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Introduction to Astronomy

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> As we enjoy great Advantages from the Inventions of others we should be glad of an Opportunity to serve others by any Invention of ours, and this we should do freely and generously.
>
> — Benjamin Franklin, from The Autobiography of Benjamin Franklin, Chapter X

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Introduction to Astronomy

Preface

Education is what survives when what has been learned has been forgotten.

-- B. F. Skinner, *New Scientist*, 1964 May 21

This Web-based course, or "webbook", is a college-level, semester-long, non-calculational introduction to astronomy (it may also be suitable for a high school course). It was initiated while I was a teaching affiliate in the Physics Department at Emory University in Atlanta, Georgia. I taught the class for many years in a traditional manner using a blackboard, models, slides, transparencies, and video, but was frustrated by many aspects of it. If I attempted to cover all of the material I wanted to discuss, I had to proceed very quickly, resulting in much information only "in the air" rather than written on the blackboard. Images I drew were necessarily schematic and even then were difficult for the students to reproduce in their notes. Many of the concepts I was presenting involved motion or other changes with time, and sequential images and/or arrows on a blackboard are not as descriptive as a real animation. When I used slides and videos, they were not generally accessible to the students for review. The common result was that the students' record of the course material was often poor, and their understanding suffered.

Also, I found that the students I was teaching were changing. They had more difficulty absorbing and integrating information, especially when presented textually. They were becoming less focused and more easily bored. A traditional "chalk talk" could easily lose their attention.

I was therefore pleased when I began to find many digital images of astronomical phenomena appearing on the World-Wide Web. (Astronomy Picture of the Day has been a favorite place to discover new and interesting images of the cosmos.) These photographs could be easily integrated together with text, animated images, video, and sound to form the basis for class presentations, as well as a record that the students could use later for studying. In addition to addressing the issues described above, it becomes possible to spend more time on areas of difficulty (Just-in-Time Teaching) or with in-depth inquiry-based activities.

The order of presentation of the material differs from all of the astronomy textbooks I have seen, though it is largely inspired by the early editions of *Discovering the Universe*, by William J. Kaufmann III, in which a comparative approach is emphasized. It is certainly also influenced by the fact that I am a physicist first and an astronomer second.

As is common in introductory astronomy textbooks, the **Foundations** section discuss early astronomy and astronomical technology. This results in an almost complete overview of basic physics, but other sources usually leave important pieces of physics out, waiting until absolutely necessary to introduce them to explain astronomical phenomena. I found this approach to be very fragmentary, and I believe a more complete, self-consistent introduction of physics provides a better foundation for understanding our universe. Therefore, if a physical principle is used to understand astronomy multiple times, or if it closely fits in with the overview, I have included it in the **Foundations**. When the principle shows up again, it provides an opportunity for comparison and review, which enhance comprehension. Only if a physical principle is relatively isolated, conceptually, is it introduced later.

I have also long been puzzled by the lack of discussion of the concept of energy in introductory astronomy textbooks, the conservation thereof being so important in physics and astronomy. The term is commonly used, but never fully defined, except in a few instances, such as in special relativity. I have therefore provided a complete though basic treatment of the subject. Other conservation laws (mass, charge, angular momentum, etc.) are also mentioned.

After **Foundations** I have taken yet another deviation from the "standard", by placing the **Stars** section before the **Planetary Systems** section. This is for two reasons, the primary one being that the formation and death of stars are necessary precedents to the formation of planetary systems, and so I feel it helps to have an understanding of the former process first. In addition, with stars there is a greater opportunity to apply or reapply much of the physics learned in earlier chapters, and so reinforce it sooner.

Not surprisingly by now, the **Planetary Systems** chapters have their own uncommon order, beginning with a general consideration of what we know about observed planetary systems, followed by a discussion of the smallest objects (dust, comets, asteroids, and icy asteroids), proceeding to the smaller terrestrial worlds (Mercury and the Moon), the Jovian Moons, and then the larger terrestrial worlds (Earth, Venus, and Mars). The Jovian worlds round out the section. In this order I can progressively discuss cratering, the existence of water and atmospheres, etc., and apply Kaufmann's comparative approach.

