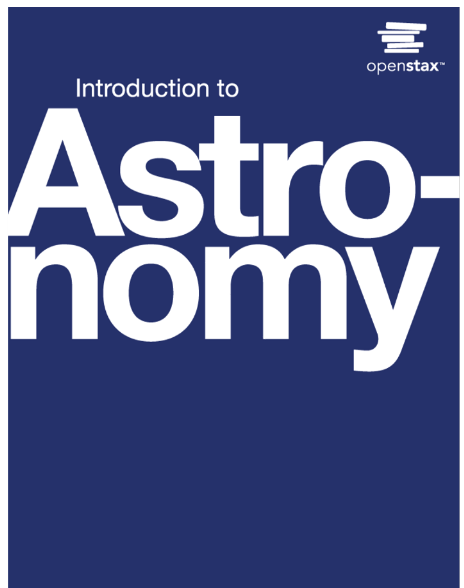
ASTRONOMY

Chapter 24 BLACK HOLES AND CURVED SPACETIME



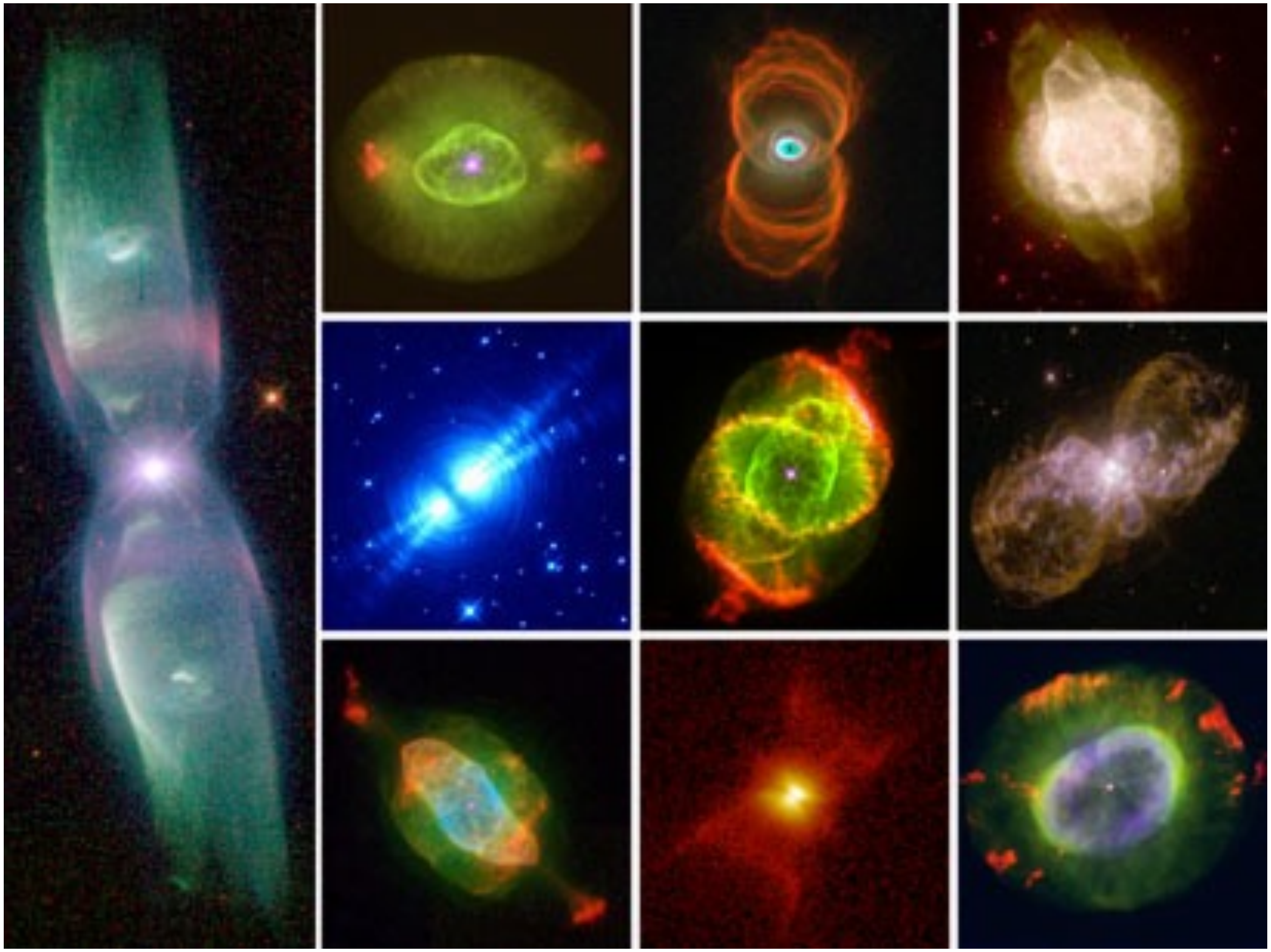
STELLAR CORPSES

Stars of different masses leave different types of stellar corpses.

Low-mass stars like the Sun leave behind white dwarfs.

Higher-mass stars die in the massive explosions called supernovae, leaving behind neutron stars or black holes.

PLANETARY NEBULAE



http://www.astro.washington.edu/users/balick/WFPC2/

POST MAIN SEQUENCE LIFE OF THE SUN

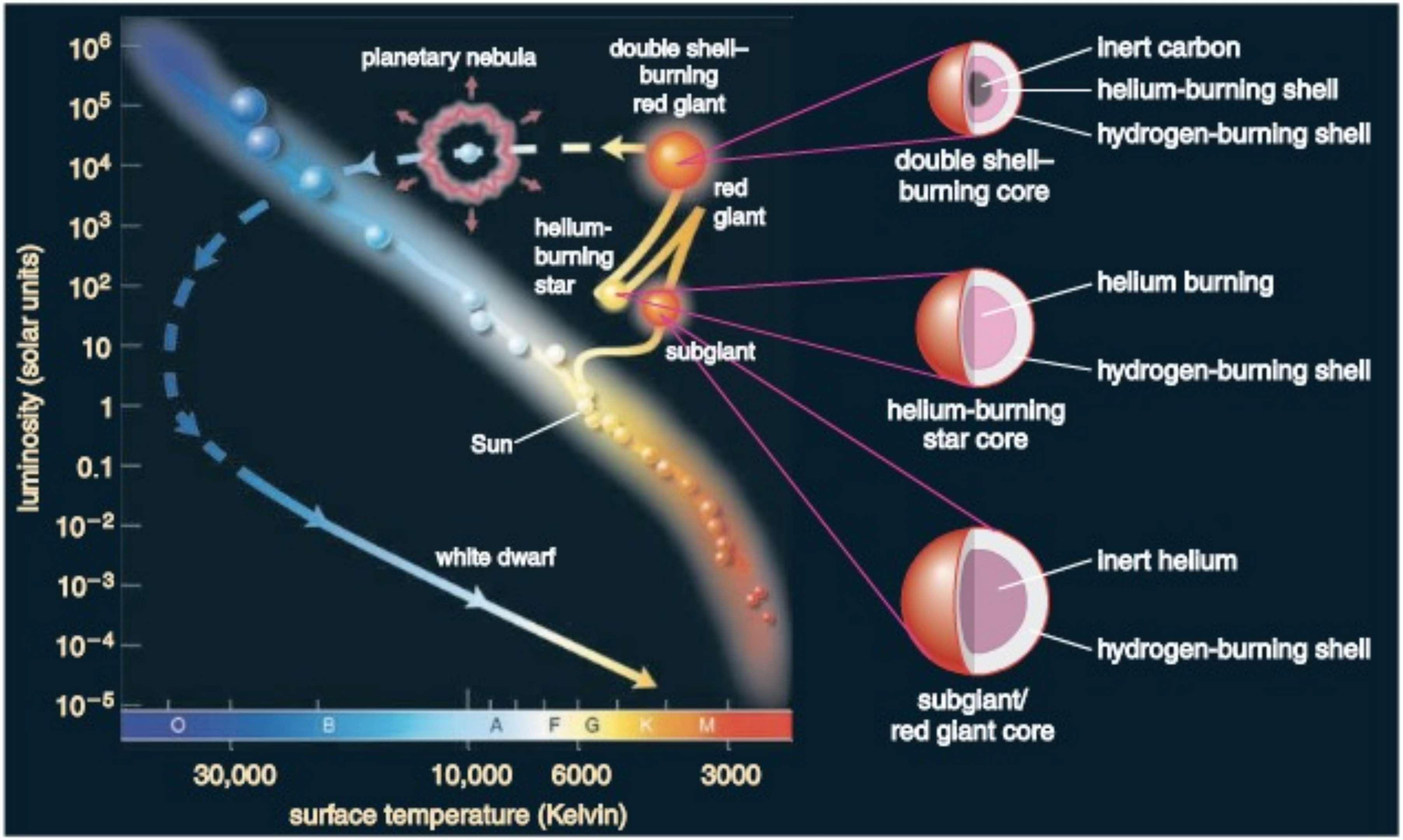


Figure 9.11. Page 151. ***The Cosmic Perspective Fundamentals.***
Publisher: Addison-Wesley. © 2010

WHITE DWARF

A white dwarf is essentially the exposed core of a low-mass star that has died and shed its outer layers in a planetary nebula.

It is quite hot when it first forms, because it was recently the inside of a star, but slowly cools with time.

White dwarfs are stellar in mass but small in size (radius), which is why they are generally quite dim compared to stars like the Sun.

However, the hottest white dwarfs can shine brightly in high-energy ultraviolet and X-ray light.

WHITE DWARF COMPOSITION

Because a white dwarf is the core left over after a star has ceased nuclear burning, its composition reflects the products of the star's final nuclear-burning stage.

The white dwarf left behind by a 1 Msun star will be made mostly of carbon, since stars like the Sun fuse helium into carbon in their final stage of life.

WHITE DWARF DENSITY

Recall that Earth is smaller than a typical sunspot, then imagine that packing the entire mass of the Sun into the volume of Earth.

The density of a white dwarf is so high that a teaspoon of its material would weigh as much as a small truck if you could bring that material to Earth.

