The conservation of energy

Astronomy 101
Syracuse University, Fall 2020
Walter Freeman

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Understanding is, after all, what science is all about — and science is a great deal more than mindless computation.

–Roger Penrose

Announcements

The final draft of your first paper is due at the end of the day today.

If you were seeking feedback and didn't get any, come to my discussion hours today (4-5:30) on the steps of Hendricks or on Zoom. If we discuss modifications that you won't have time to make in full, we can discuss extra time.

Project 3 will be assigned tomorrow. You will have a week and a half or so to do it from the date that it is assigned, so don't worry.

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Three folks won the Nobel Prize for work on black holes!

Roger Penrose | Reinhard Genzel | Andrea Ghez

Einstein's theory of general relativity relates the presence of matter or energy to the curvature of spacetime.

Penrose, whose background straddles mathematics and physics, showed mathematically that enough matter and energy together in one place should form a black hole according to Einstein's equations.

Genzel and Ghez used fancy imaging techniques to look at the center of the Milky Way. This is very hard to do, since dust in the Milky Way blocks visible light. They looked at infrared light which penetrates dust better, and used the giant Keck Telescope to take extremely high resolution pictures, and used "adaptive optics" to get a clear image through Earth's atmosphere.

There, they saw stars orbiting something *very rapidly* – since 1995, one star has even made a complete orbit!

Their detailed images could be used with Kepler's third law to calculate the *mass* of the thing at the center of the Solar System, and discovered that it has a mass of 4 million suns.
... a supermassive black hole!

Black holes

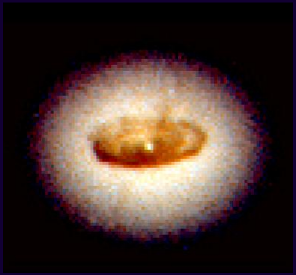
A black hole is a place where matter is so dense that its gravity becomes strong enough that light can't escape.

The black hole is surrounded by a boundary called the *event horizon*, which delinates the region from which light can't escape.

Anything that gets near a black hole orbits it, like the planets orbit the Sun. But:

- Friction between these bits of dust does negative work on them, reducing their velocity
- This reduces their kinetic energy, so gravity pulls them closer to the black hole
- This does positive work on them (see our exam!), speeding them back up.
- As they get closer and closer, they get hotter and hotter, and glow brighter and brighter

The event horizon can be surrounded by a glowing disk of gas at millions of degrees.



(Hubble image of a very bright accretion disk)

(Artist's rendering, if the BH didn't bend its own light)

Black holes

There are two types of black holes:

- Ones that form from the dead cores of huge stars (mass of a few times that of our Sun)
- Ones that form from the junk that falls to the center of a galaxy (mass billions of times larger)

This famous image is of a supermassive black hole around 50 million light years away, at the core of a galaxy called M87. (The Nobel was for images of stars orbiting the center of our galaxy, not of the black hole itself.)

This is exciting because it's an image of the *actual event horizon*, not just the *accretion disk*.

Interferometry

The smallest angular size you can make out in a picture is given by:

$$\theta = \frac{\text{wavelength of light}}{(\text{size of lens})}$$

So, to get a detailed picture, you need to measure very short wavelengths with a very big aperture (lens/mirror size).

Your "aperture" is just the region over which you can correlate the *phase* (whether a wave is going up or down at any given time) at different points.

If you can do that by another means (by making a machine that detects phase as well as the presence of light), you can count different observing stations as part of the same aperture.

This process is called "interferometry" or "synthetic aperture imaging".

Interferometry

This gets harder as the frequency goes up, since the wave switches from "up" to "down" faster.

Also: frequency is inversely proportional to wavelength.

Remember that we need a combination of *large aperture* and *short wavelength* (meaning high frequency) to get a detailed picture.

The Very Large Array, a synthetic aperture radio "telescope", in New Mexico. The telescopes are on railroad tracks to allow operators to customize the aperture shape.