The course ends in the usual way with a **Galaxies and the Universe** section. I haven't seen much uniformity in the way that the Universe is discussed, but I've organized it with an initial presentation on its structure as we understand it now, followed by its past and future evolution.

I have always made these web presentations available to the entire Internet, and it has been gratifying to receive so many positive responses from students, teachers, and others who have discovered them and learned from them. Although I am no longer at Emory, I am pleased to be able to continue to develop and publish these educational materials.

I encourage questions, comments, suggestions, and corrections.

Scott R. Anderson, Ph.D.
Sandia Research and Computing Associates
Albuquerque, New Mexico, USA

Introduction to Astronomy

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Introduction to Astronomy

Lecture 1: The Science of Astronomy

Science is simply common sense at its best -- that is, rigidly accurate in observation, and merciless to fallacy in logic.

-- Thomas H. Huxley, *The Crayfish*, 1879

1.1 What is Astronomy?

(Discovering the Universe, 5th ed., §I-0, §I-1, §I-3)

- Astronomy initially began tens of thousands of years ago as a descriptive science, tracking the motion of the Sun, Moon, planets, and stars.

- Nowadays, astronomers mostly concern themselves with understanding the "why" of astronomical phenomena, e.g. what a star consists of, why it emits light, etc.

  These subjects will be the main topics of this course.

  The term "astronomy" means the "laws of the stars", and is therefore very appropriate.

- Understanding astronomical phenomena requires extensive application of physics, hence most astronomers call themselves **astrophysicists**.

- Other fields of knowledge that are useful in astronomy include chemistry, geology, and, increasingly, biology.

1.2 The Scientific Method

(Discovering the Universe, 5th ed., §I-2, §I-3)

- In astronomy, the **scientific method** is extensively used:

  1. New observations are made
  2. Theories are developed to explain the observations in terms of the already accepted body of knowledge.
  3. If two or more theories explain the same observations, the principle of **Occam's Razor** states that the simplest theory is the best.
  4. A theory which explains a larger number of observations is also better

     Such a theory will often replace a previously accepted theory.

5. A good theory can be used to make predictions, which can be confirmed or refuted by subsequent observations.

- For example, it used to be believed that the planets revolved around the Earth.

  However, detailed observations of their motions could not be explained unless complicated additions were made to this model.

  Ultimately, the model was replaced by the simpler theory that the planets revolve around the Sun.

1.3 Numbers, Numbers, Everywhere

(Discovering the Universe, 5th ed., §I-2)

- Comparisons of different astronomical objects require the use of numbers, e.g. which is bigger, the Earth or the Sun?

- To describe the wide range of values that show up in astronomy, power-of-ten notation is used:

  10^{12} = 1,000,000,000,000 = trillion = tera = T

  10^{9} = 1,000,000,000 = billion = giga = G (commonly pronounced with both hard and soft "g")

  10^{6} = 1,000,000 = million = mega = M

  10^{3} = 1000 = thousand = kilo = K (officially lower case)

  10^{2} = 100 = hundred

  10^{1} = 10 = ten

  10^{0} = 1

- The exponent means that you are multiplying 10 together that many times, e.g.

$10^3 = 10 \times 10 \times 10 = 1000$.

- A simple rule to determine the exponent is to count the number of zeros.

- The abbreviations on the right are simpler to use and are therefore very common.

- Continuing to fractional powers of 10, *negative* exponents are used:

  $10^{-1} = 0.1$ = tenth

  $10^{-2} = 0.01$ = hundredth = centi = c

  $10^{-3} = 0.001$ = thousandth = milli = m

  $10^{-6} = 0.000001$ = millionth = micro = μ (Greek letter mu)

  $10^{-9} = 0.000000001$ = billionth = nano = n

  $10^{-12} = 0.000000000001$ = trillionth = pico = p

- A simple rule to determine a negative exponent is to count the number of places to the right of the decimal point, up to and including the first non-zero digit.

