, however, you'd better do it relative to that point, otherwise it would be changing in time.

It's only uniquely defined if you take this special point, because only about that point, which is the location of the Sun, is the angular momentum--

the orbital angular momentum of the Earth--

not changing.

I'm going to do a daredevil experiment with you and that is called ice-skater's delight.

You will see that it is not a delight at all.

But in any case, it is definitely a fun experiment.

I have here a turntable--

very little friction--

and I'm going to rotate the turntable about the center and I'm going to stand on that turntable and I will hold in my hand two weights, these two.

They're each about 1.8 kilograms.

So these weights m, 1.8 kilograms...

My entire mass--

including the turntable and my body, let's say--

is about 75 kilograms.

And I'm going to ask someone to give me a little twist to rotate me about this axis of symmetry.

Rotate me, say, if you look from below, let's say I'm being rotated clockwise.

So we have here a situation of a rotation about the center of mass so we can talk about the intrinsic angular momentum of this rotating system.

And the angular momentum vector will obviously be pointing upwards.

That's clear.

If you rotate clockwise from below...

Remember, here you were rotating counterclockwise; it was coming out of the blackboard.

Here you rotate clockwise, it will be going up.

So far, so good.

There is a force on me due to gravity--

mg, no concern.

There is an equally strong force, normal force up, and the two cancel each other out.

Once I have been given a certain rotation, a certain angular velocity I'm going to pull my arms in and pull my arms out and pull my arms in, and when I do that, that does not cause a net torque on the system.

I can keep doing that all the time and there is no net torque.

And so angular momentum as we have specified for a spinning object must be conserved, cannot change.

L equals I omega.

But as I pull my arms in, my moment of inertia will go down.

And if my moment of inertia goes down, then if this product has to remain constant, my angular velocity must go up.

And vice versa, so when I pull my arms in, I will go faster and when I do this, I will go slower.

And I want to be a little bit quantitative with you.

I simplify my own body by a geometric object for which I can calculate the moment of inertia which is a cylinder.

I may not look like a cylinder, but close enough for all practical purposes.

And this cylinder has a radius of about 20 centimeters--

not too bad, it sort of fits me--

and I'm going to rotate this cylinder around this axis and I can calculate now what the moment of inertia is.

The cylinder has a mass of 75 kilograms, has a radius of 20 centimeters, and so the moment of inertia--

in the situation that, for instance I have these two objects next to my body here or I have them like here, so this is my shorthand notation--

equals simple one-half M R squared.

Remember, that was the moment of inertia--

we discussed that last time--

of a rotating disk which rotates about the line of symmetry.

And so, if I put in the numbers here, the 75 kilograms, and I take a radius of 20 centimeters, then I found that this is about 1.5 in our mks units.

But now I'm going to put my arms like this and now the moment of inertia will go up.

And I'll make a very crude calculation how much it goes up.

My arm length is about 90 centimeters.

The weights here are 1.8 kilogram.

So I just assume that my arms have no weight for simplicity, that all the weight is in these two objects.

It's a simplification, but you will see it's a dramatic change and that's all I want you to see.

So now the moment of inertia, when my arms are like this.

Of course, there's my body, which is the 1.5.

That is still there but now there is an additional component: one from this mass, which is M R squared, and one from this mass, which is M R squared, where this is now that radius r.

And so I get twice that mass and then I have to take R squared, which is 0.9 squared, and I have to take the 1.8, because that's the moment of inertia of this object about this point.

It is M R squared, I assume that my arm has no mass.

And when you add this up, you'll find 4.5 in mks units, kilograms meters squared.

And now you see, if I go from this situation to this, my moment of inertia goes down by a factor of three and if my moment of inertia goes down by a factor of three, my angular velocity must go up by a factor of three.

And vice versa.

I want to do this experiment but this experiment is not without danger.

The problem with this experiment is that the moment that you pull your arms in you get immediately extremely dizzy and you can lose your balance and you can fall flat out on the floor.

And I have just talked this morning with some student here who did that in high school and he told me that, indeed, one of the teachers went flat down and I'll try not to do that today.

So I need really assistance from someone whom I can trust.

Do you think I can trust you? Not you.

[class laughs]

LEWIN: That's an honest answer.

You're a strong man--

can I trust you? The first thing I want you to do is to help me get on here, because even getting on here is not easy.