MORE MASSIVE WHITE DWARFS ARE SMALLER

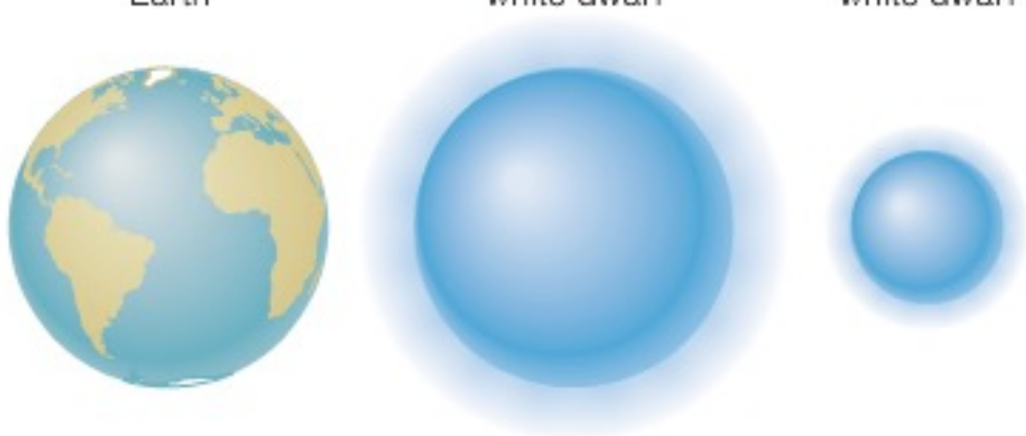


Figure 10.2 | More massive white dwarfs are actually *smaller* (and thus denser) than less massive white dwarfs. Earth is shown for scale.

Figure 10.2. Page 163. ***The Cosmic Perspective Fundamentals.***
Publisher: Addison-Wesley.

THE WHITE DWARF LIMIT

The fact that electron speeds are higher in more massive white dwarfs leads to a fundamental limit on the maximum mass of a white dwarf.

Theoretical calculations show that electron speeds would reach the speed of light in a white dwarf with a mass of about 1.4 times the mass of the Sun .

Because neither electrons nor anything else can travel faster than the speed of light, no white dwarf can have a mass greater than this white dwarf limit

- called the Chandrasekhar limit, after its discoverer.

ACCRETION ONTO A WHITE DWARF

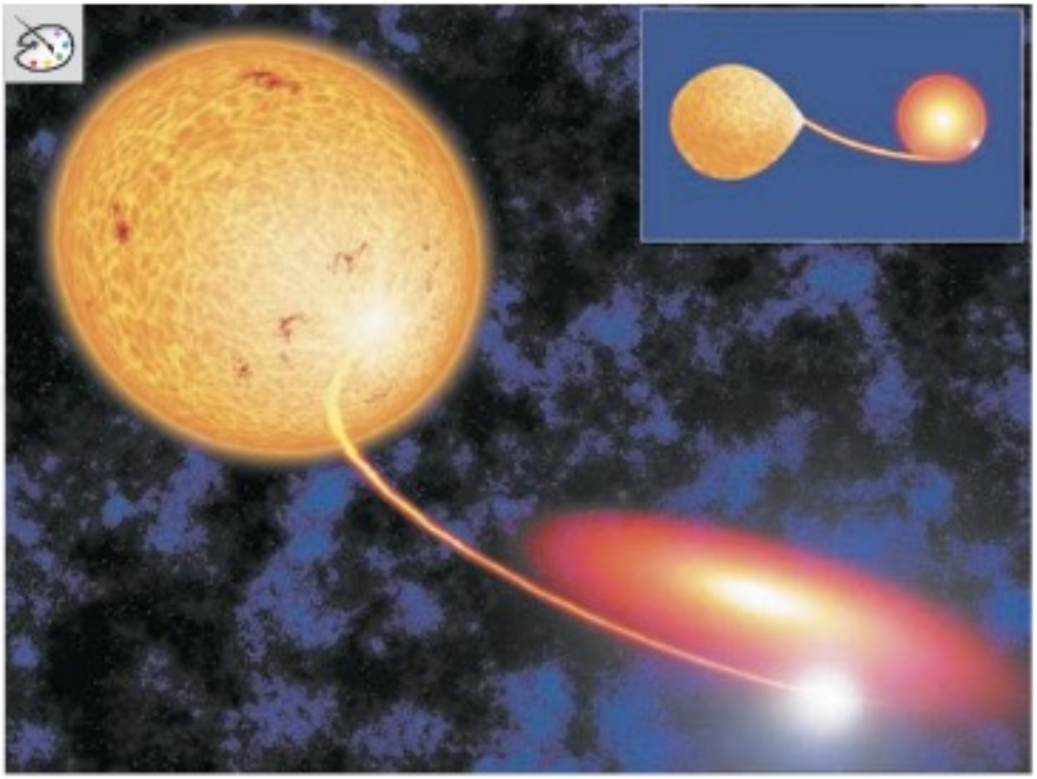


Figure 10.3 | This artist's conception shows how mass spilling from a companion star (left) forms an accretion disk (right) around a white dwarf (at the center of the disk). The inset shows how the system looks from above rather than from the side.

Figure 10.3. Page 164. ***The Cosmic Perspective Fundamentals.***
Publisher: Addison-Wesley. © 2010

NOVAE

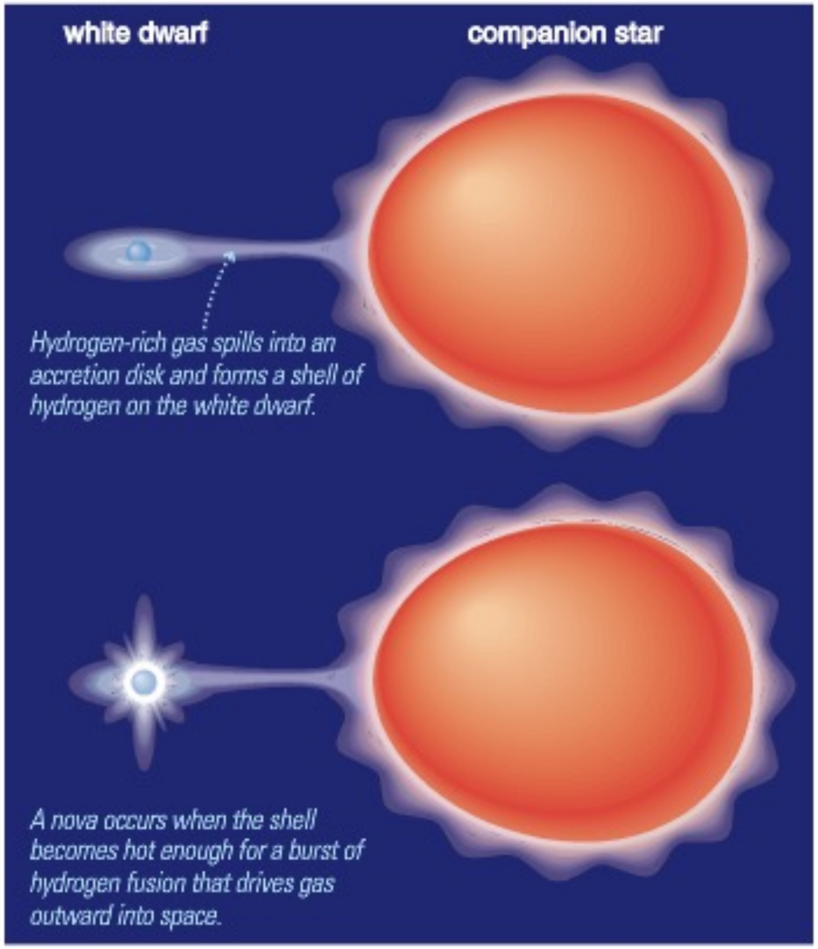


Figure 10.4 | A nova occurs when hydrogen fusion ignites on the surface of a white dwarf in a binary star system.

Figure 10.4. Page 164. ***The Cosmic Perspective Fundamentals*****.**
Publisher: Addison-Wesley. © 2010

WHITE DWARF SUPERNOVAE

Accretion in binary adds mass to WD

If mass becomes greater than the Chandrasekar Limit, leads to WD SN explosion!

Can easily distinguish from SN that results from a massive star’s death, because WD SN has no hydrogen lines and a different light curve.

A NEUTRON STAR

Essentially a ball of neutrons created by the collapse of a high-mass star’s iron core in a massive star supernova.

Typically just 10 kilometers in radius yet more massive than the Sun, neutron stars are like giant atomic nuclei made almost entirely of neutrons and held together by gravity.

Like white dwarfs, neutron stars resist the crush of gravity with the degeneracy pressure that arises when particles are packed as closely as nature allows.

In the case of neutron stars, however, it is neutrons rather than electrons that are closely packed, so neutron degeneracy pressure supports them against the crush of gravity.

NEUTRON STARS IN BINARY SYSTEMS

Like white dwarfs, neutron stars in close binary systems can produce brilliant bursts of fusion as gas overflowing from a companion star creates a hot, swirling accretion disk.

However, in the neutron star’s extremely strong gravitational field, infalling matter releases an amazing amount of gravitational potential energy.

- Dropping a brick onto a neutron star would liberate as much energy as an atomic bomb.

BINARIES WITH NEUTRON STARS

Close binaries with neutron stars emit 100,000 times as much energy in X rays as our Sun emits in all wavelengths of light combined, so we call them X-ray binaries.

Like accreting white dwarfs that occasionally erupt into novae, accreting neutron stars sporadically erupt with a pronounced spike in luminosity.