- Numbers in between the powers of ten, e.g. 5237, can be written more compactly as 5.237×10^3, and even more simply as 5.237 K.

  This format is formally known as **scientific notation**.

- Generally each subsequent non-zero digit in a number is less "well-known" or precise because it is harder to measure.

  Therefore, we will usually not specify more than 2 or 3 digits.

1.4 Physical Quantities

(Discovering the Universe, 5th ed., §I-2)

- We will be using several fundamental physical quantities in this class:
  - **Angle**
  - **Distance** or **length**
  - **Time**
  - **Mass**: a characteristic of an object which partially defines the force of gravity it feels (its **weight**).

    Mass also describes an object's resistance to a change in its motion (**inertia**).

    Mass is always positive or zero.

    Conservation of mass is a fundamental law of nature; it can neither be created or destroyed.

    Note that weight and mass are *not* the same!

    An object with *mass* only has *weight* if another object (e.g. a planet) is nearby to provide a gravitational field.

    So, for example, your weight on the Moon is only 1/6 of what it is on the Earth, but your mass is the same.
  - **Electric Charge**: a characteristic of an object which partially defines the forces of electricity and magnetism it feels.

    Benjamin Franklin performed many experiments in electricity, and he discovered that electric charge can be positive, zero, or negative.

    Conservation of electric charge is also a fundamental law of nature; the total amount is zero, so if you find some positive charge somewhere, there must be an equal amount of negative charge somewhere else!

    In nature there is a **fundamental electric charge** (e), which is characteristic of atomic particles, and all other charges are an integer multiple of that value.

    For example, the electron has charge $-e$, and the proton has charge $+e$ (per Franklin's arbitrary choice).

Question: What is the charge of the neutron?

- We will also be using many other quantities which depend on the above, e.g.
  - **Volume**: length x length x length
  - **Density**: mass/volume
  - **Speed**: distance/time
  - **Electric Current** (the flow of electric charge): electric charge/time.

1.5 Units

(Discovering the Universe, 5th ed., §I-2)

- Each of these physical quantities are described by one or more **units**, which are all related to each other by some conversion factor:
  - **Angle**: 1 revolution = 360 degrees = 2 pi radians
  - **Distance** or **length**: 1 meter = 1.094 yard

    1 yard = 3 feet
    1 foot = 12 inches
    1 mile = 5280 feet
  - **Time**: 1 minute = 60 seconds

    1 hour = 60 minutes
    1 day = 24 hours
    1 year = 365.25 days
  - **Mass**: gram = the mass of 10^{-6} cubic meters of water
    (one teaspoon has about 5 grams of water)
  - **Electric Charge**: *e*

    1 Ampere-hour = 2.25×10^{22} *e*
    (a D-cell battery provides about 3 Ampere-hours)

- Rather than electric charge, you are probably more familiar with:
  - **Electric Current**: Ampere = 6.24 x 10^{18} *e*/second

- As in all sciences, we will use the **International System** (commonly known as the **metric system**), a precisely defined set of units maintained by the International Bureau of Weights and Measures in Sèvres, France.

  The fundamental units are meter for length, second for time, gram for mass, and Ampere for electric current.

  In physics, the kilogram (1000 grams) is more commonly used.

- All units have standard abbreviations, which we will use regularly:
  - **Angle**: revolution = rev
degree = °
  - **Distance** or **length**: meter = m
mile = mi
  - **Time**: second = s = "
minute = min = '
hour = h
day = d
year = y
  - **Mass**: gram = g
  - **Electric Current**: Ampere = A