If I just step on here, I will probably fall.

Okay, so stand there, put your arm around my neck.

Support me strongly, yeah, okay.

All right, there we go.

Now, stay with me for a while, okay, just stay there.

All right, now you give me a reasonable angular velocity, whatever you think is reasonable.

I'll tell you if it's completely unreasonable.

[class laughs]

LEWIN: Give me a push, that's fine.

Wow... is it fine? Now, you walk a little bit away.

If I fall, try to catch me.

[class laughs]

LEWIN: Okay, my arms go in now.

My arms go out.

My arms go in.

My arms go out.

Okay, now I'm completely dizzy now.

This is no joke, so stop me, yeah? Just hold it.

[class laughs]

LEWIN: No, just hold me, hold me.

Okay, get my hand.

Okay... okay, you passed the course.

[class laughs]

[class applauds]

Whew! Sacrifice for the sake of science.

[groans theatrically]

All right, I've done worse.

If we have a collection of many points--

like we earlier discussed with momentum--

points that interact with each other...

They could be stars who gravitationally interact.

They could be objects which are connected with springs.

They have internal interactions which go on all the time.

They bounce off each other, they collide, they break up in pieces, internal friction, anything.

Then if I take two of these objects, if this one, for instance, is attracted towards this one, then action equals minus reaction and these two forces are identical in magnitude.

So if I take any point Q here, no matter where you choose it, that will never put a torque on that system because the two forces cancel each other out.

And so now we get the final conservation of angular momentum in all its glory if only we add, here, one little word--

"external." The angular momentum of a system... This was angular momentum of just one object; this is the angular momentum of a system of many particles.

They could be connected with springs.

There could be chemical explosions going on.

They could plow into each other.

They could break each other up.

The angular momentum will not change if there is no net external torque on that system, because all the internal torques cancel out because action equals minus reaction.

So if we now compare conservation of angular momentum with conservation of momentum, then in the case of the conservation of momentum, remember, when we have a system of objects, in the absence of an external force on the system as a whole, the net external force, momentum was conserved.

Now we have...

with a system of particles in the absence of a net external torque, angular momentum is conserved.

In the case of the ice-skater's delight, when you pull your arms in, the moment of inertia goes down and so your frequency goes up.

When a star shrinks, its radius goes down, its moment of inertia goes down, and therefore its angular velocity must go up.

Moment of inertia goes with R squared.

What determines the size of a star? If this is a star, then inside this star is a furnace, nuclear furnace.

Nuclear fusion is going on.

That produces heat and pressure, which wants to expand the star.

On the other hand, there is gravity, which says, "Sorry, you can't do that.

I want to hold you together." In fact, gravity would like to collapse the star.

And nature finds a balance between the gravity and this pressure due to the nuclear furnace.

Now, there comes a time that the nuclear furnace has been completely consumed.

For our Sun, that takes an additional five billion years.

The Sun has already been burning nuclear fuel for five billion years.

It has another five billion to go.

And once the nuclear fuel has been consumed, there are three end-products of the dead star that is left over.

And these three end-products are the following: Number one is called a white dwarf.

It has a radius approximately the same as the Earth, some 10,000 kilometers, and the mass of a white dwarf...

There's a whole range of them, but a typical number, say, is half the mass of the Sun.

So that's one possible end-product.

This will be the fate of our Sun, by the way.

The density of such an object is quite high--

some ten to the rho--

will be roughly ten to the 6th grams per cubic centimeter.

Another possibility is that you end up with a neutron star.

A neutron star has a radius of about ten kilometers, and it has a mass of roughly 1.5 times the mass of the Sun, and its density is about ten to the 14 grams per cubic centimeter, which is even higher than the density of nuclei.

And then there is a possibility, which is even more bizarre, that you end up with a black hole.

I will not talk about black holes today but I will get back to that later in 8.01.

And a black hole, for all practical purposes, has no size at all.

The mass of the black hole must be larger than we think--

three solar masses--

and so the density is infinitely high.

Whether you end up to be a white dwarf, a neutron star or a black hole depends on the mass of the progenitor--

of the star that collapsed when the fuel, when the nuclear fuel was gone.

And in order to form a neutron star, you would have to start off with a star of probably at least ten solar masses, maybe even more.

So our Sun will not become a neutron star, but our Sun will ultimately become a white dwarf.