AN X-RAY BURST

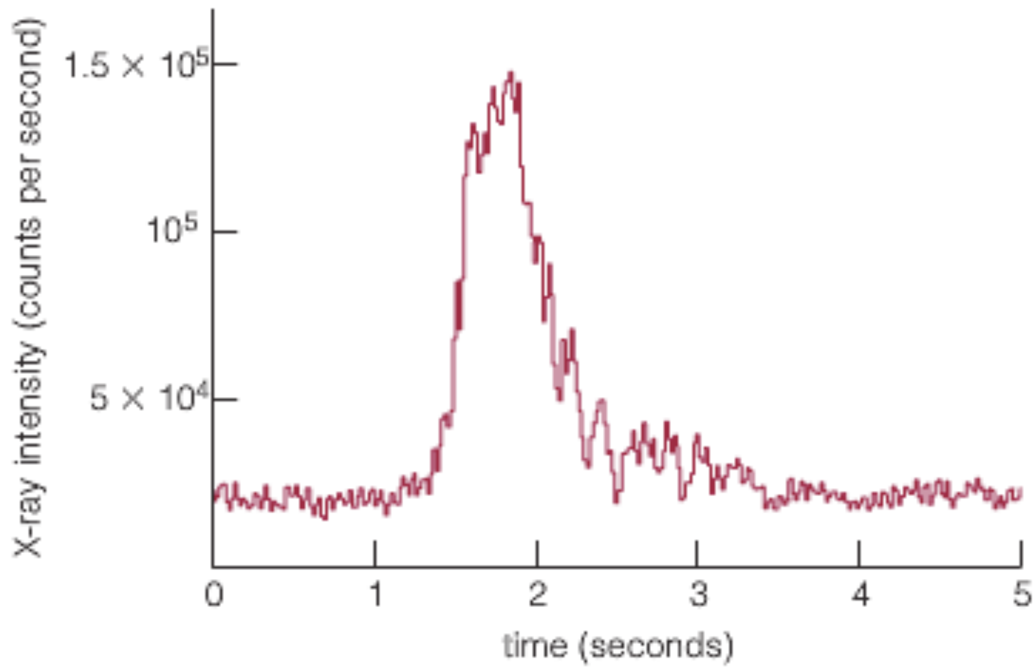


Figure 10.10 | Light curve of an X-ray burst. In this particular burst, the X-ray luminosity of the neutron star spiked to over 6 times its usual brightness in a matter of seconds.

Figure 10.10. Page 168. ***The Cosmic Perspective Fundamentals*.**
Publisher: Addison-Wesley.

BLACK HOLES

Sometimes, the gravity of a stellar corpse becomes so strong that nothing can prevent it from collapsing under its own weight.

The stellar corpse collapses without end, crushing itself out of existence and forming a black hole.

WHAT ARE BLACK HOLES?

The basic idea behind a black hole originated near the end of the 18th century.

Newton’s laws of motion and gravity were well known by that time, and scientists were starting to think about the force of gravity at the surface of an object with a large amount of mass but a small radius.

In particular, they wondered whether the gravity of such an object could be so strong that nothing, not even light, could escape its gravitational pull.

ESCAPE VELOCITY

The escape velocity from Earth's surface is about 11 km/s.

This is the minimum speed required to escape Earth's gravity for any object that starts near Earth's surface.

If we could make Earth smaller while keeping its mass the same: making Earth more compact would raise the escape velocity, because the strength of gravity at Earth's surface depends on the inverse square of its radius.

If we could squeeze Earth down to about the size of a golf ball, its escape velocity would reach the speed of light.

COLLAPSE

Extreme squeezing can happen inside a massive star when its iron core reaches white dwarf limit = 1.4 M_{sun}

Electron degeneracy pressure cannot resist gravity above that mass, and the core collapses to form a neutron star, causing a supernova explosion.

Calculations show that the mass of a neutron star has a limit that lies somewhere between about 2 and 3 M_{sun}. Above this mass, neutron degeneracy pressure cannot hold off the crush of gravity in a collapsing stellar core.

BLACK HOLES IN BINARY SYSTEMS

Strong observational evidence for black holes formed by supernovae comes from studies of X-ray binaries.

Recall that the accretion disks around neutron stars in close binary systems can emit strong X-ray radiation, making an X-ray binary. The accretion disk forms because the neutron star's strong gravity pulls in mass from the companion star.

Because a black hole has even stronger gravity than a neutron star, a black hole in a close binary system should also be surrounded by a hot, X-ray-emitting accretion disk.

In other words, an X-ray binary might contain either a black hole or a neutron star. We can learn which type of corpse resides in an X-ray binary by measuring the object's mass.

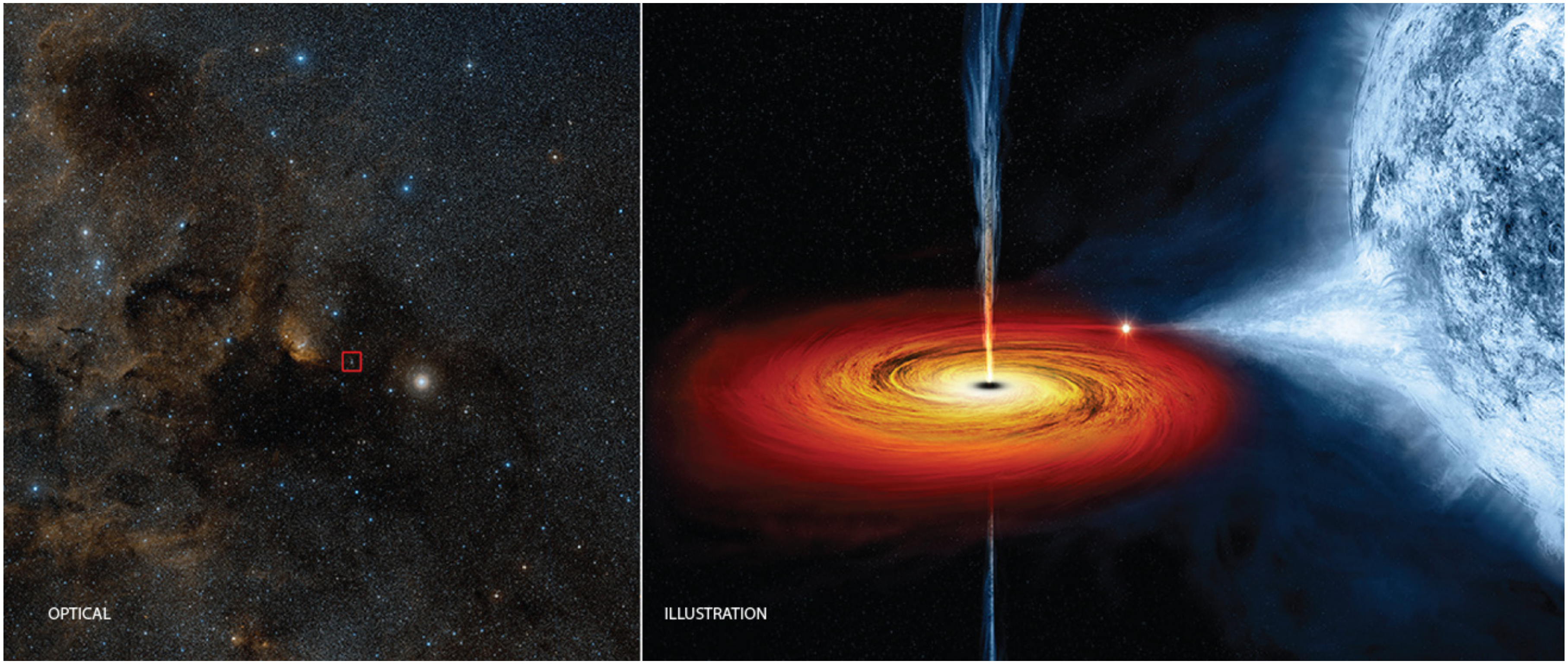
AN X-RAY BINARY CALLED CYGNUS X-1

This system contains an extremely luminous star with an estimated mass of 18 solar masses. Based on Doppler shifts of its spectral lines, astronomers have concluded that this star orbits a compact, unseen companion with a mass of about 10 solar masses.

The mass of the invisible accreting object clearly exceeds the neutron star limit of about 3 solar masses. It is therefore too massive to be a neutron star, so by current thinking it must be a black hole.

A few dozen other X-ray binaries offer similar evidence for black holes formed from the collapse of massive stellar cores.

FIGURE 24.1



Stellar Mass Black Hole. On the left, a visible-light image shows a region of the sky in the constellation of Cygnus; the red box marks the position of the X-ray source Cygnus X-1. It is an example of a black hole created when a massive star collapses at the end of its life. Cygnus X-1 is in a binary star system, and the artist's illustration on the right shows the black hole pulling material away from a massive blue companion star. This material forms a disk (shown in red and orange) that rotates around the black hole before falling into it or being redirected away from the black hole in the form of powerful jets. The material in the disk (before it falls into the black hole) is so hot that it glows with X-rays, explaining why this object is an X-ray source. (credit left: modification of work by DSS; credit right: modification of work by NASA/CXC/M.Weiss)

FIGURE 24.2

Albert Einstein (1879–1955). This famous scientist, seen here younger than in the usual photos, has become a symbol for high intellect in popular culture. (credit: NASA)

TWO THEORIES

Special Relativity 1905

- No accelerations
- “Inertial Frames”

General Relativity 1916

- Describes a geometric theory of gravitation

SPECIAL RELATIVITY.

Two things in the universe are absolute

- The laws of nature are the same for everyone.
- The speed of light is the same for everyone.

THE LAWS OF NATURE ARE THE SAME FOR EVERYONE

This statement implies that no one can claim to be standing absolutely still, because the only kinds of motion that matter to the laws of nature are relative motions of one object with respect to another.

Otherwise, observers moving through space at different speeds would disagree about the laws of physics.

There are no preferred frames of reference.

ON THE ELECTRODYNAMICS OF MOVING BODIES BY A. EINSTEIN JUNE 30, 1905

….unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest.

We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity *c* which is independent of the state of motion of the emitting body.

These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies.

The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor assign a velocity-vector to a point of the empty space in which electromagnetic processes take place.

http://www.fourmilab.ch/etexts/einstein/specrel/www/

THE SPEED OF LIGHT IS THE SAME FOR EVERYONE

This statement is much more surprising.

From our everyday experience, we expect speeds to add and subtract.

If you watched someone throw a ball forward from a moving car, you'd see the ball traveling at the speed at which it was thrown plus the speed of the car.

But if a person shined a light beam from a moving car, you'd see it moving at precisely the speed of light (about 300,000 kilometers per second), no matter how fast the car was going.

This strange fact has been experimentally verified countless times.

http://upload.wikimedia.org/wikipedia/commons/0/00/Michelson-Morley_Experiment_Plaque.JPG

THE

AMERICAN JOURNAL OF SCIENCE.

