The beginnings of physics

Astronomy 101
Syracuse University, Fall 2019
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October 8, 2019

Announcements

- The prelab for this week originally contained an error; I've fixed it now
- The next paper will be assigned in a week or so, and will be due three weeks after that
- **Our Exam 2 is next Thursday**

Exam 2 is next Thursday. Reminders:

- You may bring a single-sided page of notes, as before
- I'll be holding an extra review on Monday from 2PM-5PM
- Last year's Exam 2 is posted; the answer key will be posted Monday
- The study guide is posted, too

The story so far

Kepler realized that all the planets moved in elliptical orbits, and described their properties.

He didn't know *why* they moved like that, only that they did.

Isaac Newton uncovered fundamental laws that (when combined with mathematics) explained *why* they move in ellipses.

Today, we will:

- Explore a little more of the physical science of motion
- Talk about how Newton's laws of motion connect to astronomy
- See why the mass of a planet doesn't matter for its motion

Newton's four ideas

1. The law of gravity: all objects attract each other
2. The first law of motion: without a force, objects keep moving with the same velocity
3. The second law of motion: forces make objects accelerate (change their velocity)
4. The third law of motion: forces come in pairs

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Two of these are more important to us than the others...

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The force of gravity

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G is just a number telling how strong gravity is: about a ten-billionth of the weight of an apple for two kilogram objects a meter apart.

I know the earth, moon, stars, etc. are moving, but [is] the Milky Way Galaxy also moving? In which direction? ... Towards where? How does the whole universe travel?

–Chris Ruan

If we are "free falling around the sun (in orbit)" does that mean our solar system is free falling around something bigger? And so on? Or are we suspended in a constant frozen place with the sun?

–Ryan Yon

I read somewhere that our solar system is moving through the universe in a helix... is this true? And if so, how does this work?

–Shannon Kirkpatrick

Newton's first law

What happens to a ship at sea whose engines die?

A: It comes to a stop

B: It keeps going forward until it hits something

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On Earth things come to rest only because of the forces of friction. (Aristotle was wrong!)

In space we don’t have these, so things “coast” forever without another force to change their motion.

Newton's biggest idea: the second law of motion

"Forces cause objects to accelerate"

$$F = ma$$

$$F/m = a$$

"The strength of a force, divided by the mass of the thing it acts on, gives that thing's acceleration"

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More generally, gravity causes the same change in motion on all objects, regardless of their mass.

Why?

Remember:

- The law of gravity lets us figure out the force that a mass M (like the Sun) exerts on another mass m (like a planet)
- Newton's second law lets us figure out how that force causes that mass m to accelerate.

Suppose I have two satellites next to each other orbiting the Earth at a distance r. The small one has a mass m_A; the big one has mass m_B; the Earth has mass m_E.

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Suppose I have two satellites next to each other orbiting the Earth at a distance r. The small one has a mass m_A; the big one has mass m_B; the Earth has mass m_E.

What is the force of gravity ("weight") on satellite B from the Earth?

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The *force* that they feel depends on their own masses. How does this change how they move?

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What is the acceleration of satellite A because of the Earth's gravity?

Newton's second law: $F = ma \rightarrow a = F/m$

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The mass of the satellite cancels from the equation!

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The mass of the satellite *doesn't affect* how Earth's gravity makes it move!

Acceleration

Acceleration has a direction; it can increase, decrease, or redirect an object's velocity:

- Apply engine power to a car going East: force to the East $\rightarrow$ it goes East faster
- Apply brakes to a car going East: force to the West $\rightarrow$ it goes East more slowly
- Turn steering wheel left: force to the North $\rightarrow$ car starts traveling Northeast

(illustration on document camera)

What does acceleration do?

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Velocity causes changes in an object's position.

Using the mathematics of changes (calculus), you can work out *everything* about how an object moves this way!

Suppose two asteroids are floating out in space. Asteroid A is twice as massive as asteroid B.

If the force of A's gravity on B is ten tons, the force of B's gravity on A will be...