Now, it would be a reasonable question to ask, Why do you end up only with these three possibilities? Why is there nothing in between? Look, there is a huge difference from 10,000 kilometers to ten kilometers.

Is there nothing in between? And the answer to that lies in quantum mechanics, which is not part of this course but you will see that in 8.05.

Why are there only these two? And then if you get into general relativity, then you will understand why there is, then, this third, very bizarre possibility.

When a star collapses, two things happen.

First of all, there is a huge amount of gravitational potential energy that is released in the form of kinetic energy.

The stuff falls in--

we call it gravitational collapse.

And that gravitational potential energy converts to kinetic energy and that ultimately converts to heat and to radiation.

If I take an object here, a piece of chalk, and I drop that, that you can call gravitational collapse.

Gravitational potential energy is converted to kinetic energy and, ultimately, it goes to heat.

Here we're talking about a star which is imploding, collapsing, and the amounts of gravitational potential energy that become available are enormous.

In addition to this huge amount of energy release, the star must spin up, because its moment of inertia goes down and therefore the angular velocity must go up.

I want to do a little bit of quantitative work on this.

And I want to take an object like our Sun and I would like to collapse that object from its present radius--

of the Sun, which is about 700,000 kilometers--

I want to collapse that to a neutron star with a radius of ten kilometers, even though I know and I told you that the Sun will not become a neutron star.

It's just to get some feeling for the numbers.

So we take an object like the Sun, which has a radius of about 700,000 kilometers, and we're going to collapse that to a neutron star which has a radius of about ten kilometers.

The mass of the Sun is two times ten to the 30 kilograms, and for those of you who are good at math, they can calculate--

when you collapse this object without losing any mass, you keep all the mass, but you shrink it to ten kilometers--

how much gravitational potential energy is released? And that is a staggering number, and I call that delta u.

It is a loss of gravitational potential energy which is about ten to the 46 joules.

And this number is truly mind-boggling.

This is converted to kinetic energy and then it is converted to heat and all forms of radiation.

To give you a feeling for how absurdly large this number is, if you take the Sun and you take all the energy that the Sun produces in its ten billion years that it will live, the total energy output of the Sun is a hundred times less than this number, and this comes out in a matter of seconds.

So it is a mind-boggling idea that the Sun is producing in ten billion years, the lifetime of the Sun...

It is producing less energy than what happens during a stellar collapse to a neutron star.

Hundred times less.

So, when this in-fall occurs and this huge amount of energy is released, the outer layer bounces off the inner core and is expelled and that's what we call a supernova explosion.

The outer layers are thrown off with speeds typically some 10,000 kilometers per second.

Our Sun will not become a neutron star, but it will become a white dwarf.

We talked about the Crab Nebula last time, and the Crab Nebula is a remnant of a supernova explosion which occurred--

believe it or not--

on the Fourth of July in the year 1054.

Talking about fireworks.

The supernova explosion was noticed by Chinese astronomers.

They called this a guest star.

Chinese astronomers were very prestigious.

The reason for that was that these Chinese astronomers advised the emperor.

They looked at the sky and they derived from the sky information that was key for the emperor.

They knew how to interpret the occurrence of comets or, for instance, shooting stars, or a particular line-up of planets and certainly the appearance of a guest star.

And they would know that, for instance, a comet in a certain part of the sky might mean that there would be hunger or there would be diseases, there would be famine, or it would be a good time for a battle or it would be a bad time for a battle.

And that's what these people were doing.

They were advising the emperor and therefore they were keeping a very close eye on the sky.

No pun implied.

This star was visible for weeks during the day when it exploded, and it was the brightest star in the sky for years to come.

It is a complete puzzle why there isn't a single report by any European astronomer on the occurrence of the supernova of 1054.

It is very puzzling.

Now, you can argue that in the Netherlands and in England there are always clouds, it's always raining, so you can't see the sky--

okay, I grant you that.

But then we have Italy, and we have Spain and we have France.

And it is very strange.

It must have been a cultural thing.

Somehow in the 11th century, somehow, Europe was not interested in looking at the sky.

This is something they could not have missed, but they didn't write it down.

I now want to pursue the spin-up of this star when it collapses from 700,000 kilometers to ten kilometers.

If we round the numbers off a little bit, then the reduction in radius is about 100,000.