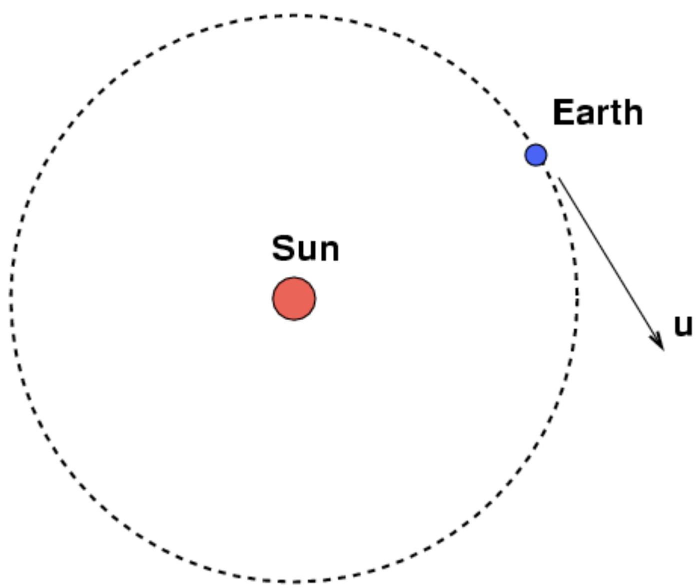
[THIRD SERIES.]

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

http://spiff.rit.edu/classes/phys200/lectures/mm_results/mm_results.html

THE (INCORRECT) IDEA BEHIND THE MICHELSON-MORLEY EXPERIMENT

As the Earth orbits around the Sun, it must run through the ether. That will cause an "ether wind" w near the Earth's surface, blowing in the direction opposite to the Earth's motion u.



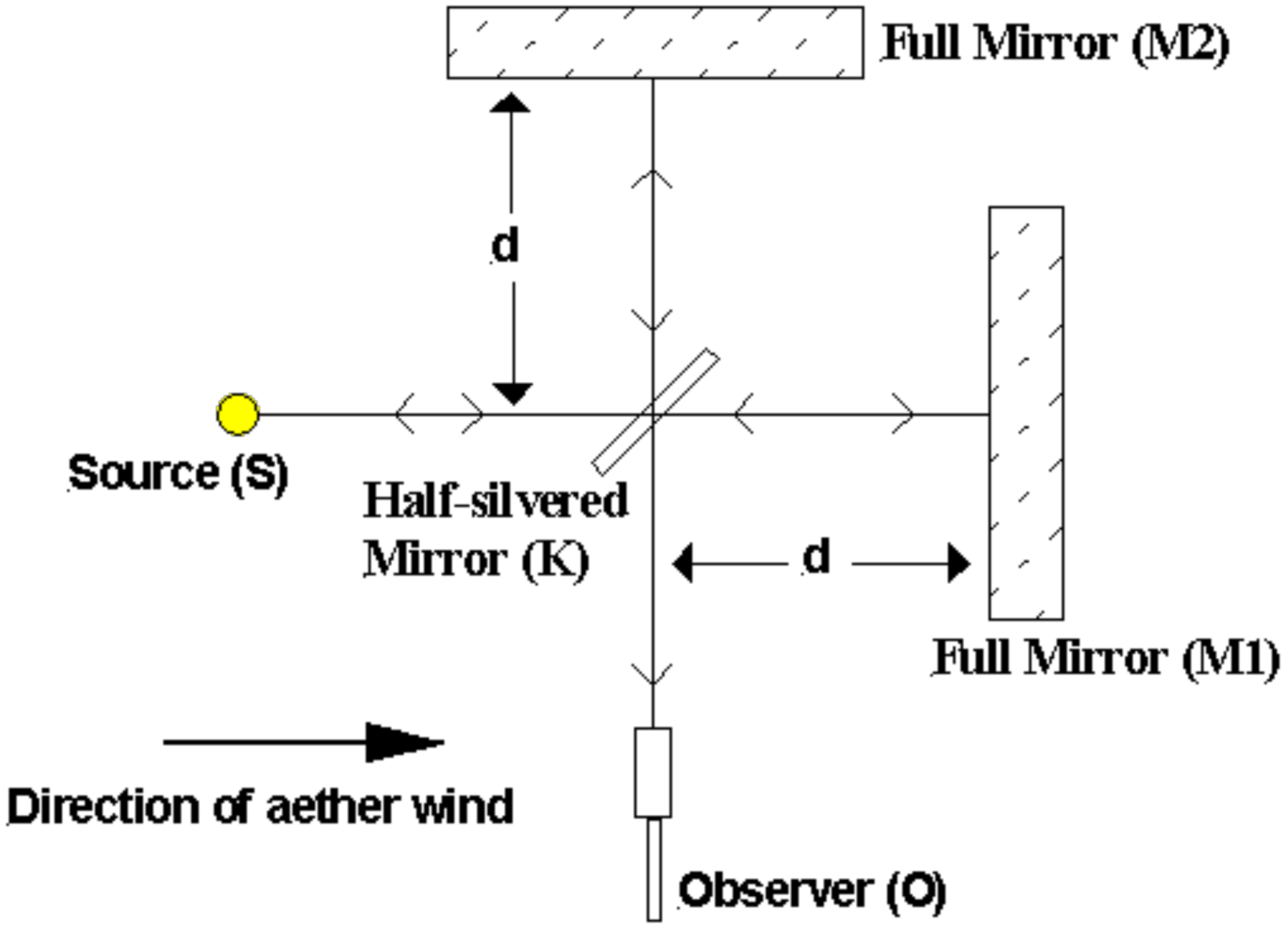
http://spiff.rit.edu/classes/phys200/lectures/mm_results/mm_results.html

DESIGN OF MICHELSON-MORLEY EXPERIMENT

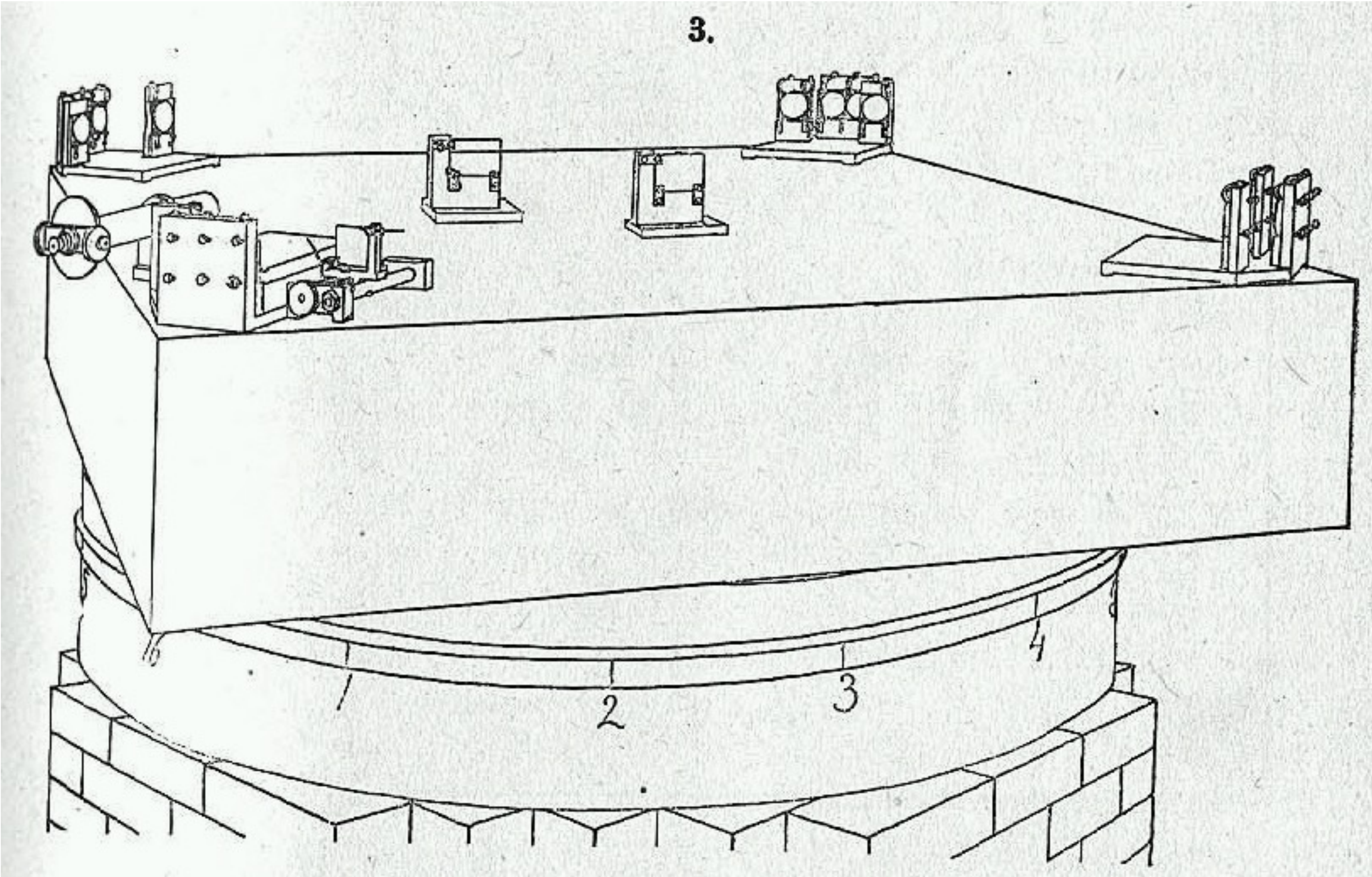
The Michelson-Morley experiment was designed to measure the extra time it took a light beam to travel "there-and-back" against the ether wind, compared to a light beam travelling "sideways across" the ether wind.