- Combined with the previous numeric abbreviations we have a very flexible, compact notation for describing physical quantities:

kilometer = Km = 1000 m (~5/8 mile)

centimeter = cm = 0.01 m (1 inch = 2.54 cm by U.S. law)

kilogram = Kg = 1000 g (1 Kg has a weight on Earth of 2.2 pounds)

gigayear = Gy = 10^9 y (age of the universe ~13 Gy)

milliAmpere = mA = 10^{-3} A (common current used by electronic equipment)

megabyte = MB = 10^6 B (a **byte** is the computer memory required to hold one character)

- Note the symbol ~, which means "about" or "approximately"

- Let's consider some astronomical distances:

Earth's Radius	6.4×10^3 Km = 6.4 Mm		
Earth-Moon	3.8×10^5 Km = 380 Mm	2.5×10^{-3} AU = 2.5 mAU	
Earth-Sun	1.5×10^8 Km = 150 Gm	1 AU	8.3 lmin
Sun-Pluto	5.9×10^9 Km = 5900 Gm = 5.9 Tm	39 AU	324 lmin = 6.2×10^{-4} ly
Sun-Nearest Star	4.0×10^{13} Km	2.7×10^5 AU	4.2 ly
Sun-Center of Galaxy	2.6×10^{17} Km		2.8×10^4 ly = 28 Kly
Nearest Comparable Galaxy (Andromeda)	2.1×10^{19} Km		2.2×10^6 ly = 2.2 Mly
Farthest we can see	~1.2×10^{23} Km		~1.3×10^{10} ly = 13 Gly

- A more useful measure for *interplanetary* distances is the **astronomical unit** (abbreviated AU), defined as the average distance between the Earth and the Sun:

1 AU = 1.496×10^8 Km

- For *interstellar* distances, it is easiest to use the **light year** (abbreviated ly), defined as the distance that light travels in one year:

  1 ly = 9.46×10^{12} Km = 6.32×10^4 AU

  For galactic and intergalactic distances, astronomers use Kly and Mly, respectively.

- Within the solar system, it is also possible to use the **light minute**:

  1 lmin = 1.80×10^7 Km = 0.120 AU

- **Extra:** a visual representation of distance powers-of-10 can be observed at the National High Magnetic Field Laboratory (requires Java). Thanks to former Emory student Mindy Tabin for bringing this to my attention!

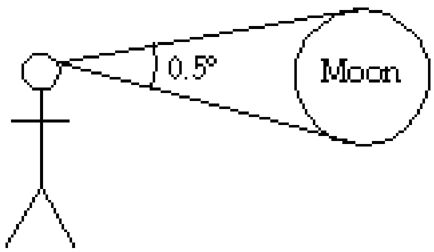
1.6 Angular Measurement

(Discovering the Universe, 5th ed., §I-2)

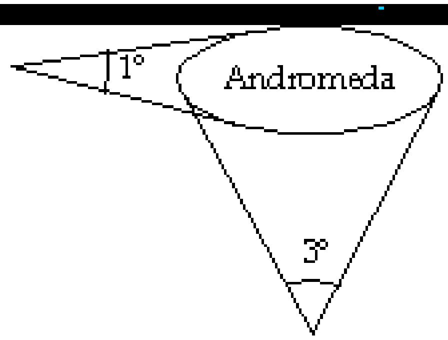
- For observational astronomy, a common tool is *angular measurement*, which describes the apparent size of an object (**angular diameter**), or the apparent distance between two objects (**angular separation**), as viewed from the Earth:

  For example, the Moon has an angular diameter of 1/2°.

  We say that the Moon **subtends** 1/2°.



The Andromeda Galaxy is even larger than the Moon; it subtends angles of 1° by 3°:



- When objects are magnified in a telescope, the **field of view** (the portion of the sky we can see) gets smaller and smaller.

  Therefore, small angular sizes are very common.

  To talk about fractions of a degree, astronomers use the **minute of arc** and the **second of arc**:

  1° = 60 arc min = 60'

  1' = 60 arc sec = 60"

  Note that this is the same relation to the degree that minutes and seconds have to the hour.

  So, the Moon subtends 30'.

- Note that angular measurement depends on how far away something is!