A: 5 tons

B: 10 tons

C: 20 tons

D: 40 tons

The solution

Let's look at that expression again:

$$F_{\text{grav}} = \frac{Gm_1m_2}{r^2}.$$

(Remember, r is the distance between the objects)

Notice that switching m_1 (one asteroid) and m_2 (the other) in this expression doesn't affect the result!

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"For every action there is an equal and opposite reaction": if the Earth's gravity pulls me down with a force of 160 pounds, I pull *up on the Earth* with the same force of 160 pounds.

Suppose two asteroids are floating out in space, 20 miles apart. Asteroid A is twice as massive as asteroid B, and the force of A's gravity on B is 20 tons.

Suppose I now move the two asteroids further apart, so they're 40 miles apart. What will the force of A's gravity on B be now?

A: 5 tons

B: 10 tons

C: 20 tons

D: 40 tons

E: 80 tons

The solution

Recall:

$$F_{\text{grav}} = \frac{Gm_1m_2}{r^2}.$$

If I increase the distance between the asteroids by a factor of 2, then I increase the denominator of this fraction by a factor of ________, which will ________ the whole fraction by a factor of ________.

Complete *Lecture Tutorials pp. 29-32.*

We will do something else after this.

Newton's third law of motion

Newton's third law says that if object A exerts a force on object B, object B exerts the same force back on A.

This is easily apparent from the form of the gravitational law:

$$F_g = \frac{G m_A m_B}{r^2}$$

The math doesn't distinguish between "the object pulling" and "the object being pulled": the force is the same on both ends.

Consider the gravity between the Earth and the Moon:

- The gravitational force is the same on both objects

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Consider the gravity between the Earth and the Moon:

- The gravitational force is the same on both objects
- ... but this force causes a greater acceleration on the Moon, because its mass is smaller

(I wrote this slide last year)

Student A: “Kepler’s laws say that the planets orbit around the Sun in elliptical orbits, with the Sun fixed at one focus of the ellipse. The Sun doesn’t move.

Student B: “But the laws of gravitation say that if the Sun pulls on the planets, which it must in order to hold them in their orbits, the planets must pull back on the Sun. This pull makes the Sun accelerate, so it has to wobble a bit.”

Who’s right?

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Who’s right?

Student A: “Why don’t we see the wobble, then, if the force pulling on the Sun is the same as the force pulling on the planets?”

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Student A: “Why don’t we see the wobble, then, if the force pulling on the Sun is the same as the force pulling on the planets?”

A: The gravitational forces from all the planets on the Sun cancel each other out

B: The planets are so far away that the force they exert on the Sun is small

C: The Sun’s mass is so big that this amount of force doesn’t affect it that much

D: We *do* see this wobble, if we look closely enough

Someone else might see it, too...

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Someone else might see it, too... and “listen” to it ... **and win a Nobel Prize for it...**

How does this create circular motion?

Without a force, things travel in straight lines at constant speeds (Newton's first law).

It requires a force *directed toward the center* to hold something in circular motion.

Let's demonstrate and watch this.

What about elliptical orbits?

For gravity, the force depends on the distance from the center, as you know.

The particular mathematics that produces ellipses is too hard for our pencils. But our computers can do it!

To make our simulator, all I did was program $F = \frac{GMm}{r^2}$ and $F = ma$ into my computer and make it do the math for me! (This is next week's homework in my other class!)

How far can we take this?

https://www.youtube.com/watch?v=W-csPZKAQc8

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The only difference between this and what you will do in lab is the number of objects!

Gravitation

$$F_g = \frac{G m_1 m_2}{r^2}$$

- All objects attract all other objects
- The force is proportional to the product of the masses...
- ... divided by the squared distance between their centers.

Second law of motion

$$a = F/m$$

- Forces make objects accelerate
- The acceleration is in the direction of that force...
- ... and is equal to the size of the force divided by that thing's mass.

Gravity tells us the forces on all objects in space; the second law of motion tells us how that causes them to move. From this, and a little math, you can predict everything about their motion.