The set up a light source, mirrors, and a telescope on a big slab of stone:

http://spiff.rit.edu/classes/phys200/lectures/mm_results/mm_results.html



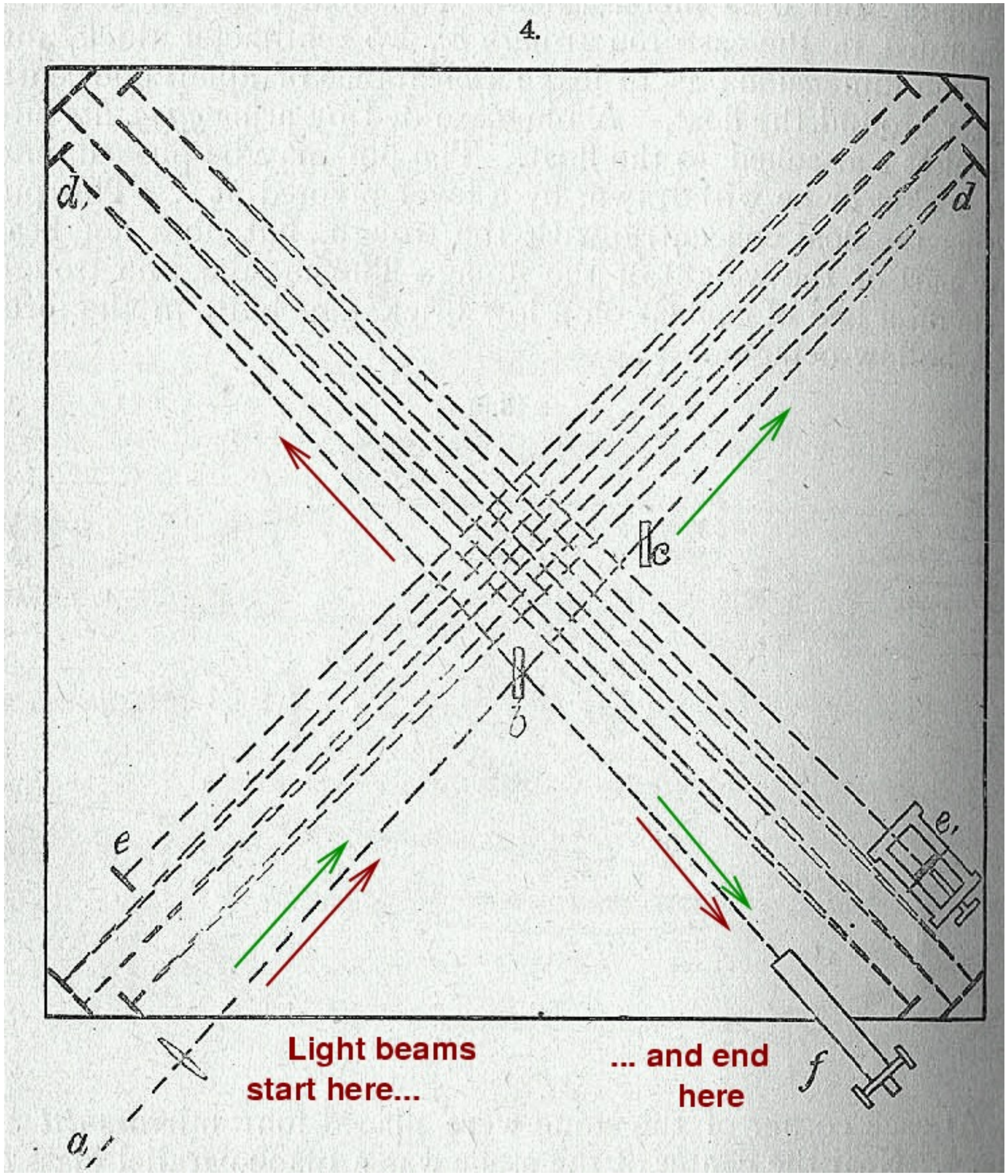
http://webs.mn.catholic.edu.au/physics/emery/hsc_space_continued.htm



http://spiff.rit.edu/classes/phys200/lectures/mm_results/mm_results.html

A single beam of light was split into perpendicular paths and sent bouncing back and forth four times across the stone. The two beams were then re-combined before they entered a telescope

http://spiff.rit.edu/classes/phys200/lectures/mm_results/mm_results.htm



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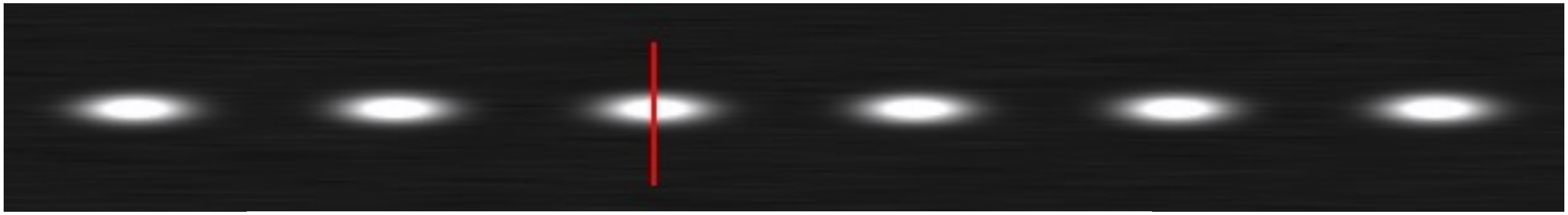
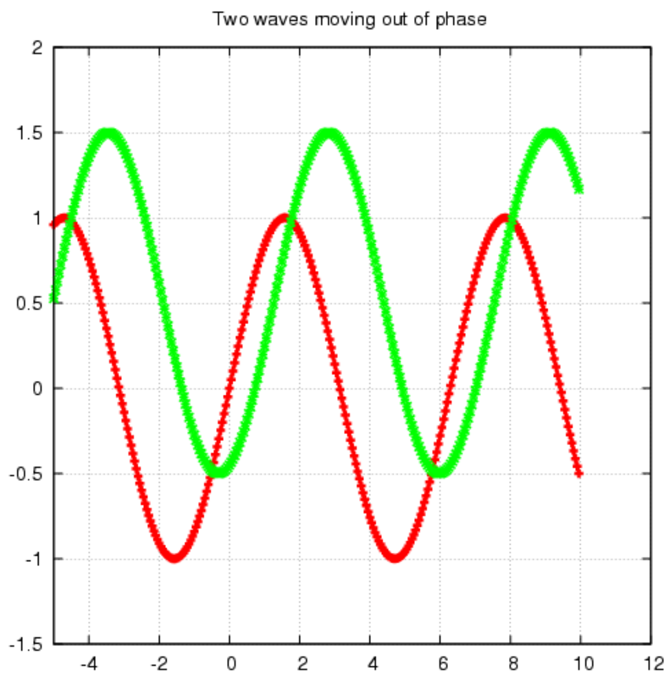




http://spiff.rit.edu/classes/phys200/lectures/mm_results/mm_results.html

NO EFFECT WHATSOEVER WAS OBSERVED!

But since the displacement is proportional to the square of the velocity, the relative velocity of the earth and the ether is probably less than one sixth the earth's orbital velocity, and certainly less than one-fourth.

In what precedes, only the orbital motion of the earth is considered. If this is combined with the motion of the solar system, concerning which but little is known with certainty, the result would have to be modified; and it is just possible that the resultant velocity at the time of the observations was small though the chances are much against it. The experiment will therefore be repeated at intervals of three months, and thus all uncertainty will be avoided.

It appears, from all that precedes, reasonably certain that if there be any relative motion between the earth and the luminiferous ether, it must be small; quite small enough entirely to refute Fresnel's explanation of aberration.

http://spiff.rit.edu/classes/phys200/lectures/mm_results/mm_results.html

THE FACT THAT THE SPEED OF LIGHT IS ALWAYS THE SAME LEADS TO SEVERAL FAMOUS CONSEQUENCES.

First, it means that no physical object can move faster than light.

Einstein's famous equation $E = mc^2$

An object moving by you seems to have slower time, shorter length, and greater mass than it would at rest.

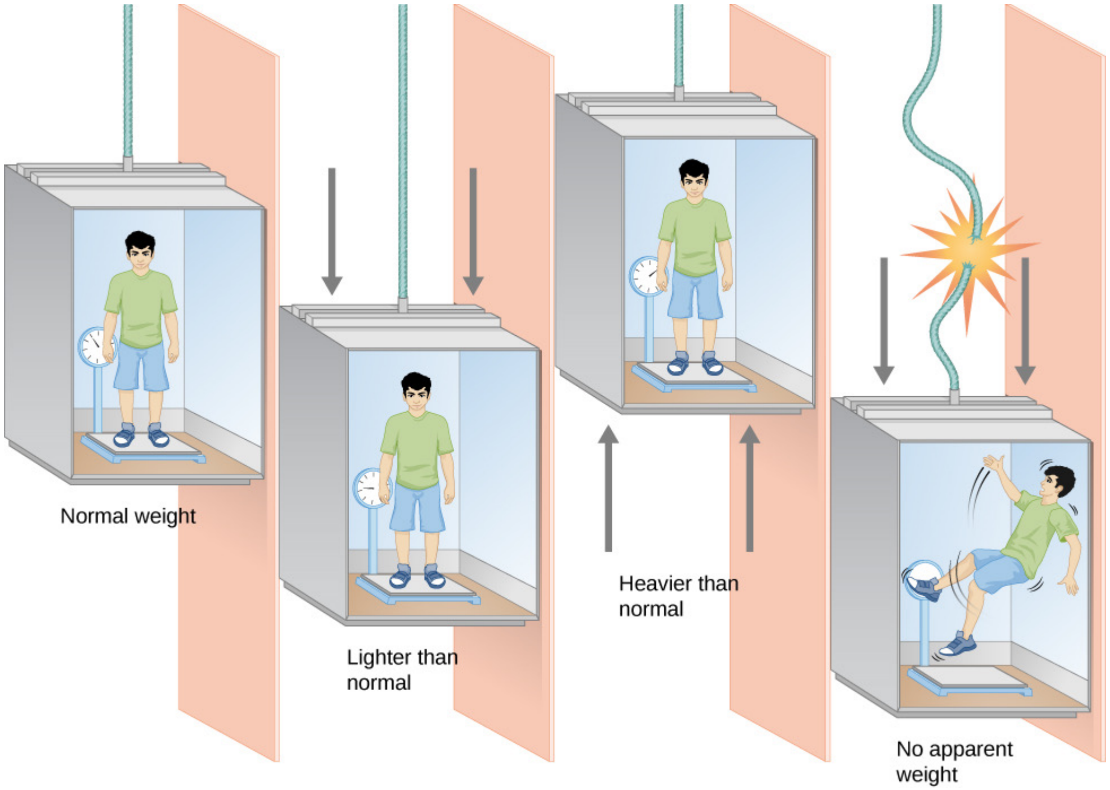
GENERAL RELATIVITY

Einstein's general theory extended special relativity by including the effects of gravity, and it led to a radical revision in how we think about space and time.

Special relativity had showed that, instead of thinking about the three dimensions of space and the one dimension of time as separate, we should think of them as a seamless, four-dimensional entity known as spacetime.

The general theory of relativity showed that what we perceive as gravity arises from curvature of this four-dimensional spacetime.

FIGURE 24.3



Your Weight in an Elevator. In an elevator at rest, you feel your normal weight. In an elevator that accelerates as it descends, you would feel lighter than normal. In an elevator that accelerates as it ascends, you would feel heavier than normal. If an evil villain cut the elevator cable, you would feel weightless as you fell to your doom.