  So, Venus will have a wide range of angular diameters because its distance from the Earth is constantly varying:

  Venus closest: 1.0' = 60"

  Venus farthest: 0.16' = 9.7"

- Similarly, the Moon's distance changes, so it has an angular diameter between 32.7' (closest) and 29.6' (farthest), and the Sun varies between 32.5' (closest) and 31.5' (farthest).

  Question: What would happen if the Moon passed in front of the Sun?

- Stars are so far away that they have angular diameters of zero, i.e. they are **point**

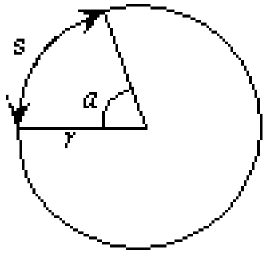
objects.

1.7 The Parsec

(Discovering the Universe, 5th ed., §I-2)

- Angular measurement can be used to define yet another measure of linear distance, which arises naturally out of observational astronomy.

  An angle *a* is related to the arc length *s* it subtends along a circle and the radius *r* of the circle:

  Obviously, the larger the angle *a* is, the larger *s* will be.

  The exact relationship is

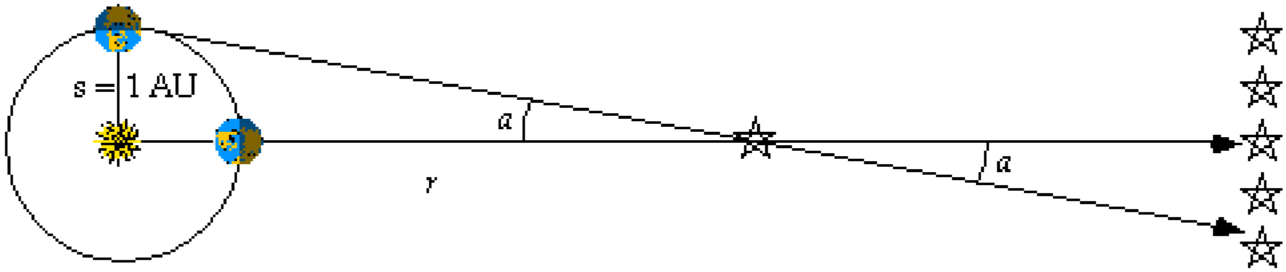
  $s = kra$

  where *k* is a constant that depends on the units used (e.g. if *a* is measured in radians and *s* and *r* are measured in the same units, then *k* = 1).

- When the Earth moves in its orbit, nearby stars can be observed to move against the static background of far-away stars.

  This apparent motion of an object due to the motion of the observer is known as **parallax**.

  You are familiar with parallax from riding in a car: trees outside appear to move past you when in fact it is *you* that moves.



Extra: an animation of stellar parallax can be observed at [Cornell University]() (requires Java).

- The angular change *a* in the position of a star when the Earth moves depends on how far away it is; the further it is, the smaller the parallax.

  Comparing with the previous picture of a circle, we can see that there is a simple relation between the distance to the star *r*, the angle of parallax *a*, and the distance through which the Earth moves *s*:

  $r = s/ka$

  If *s* is measured in AU, *a* is measured in seconds of arc, and *k* is set to 1, then

  $r = 1$ AU/a ,

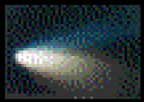
  and *r* is a unit called a **parsec** (abbreviated pc).

  So, if a star exhibits a maximum parallax of one second of arc when the Earth has moved through 1 AU, it is one parsec away.

  Question: In three months time, the star Krüger 60 exhibits a maximum parallax of 1/4 arc sec. How far away is it?

  Even if one doesn't know what an AU is (and for a long time no one did), the parsec can still be used to describe the relative distance to nearby stars.

  Once the value of the AU was determined, it could be calculated that 1 pc = 3.26 ly.