It's really only 70,000, but let's just make that 100,000, ten to the 5th.

That means R square goes down by a factor of ten billion.

And if R square goes down by a factor of ten billion, then the moment of inertia goes down by a factor of ten billion, and so omega must go up by a factor of ten billion.

If you started off with a star that rotated about its own axis in a hundred days, it ends up rotating around in one millisecond when it has become a neutron star.

A neutron star, ten kilometers.

It has about the same mass as the Sun, a little more.

And it spins around in one millisecond.

At the equator of the neutron star, you reach about 20% of the speed of light.

We know of hundreds of neutron stars in the sky.

Two of them have, in fact, rotational periods of 1.5 milliseconds--

many of them much slower--

and we discussed last time why that is.

Because remember, in the case of the Crab Pulsar, the pulsars slow down.

Nature is tapping on the rotational kinetic energy of these pulsars and is converting it into other forms of energy--

in the case of the Crab Pulsar, radio emission, optical emission, gamma rays, X rays and even jets.

The Crab Pulsar was slowing down every day 36.4 nanoseconds, which led to a staggering power output.

I still remember the number.

I think six times ten to the 31 watts.

In 75 years, the pulsar slows down by one millisecond, so the 33 milliseconds would become 34 milliseconds in 75 years.

If the star has an original...

There's no star, that was a disk, right? If the star has an original magnetic field which most stars do--

oh, I lost my star, but that's okay--

then in the collapse the magnetic fields will become stronger.

And this is something you will learn about in 8.02, why it becomes stronger.

So most of these neutron stars have strong magnetic fields and most rotate very fast.

And for reasons that we don't quite understand, many of them blink at us.

They blink at us in radio emission.

We believe that there are two beams of radio emission like a lighthouse going out from the two magnetic poles of the neutron star, and as the neutron star rotates and you are on Earth, if it sweeps over you you see radio emission, radio emission, you see nothing.

You see radio emission, you see radio emission.

So many pulsars whose beam doesn't sweep over the Earth we would never be able to see, of course.

And in the case of the pulsar in the Crab it is even more special, because that pulsar also blinks at us in the optical, in the X rays and in the gamma rays.

And so now I would like to show you some slides and discuss in a little bit more detail the supernova explosions and the fabulous light output and the spin-up, so I have to make it quite dark... make it completely dark.

There we go.

And so the first slide is simply an artist's conception--

don't take this too seriously--

of these beams of radio emission.

This is, then, the rotating neutron star, and if the axis of rotation doesn't coincide with the magnetic dipole axis, and if you have these radio beams--

which we do not understand how they are formed--

there you can see, when they rotate how they can sweep over you.

Now you may say, "Well, that's a little bit artificial, "because why would the axis of rotation be different from the magnetic dipole axis?" Well, that is not an exception at all in astronomy.

The Earth itself has a magnetic dipole axis which does not coincide with the axis of rotation.

In fact, almost all the planets in our planetary system have a magnetic dipole axis which makes a large angle with the axis of rotation, so that's the rule in astronomy, rather than the exception, even though it may not be easy to understand that.

And these blue lines, then, represent magnetic field lines.

You will see more of them than you like when you take 8.02.

And here is Jocelyn Bell.

Jocelyn Bell was a graduate student under Anthony Hewish in Cambridge, England, and she discovered pulsars.

She found in the radio data--

which were obtained using a new telescope that Anthony Hewish had built--

she found in there periodic signals--

pulses, if you want to call them--

you see some of them here at the bottom, and they were 1.3 seconds apart.

And she reported that to Anthony, and Anthony said, "Well, they've got to be nonsense, of course.

"I mean, there's not an object in the sky "that is going to give us pulses with a separation of 1.3 seconds." So they just assumed that it was caused by an elevator, by maybe milking cow machines or things of that nature, motorcycles... and so they did every conceivable thing to check whether, indeed, this was a man-made phenomenon.

But they could not find anything, and it was Jocelyn, through her incredible brilliance, who was able to convince Anthony that indeed this is an object that is in the sky and that the radiation doesn't come from the Earth.

And when they realized that, they realized that this would be the discovery of not only the century but of all of mankind, because they said, "Well, who could possibly send radio beams at us "and modulate them with a period of 1.3 seconds? Only intelligent life can do that." And so they called this first object "Little Green Man." But just before they published--

they discovered it in 1967, by the way--

they found a second pulsar which had a slightly different frequency than the 1.3 second period, and so then they realized ~that it was probably not intelligent life but that it was an astronomical object.