FIGURE 24.4

Free Fall. Two people play catch as they descend into a bottomless abyss. Since the people and ball all fall at the same speed, it appears to them that they can play catch by throwing the ball in a straight line between them. Within their frame of reference, there appears to be no gravity.

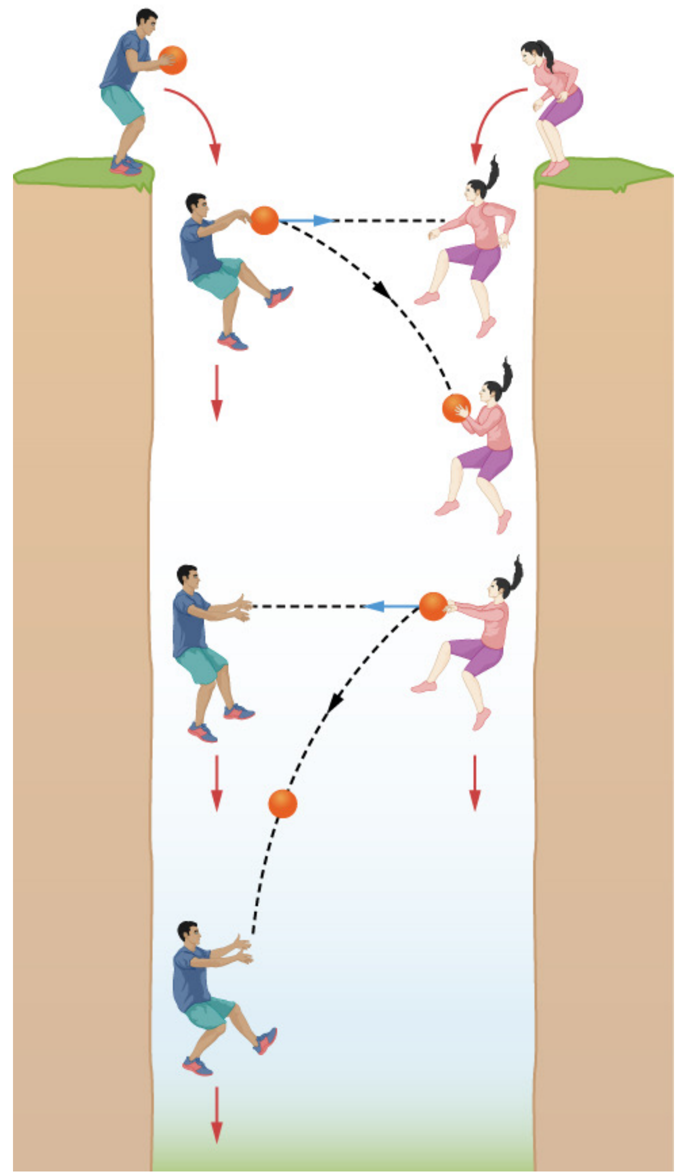
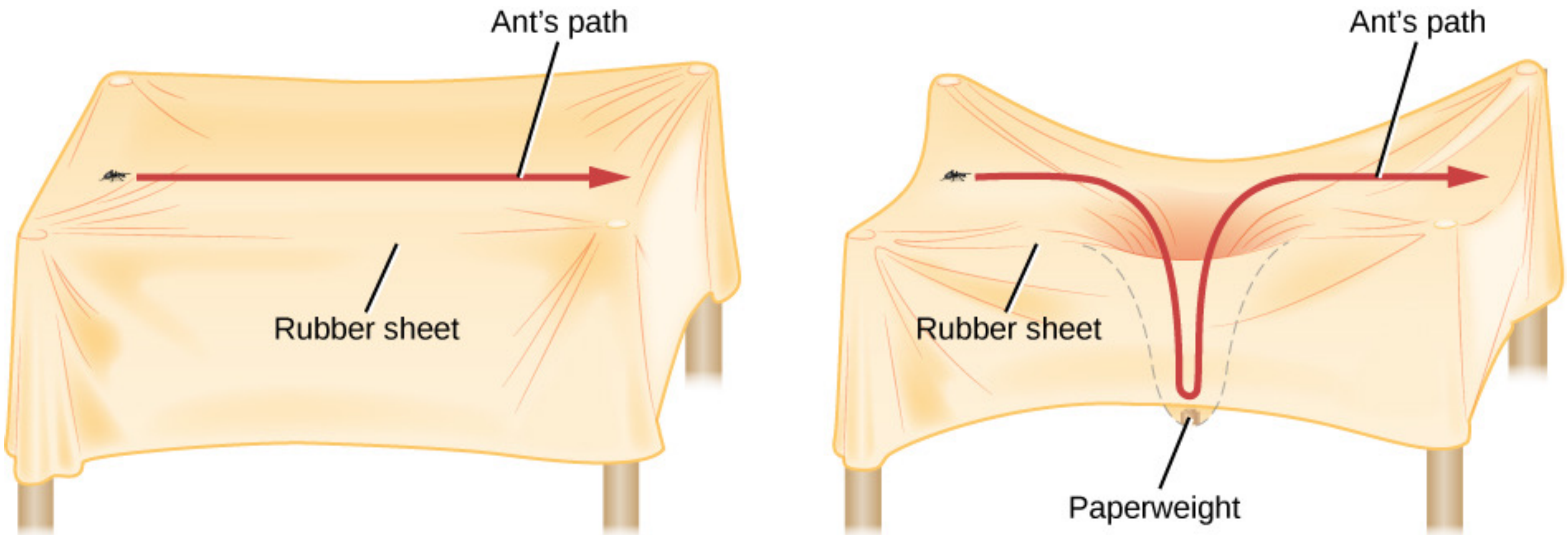


FIGURE 24.5

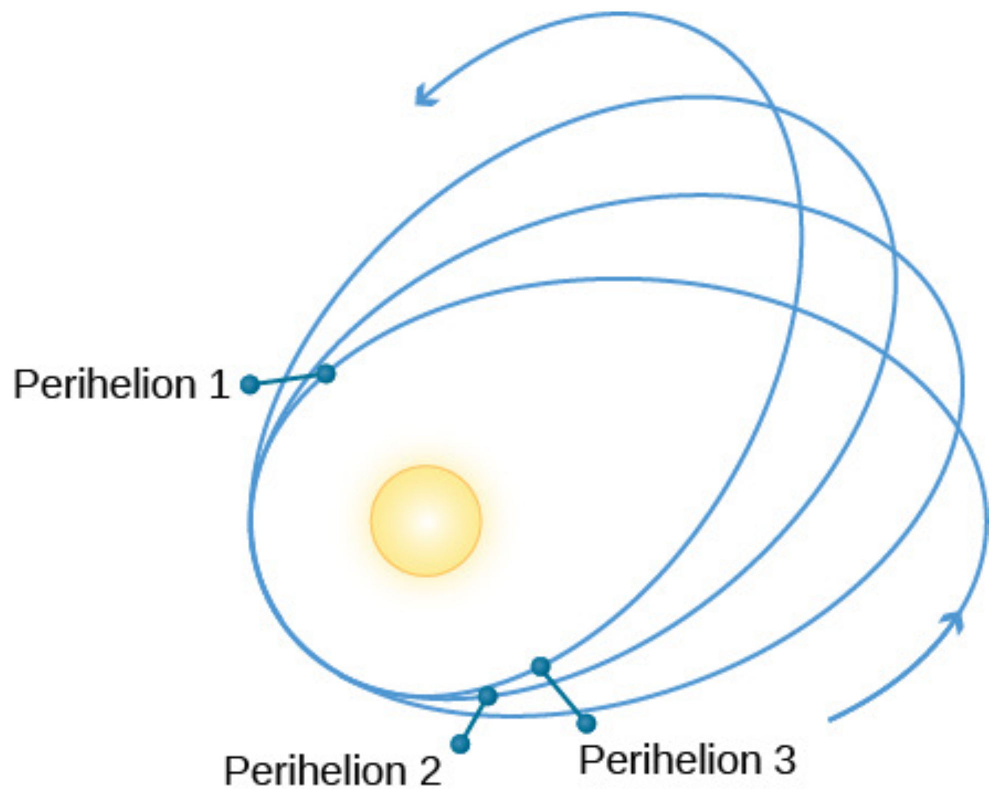
Astronauts aboard the Space Shuttle. Shane Kimbrough and Sandra Magnus are shown aboard the Endeavour in 2008 with various fruit floating freely. Because the shuttle is in free fall as it orbits Earth, everything—including astronauts—stays put or moves uniformly relative to the walls of the spacecraft. This free-falling state produces a lack of apparent gravity inside the spacecraft. (credit: NASA)

FIGURE 24.8



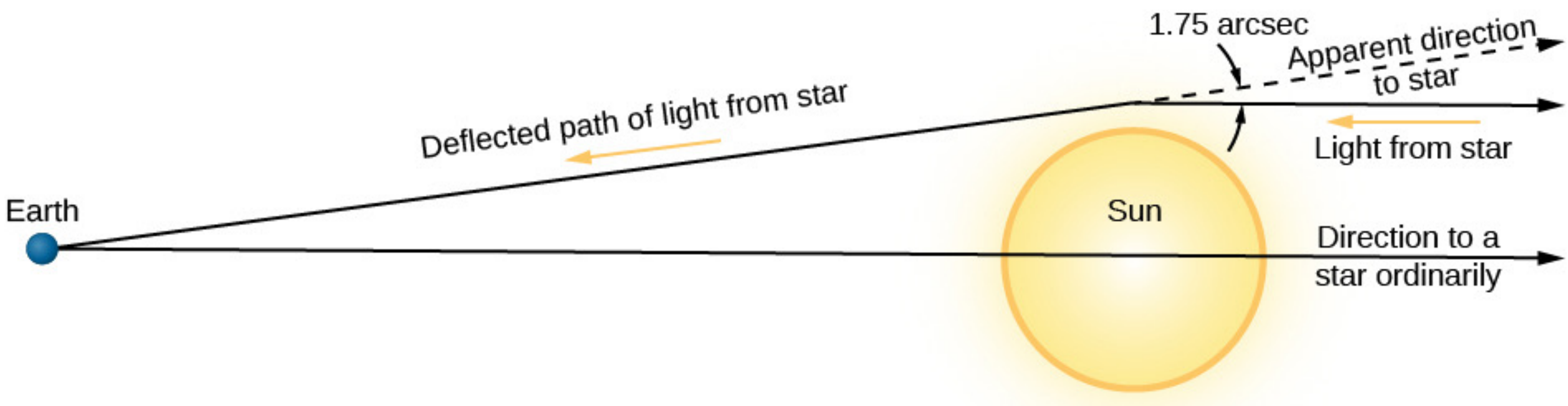
Three-Dimensional Analogy for Spacetime. On a flat rubber sheet, a trained ant has no trouble walking in a straight line. When a massive object creates a big depression in the sheet, the ant, which must walk where the sheet takes it, finds its path changed (warped) dramatically.