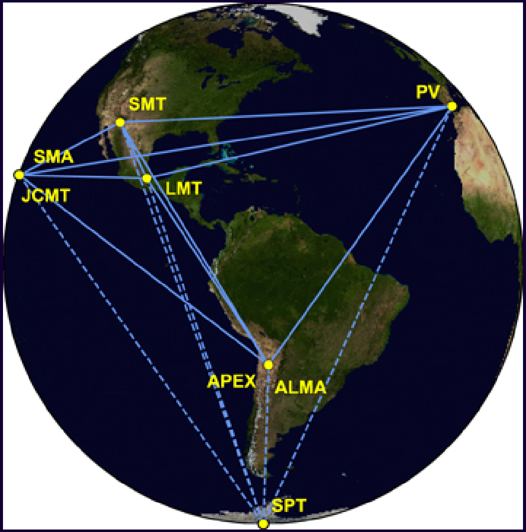
The problem:

- The very shortest wavelengths (x-rays, γ-rays) don't bend in lenses or bounce off mirrors well
- Mid-range wavelengths (like light) are long enough that it's hard to make a clear picture without a physically huge aperture, but have frequencies too fast to do interferometry
- Radio waves have a slow enough frequency to do interferometry, but have too long of a wavelength to get a clear picture even with an enormous synthetic aperture

The Event Horizon Telescope

The solution, allowing the Event Horizon Telescope to observe extremely fine detail:
(Remember: we want a large aperture and short wavelength/high frequency)

- Combine data from radio telescopes across the hemisphere
- This gives an enormous synthetic aperture
- Develop very accurate ways to measure and correlate phase over long distances (timing equipment)
- Measure at very high frequencies (a few thousand times FM radio)
- You now have a radio telescope the size of Earth, measuring very short wavelengths

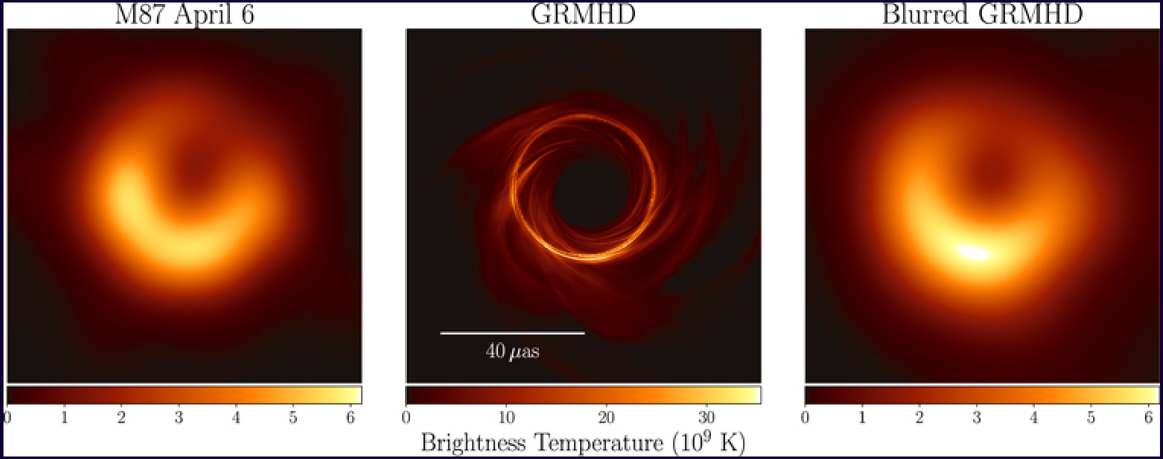


The Event Horizon Telescope

Since this is a synthetic aperture, doing the data processing is hard.

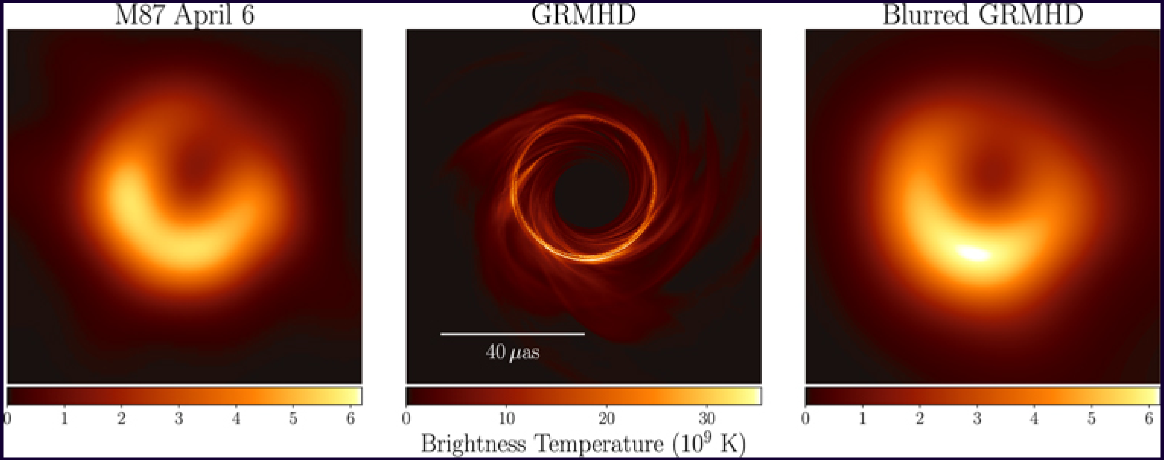
Imagine using a camera with the whole lens blacked out, except for a few tiny pinholes, and that's constantly spinning!