So they gave that second object the name "Little Green Man II," but they abandoned that idea very quickly.

Now comes the sad part of the story.

In 1974, Anthony Hewish was awarded the Nobel Prize for this discovery.

And Jocelyn, who more than deserved it, who really was the discoverer, who was the person who proved that this was astronomical, did not share in the Nobel Prize.

It is upsetting, it is sad.

I have discussed it with Jocelyn several times--

I know her quite well--

and she takes it actually very lightly, too lightly, I think.

Still, people feel unhappy about it and still, after so many years--

the Nobel Prize was awarded in 1974--

every time that I think about this magnificent discovery and I think about Jocelyn, I think about this gross injustice.

Here we see the Crab Nebula again, we've seen it before.

The red filaments that you see here are the result of matter that was blown off when the implosion occurred and when the outer layers bounced off the inner core.

And originally they had a speed of about 10,000 kilometers per second and by now--

it is about 1,000 years later--

these speeds have been reduced somewhat.

But here at the center you see the pulsar, and last time I showed you convincing evidence that this is the pulsar, because it's blinking at us.

It has a diameter of about seven light-years.

It is a distance from us of about 5,000 light-years.

In terms of angular size in the sky, it's about five arc minutes in size, which is about one-sixth of the angular diameter of the Moon.

This is a drawing, a cave drawing, made by Navajo Indians, and some people have speculated to what extent the Navajo Indians may have seen the supernova in 1054.

It's unclear, but it is a possibility.

The Moon certainly gets very close to the supernova, but it also gets very close to Venus, and so this is something that is not well established, but it is a possibility.

Here you see a galaxy in which a supernova occurred, and when the supernova occurs at its brightest, it can be brighter than all hundred billion stars in the galaxy.

That's how much energy is released in optical light.

You see that it is at least as bright as the entire galaxy.

From this picture to this picture is about one year.

This occurred in 1972 and over the period of one year, you can still see this star quite clearly, but it has diminished in strength quite a bit.

And then a great thing happened in February 1987, on the 23rd of February.

The supernova went off in the Large Magellanic Cloud, which is a satellite galaxy to our own galaxy.

It's a distance of about 150,000 light-years, and there was an astronomer who was observing in South America.

His name is Ian Shelton, and he left the dome to look at the stars and he decided to take a pee outside.

And as he was taking a pee--

these were his own words--

he looked at the Large Magellanic Clouds and he said, "Hey, that is funny! That star is not supposed to be there." And he was the discoverer of what is now known as 1987A, an enormous supernova going off so close to where we live.

And the next slide shows you the same portion of the Large Magellanic Clouds and you can clearly see that there is a very bright star.

He could see this with his naked eye.

This is a picture made by the Hubble Space Telescope of supernova 1987A.

The inner ring that you see is the result of matter that was thrown off by the star before it went into supernova explosion some 25,000 years earlier.

It expelled gas in its equator.

This is really a circle, although it looks like an ellipse because of the projection effect.

And this ring of matter moved out with a speed of about eight kilometers per second and it has a radius of about eight light-months.

And so eight months after the supernova explosion, the ultraviolet light and the X rays from the supernova caught up with this ring of matter and they excited it and it became visible.

Before the supernova explosion, this ring was not visible.

We are expecting in a few years that the matter itself that was thrown off with a much more modest speed of about 10,000 kilometers per second...

that that matter will also plow into this ring and then we expect some real fireworks again.

There is no explanation that people agree upon for these two called "hourglass" rings.

They are quite mysterious and there are papers written on it and people disagree on their origin.

Supernovae explosions in our galaxy and in the Large Magellanic Clouds are quite rare.

We expect no more than about one in a hundred years.

The previous one that could be seen with the naked eye was in the year 1604.

It's called Kepler supernova.

And 1987A was really the first that could be studied with modern equipment--

radio observatories, X-ray observatories in orbit around the Earth.

With some luck, you may see a supernova explosion naked eye in your life.

The chance is no better than ten percent, so maybe it will help if occasionally you take a pee outside and you become as famous as Ian Shelton did, who is now a very famous man.

See you Monday.