FIGURE 24.9



Mercury's Wobble. The major axis of the orbit of a planet, such as Mercury, rotates in space slightly because of various perturbations. In Mercury's case, the amount of rotation (or orbital precession) is a bit larger than can be accounted for by the gravitational forces exerted by other planets; this difference is precisely explained by the general theory of relativity. Mercury, being the planet closest to the Sun, has its orbit most affected by the warping of spacetime near the Sun. The change from orbit to orbit has been significantly exaggerated on this diagram.

FIGURE 24.10



Curvature of Light Paths near the Sun. Starlight passing near the Sun is deflected slightly by the "warping" of spacetime. (This deflection of starlight is one small example of a phenomenon called gravitational lensing, which we'll discuss in more detail in **The Evolution and Distribution of Galaxies**.) Before passing by the Sun, the light from the star was traveling parallel to the bottom edge of the figure. When it passed near the Sun, the path was altered slightly. When we see the light, we assume the light beam has been traveling in a straight path throughout its journey, and so we measure the position of the star to be slightly different from its true position. If we were to observe the star at another time, when the Sun is not in the way, we would measure its true position.

TOTAL ECLIPSE OF THE SUN 1919

The Total Eclipse of 1919 *May* 29 *and the Influence of Gravitation on Light.*

The coming eclipse of the Sun occurs in a region of the sky which is exceptionally rich in bright stars, and for this reason it affords a very favourable opportunity of investigating the influence of the Sun's attraction on the course of a ray of light. Attention was called by the Astronomer Royal to the importance of this occasion in a paper read before the Royal Astronomical Society in March 1917; and the Joint Permanent Eclipse Committee has organized two expeditions.

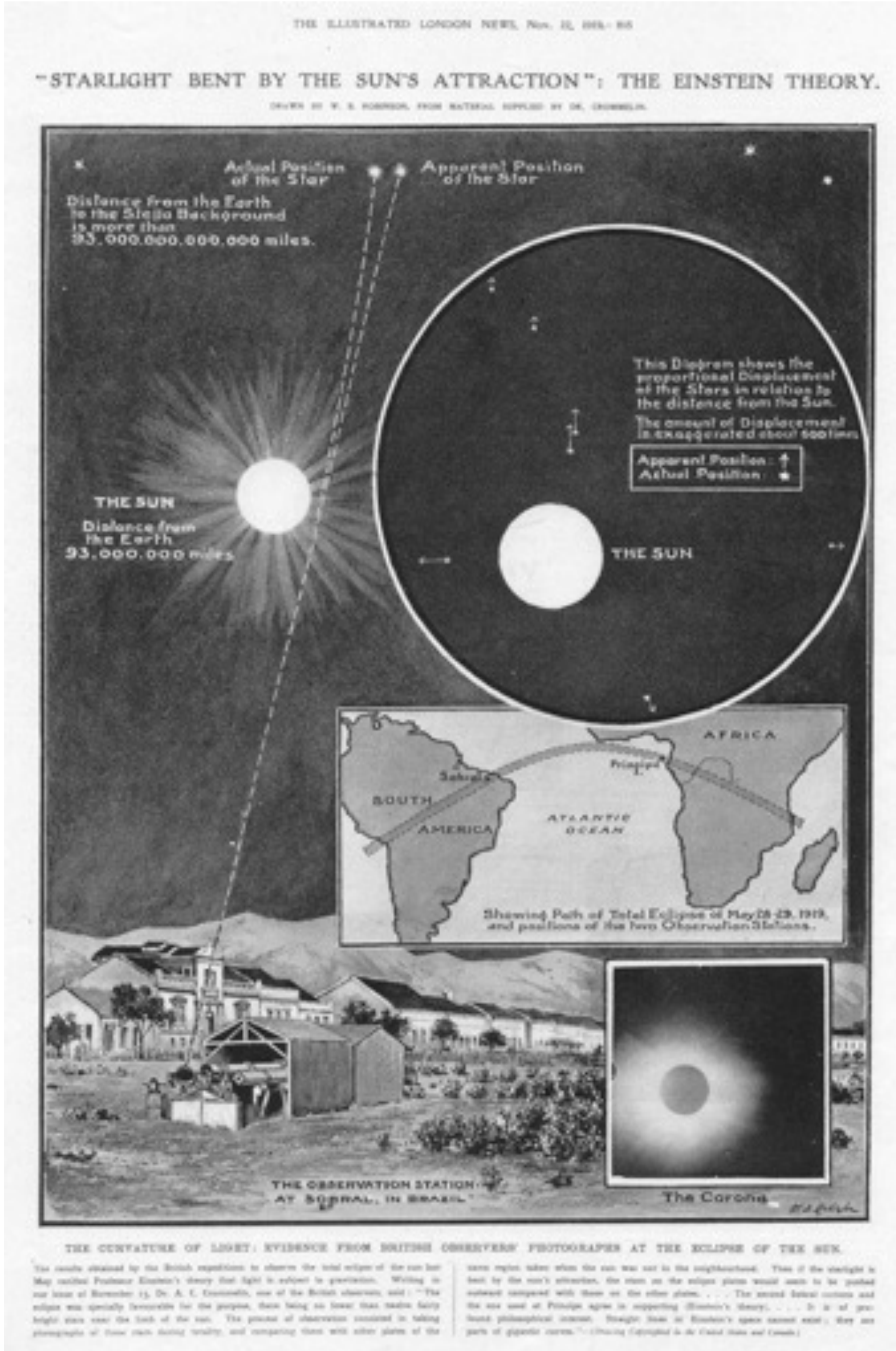
http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1919Obs....42..119E&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf

TOTAL ECLIPSE OF THE SUN 1919

It is superfluous to dwell on the uncertainties which beset eclipse observers; the chance of unfavourable weather is the chief but by no means the only apprehension. Nor can we ignore the possibility that some unknown cause of complication will obscure the plain answer to the question propounded. But, if a plain answer is obtained, it is bound to be of great interest. I have sometimes wondered what must have been the feelings of Prof. Michelson when his wonderfully designed experiment failed to detect the expected signs of our velocity through the æther. It seemed that that elusive quantity was bound to be caught at last; but the result was null. Yet now we can see that a positive result would have been a very tame conclusion; and the negative result has started a new stream of knowledge revolutionising the fundamental concepts of physics. A null result is not necessarily a failure. The present eclipse expeditions may for the first time demonstrate the weight of light; or they may confirm Einstein's weird theory of non-Euclidean space; or they may lead to a result of yet more far-reaching consequences—no deflection.

A. S. Eddington.

http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1919Obs....42..119E&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf



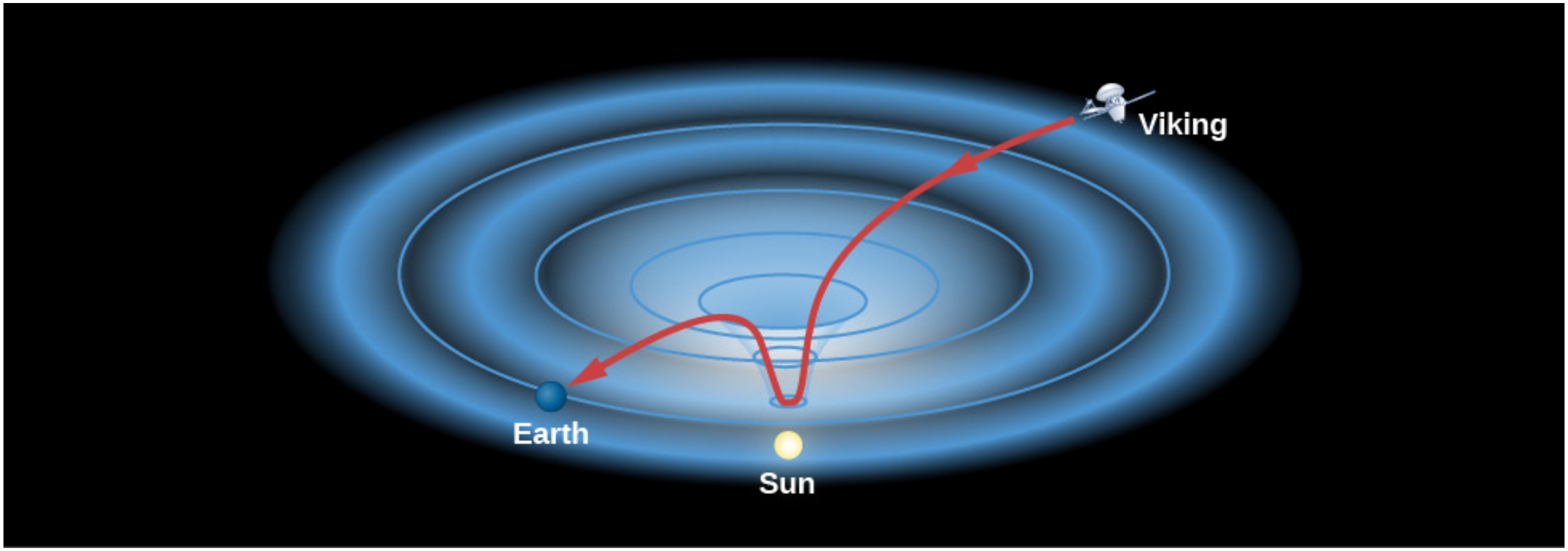
THE ILLUSTRATED LONDON NEWS, Nov. 22, 1919.–815

"STARLIGHT BENT BY THE SUN'S ATTRACTION": THE EINSTEIN THEORY.

THE CURVATURE OF LIGHT: EVIDENCE FROM BRITISH OBSERVERS' PHOTOGRAPHS AT THE ECLIPSE OF THE SUN.

http://eclipse-maps.com/Eclipse-Maps/History/Pages/1911-1920.html

FIGURE 24.11



Time Delays for Radio Waves near the Sun. Radio signals from the Viking lander on Mars were delayed when they passed near the Sun, where spacetime is curved relatively strongly. In this picture, spacetime is pictured as a two-dimensional rubber sheet.