Some very clever folks had to develop new math and algorithms for image analysis and reconstruction to do this... but here's the result:



(Left: Image from the Event Horizon Telescope. Center: Simulation of what it would look like. Right: The simulation, blurred to match the resolution of the EHT.)

Why this is a big deal



We've never seen a black hole before.

The light coming from the region near the event horizon is bent by the gravity of the black hole itself. (This is why the central region is black.)

This gives us a picture of both the gas falling into a black hole, *and the gravity around a black hole.*

Last time

We saw last time that Newton's two big ideas let us predict the motion of all the planets.

Newton's second law

$$F = ma \text{ or } a = F/m$$

Tells us the size of the acceleration created by any force

Gravitation

$$F_g = \frac{Gm_Am_B}{r^2}$$

Tells us how big the gravitational force is between two objects A and B whose centers are a distance r apart

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Kepler knew that there were underlying causes of his laws, but he wasn't good enough at math to discover them. Can we do better than Kepler? Can we find *general principles of physics* that give us insight without needing hard math?

The conservation of energy

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Energy comes in two kinds:

- Kinetic energy: the motion of objects
    - Heat, light, and sound energy are technically kinds of kinetic energy, but we usually call them by those names instead
- Potential energy: objects are in a place where they are attracted to each other
    - If I let them go, they'll move toward each other
    - *Potential* to become kinetic energy
    - Chemical energy is a kind of potential energy
    - The one we really care about is *gravitational potential energy*

The big idea: conservation of energy

Energy can never be created or destroyed.
It can only be changed from one form to another.

A pendulum swings back and forth: it converts gravitational potential energy to kinetic energy and back again.

This perspective is universal: all forces just convert energy from one sort into another

A short history of some energy:

- Hydrogen in the sun fuses into helium
- Hot gas emits light
- Light shines on the ocean, heating it
- Seawater evaporates and rises, then falls as rain
- Rivers run downhill
- Falling water turns a turbine
- Turbine turns coils of wire in generator
- Electric current ionizes gas
- Recombination of gas ions emits light

- Nuclear energy $\rightarrow$ thermal energy
- Thermal energy $\rightarrow$ light
- Light $\rightarrow$ thermal energy
- Thermal energy $\rightarrow$ gravitational pot. energy
- Gravitational PE $\rightarrow$ kinetic energy and sound
- Kinetic energy in water $\rightarrow$ KE in turbine
- Kinetic energy $\rightarrow$ electric energy
- Electric energy $\rightarrow$ chemical potential energy
- Chemical PE $\rightarrow$ light

A pendulum, revisited

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... what happens to its *total* energy?

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Conservation of energy, in general

Conservation of energy is *the biggest idea in science.*

Even if you can't track precisely how something moves, you can figure out a *lot* just from tracking the flow of energy.

Here's an example: Let's calculate how much food I need to eat to climb a mountain on a hot day, and how much water I will sweat out when I do that.

Things we need to know:

- Near Earth's surface, gravitational potential energy is about 2.5 calories (10 joules) per kilogram per meter.
- The mountain has a height of 1000 meters
- I and my stuff have a mass of 80 kilograms
- My muscles are 20% efficient at converting food into mechanical energy

Conservation of energy, for the Sun

One question we had for a long time: *how old are the Earth and the Sun?*

Maybe the source of the Sun's energy is the gravitational energy of the gas that makes it up!

- The matter in the Sun collapses under its own gravity
- As it "falls" it converts that gravitational potential energy into heat
- That heat is converted into light (we'll learn how in a few weeks)
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But we can work out how long this could sustain the Sun:

- We know the rate that the Sun converts heat into light ("how many joules per year")
- We know how much gravitational potential energy the Sun has
- Do some math:

$$\text{(lifespan of Sun in years)} = \frac{\text{(amount of potential energy, in joules)}}{\text{(rate of using energy, in joules per year)}}$$

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The answer: a few hundred thousand years.
This can't be why the Sun shines!