FIGURE 24.14

(a) (b)

Light Paths near a Massive Object. Suppose a person could stand on the surface of a normal star with a flashlight. The light leaving the flashlight travels in a straight line no matter where the flashlight is pointed. Now consider what happens if the star collapses so that it is just a little larger than a black hole. All the light paths, except the one straight up, curve back to the surface. When the star shrinks inside the event horizon and becomes a black hole, even a beam directed straight up returns.

FIGURE 24.15

Karl Schwarzschild (1873–1916). This German scientist was the first to demonstrate mathematically that a black hole is possible and to determine the size of a nonrotating black hole's event horizon.

THE EVENT HORIZON OF A BLACK HOLE

A collapsing object becomes a black hole when the escape velocity from its surface exceeds the speed of light. At that moment, a boundary called the event horizon forms between the inside of the new black hole and the universe outside of it.

The event horizon essentially marks the point of no return for objects entering a black hole: It is the boundary around a black hole at which the escape velocity equals the speed of light.

Nothing that passes within this boundary can ever escape. The event horizon gets its name from the fact that we have no hope of learning about any events that occur within it.

THE SCHWARZSCHILD RADIUS

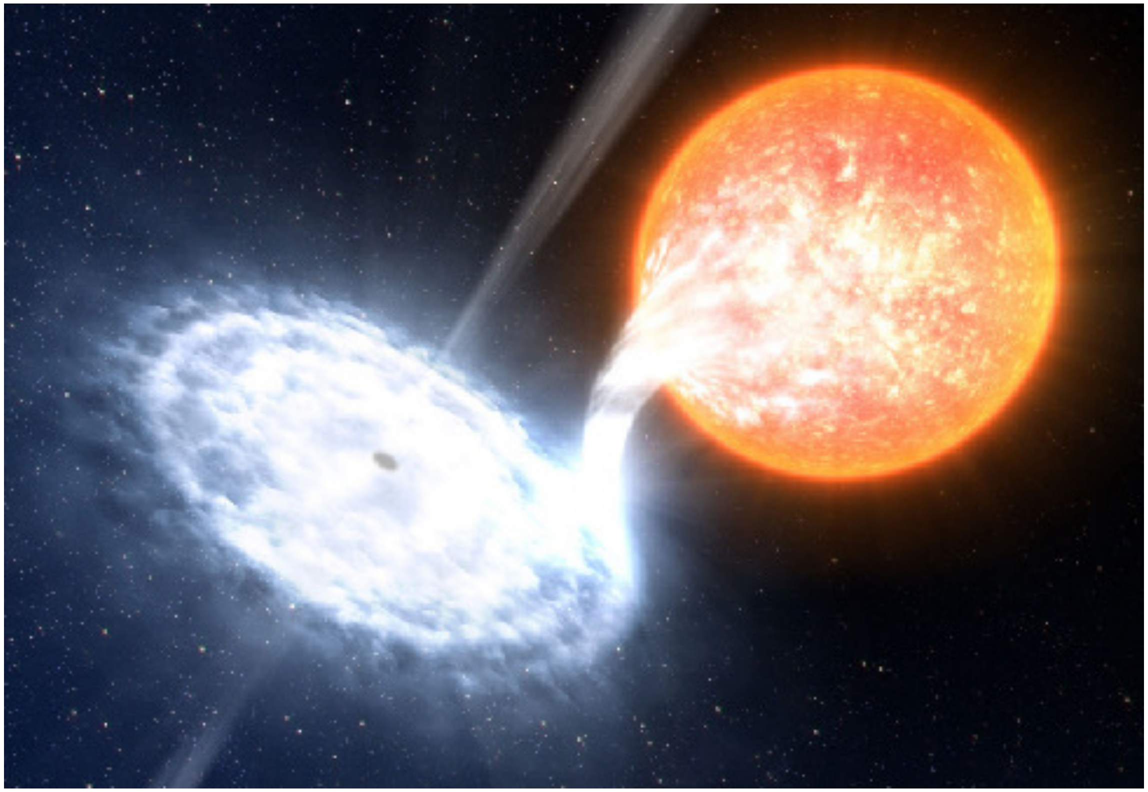
We usually think of the “size” of a black hole as the radius of its event horizon. This radius is known as the Schwarzschild radius, named for the man who derived its formula in 1916.

The Schwarzschild radius of a black hole depends only on its mass.

A black hole with the mass of the Sun has a Schwarzschild radius of about 3 kilometers—only a little smaller than the radius of a neutron star of the same mass.

More massive black holes have larger Schwarzschild radii. For example, a black hole with 10 times the mass of the Sun has a Schwarzschild radius of about 30 kilometers.

FIGURE 24.16



Binary Black Hole. This artist's rendition shows a black hole and star (red). As matter streams from the star, it forms a disk around the black hole. Some of the swirling material close to the black hole is pushed outward perpendicular to the disk in two narrow jets. (credit: modification of work by ESO/L. Calçada)

LIGO: A NEW WAY TO EXPLORE THE UNIVERSE

Suppose you watched a concert on television with the volume turned down. The rousing musical score can only be imagined. Could we, in fact, even imagine the music if we had never heard music before? Throughout human history, we have viewed the cosmos in a similar way. First with our unaided eyes, and then with telescopes, we examined the visible light from heavenly objects to discover their secrets. Eventually we learned to view a broader variety of radiation -- including infrared light, x-rays, gamma rays and radio waves -- invisible to our eyes but clearly detectable by electronic devices. Yet still, all these different kinds of radiation, including light, are made purely of electricity and magnetism.

http://www.ligo-la.caltech.edu/LLO/overviewsci.htm

LIGO: A NEW WAY TO EXPLORE THE UNIVERSE

Today we know that only about ten percent of all the matter in the universe can be observed in this way. What new tools might we use to gain insight into the majority of matter in the universe? We now have the technology to wield a very different force -- the force of gravity -- to explore this uncharted realm. LIGO, the Laser Interferometer Gravitational-Wave Observatory, is an instrument for sensing the presence of matter, whether shining or dark, in the distant reaches of the cosmos. LIGO does this by detecting the gravitational waves -- ripples in the force of gravity -- created by violent events such as the collisions of stars and the vibrations of black holes.

http://www.ligo-la.caltech.edu/LLO/overviewsci.htm

FIGURE 24.17

Gravitational Wave Telescope. An aerial view of the LIGO facility at Livingston, Louisiana. Extending to the upper left and far right of the image are the 4-kilometer-long detectors. (credit: modification of work by Caltech/MIT/LIGO Laboratory)

HOW LIGO WORKS

LIGO detects the ripples in space-time by using a device called a laser interferometer, in which the time it takes light to travel between suspended mirrors is measured with high precision using controlled laser light.

Two mirrors hang far apart, forming one "arm" of the interferometer, and two more mirrors make a second arm perpendicular to the first. Viewed from above, the two arms form an L shape. Laser light enters the arms through a beam splitter located at the corner of the L, dividing the light between the arms.

The light is allowed to bounce between the mirrors repeatedly before it returns to the beam splitter. If the two arms have identical lengths, then interference between the light beams returning to the beam splitter will direct all of the light back toward the laser. But if there is any difference between the lengths of the two arms, some light will travel to where it can be recorded by a photodetector.

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PUSHING THE LIMITS OF TECHNOLOGY

LIGO must measure the movements of its mirrors, separated by two and a half miles, with phenomenal precision. To achieve its goal, LIGO must detect movements as small as one thousandth the diameter of a proton, which is the nucleus of a hydrogen atom. Achieving this degree of sensitivity requires a remarkable combination of technological innovations in vacuum technology, precision lasers, and advanced optical and mechanical systems.

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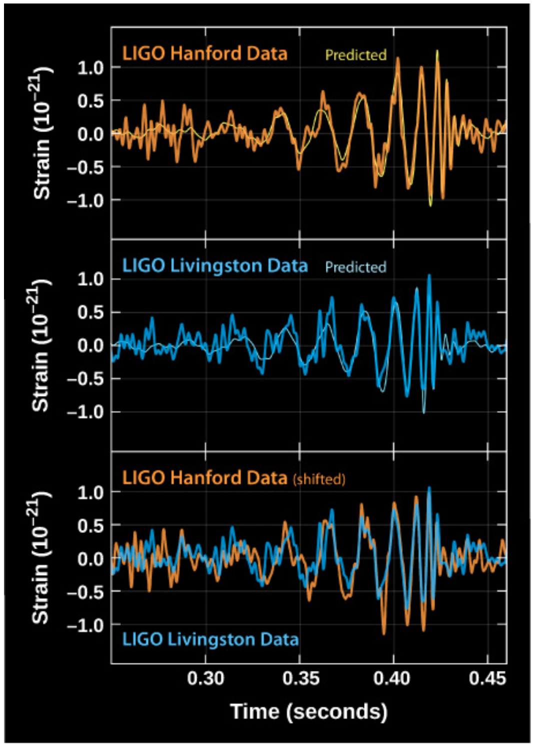
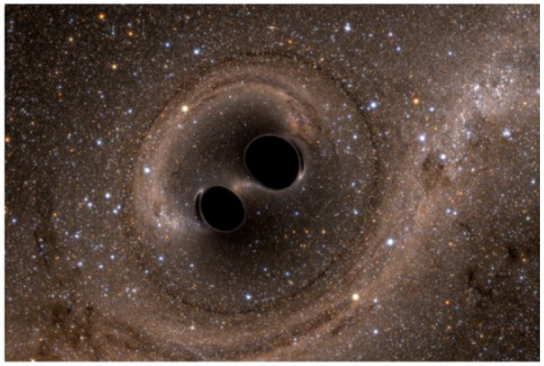
FIGURE 24.18



(a)



(b)

Signal Produced by a Gravitational Wave.

(a) The top panel shows the signal measured at Hanford, Washington; the middle panel shows the signal measured at Livingston, Louisiana. The smoother thin curve in each panel shows the predicted signal, based on Einstein's general theory of relativity, produced by the merger of two black holes. The bottom panel shows a superposition of the waves detected at the two LIGO observatories. Note the remarkable agreement of the two independent observations and of the observations with theory.

(b) The painting shows an artist's impression of two massive black holes spiraling inward toward an eventual merger. (credit a, b: modification of work by SXS)