 Prior: Preface
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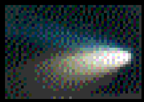
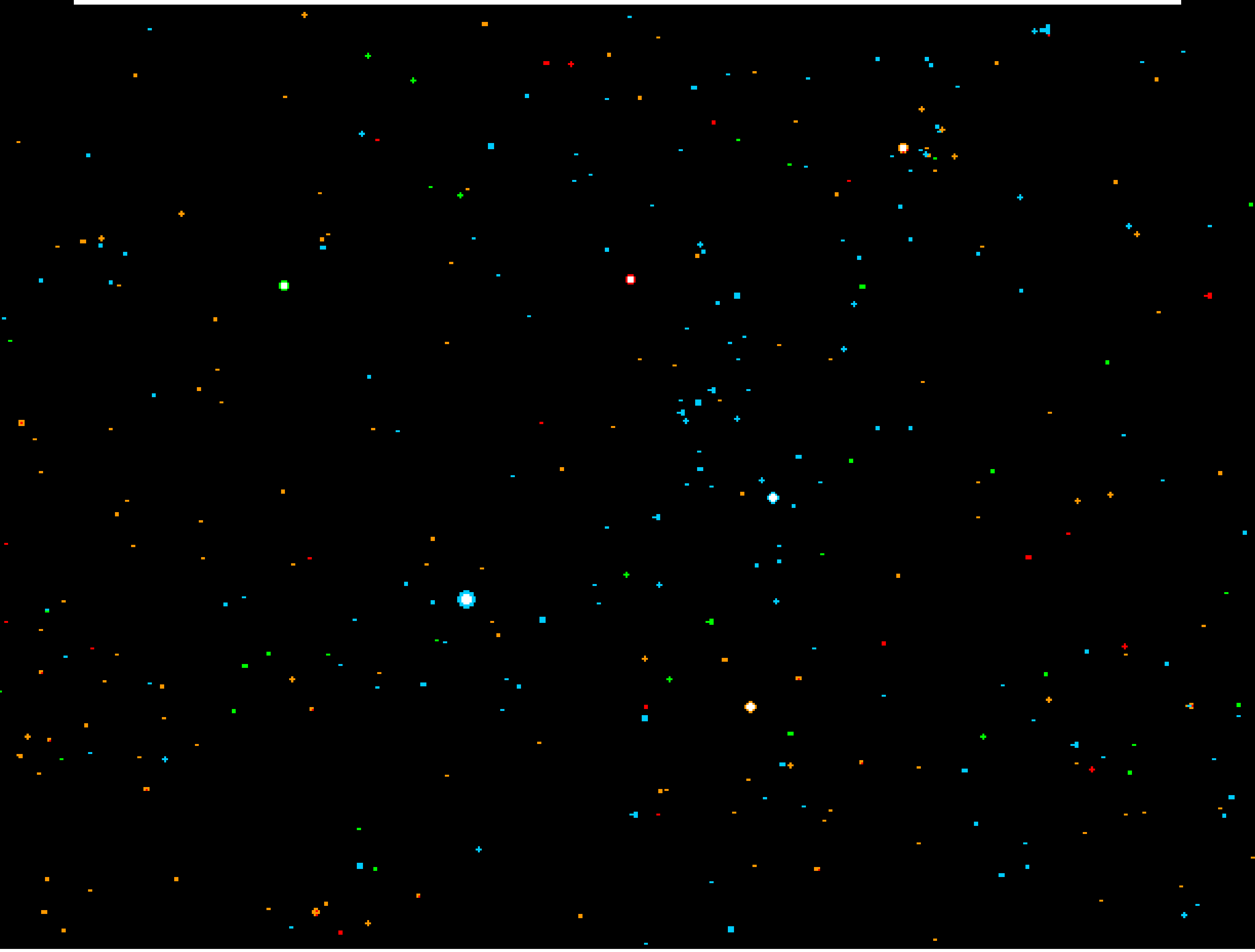
Next: §2 



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Introduction to Astronomy

Lecture 2: The Motion of the Stars and the Sun

The fault, dear Brutus, is not in our stars,
But in ourselves, that we are underlings.

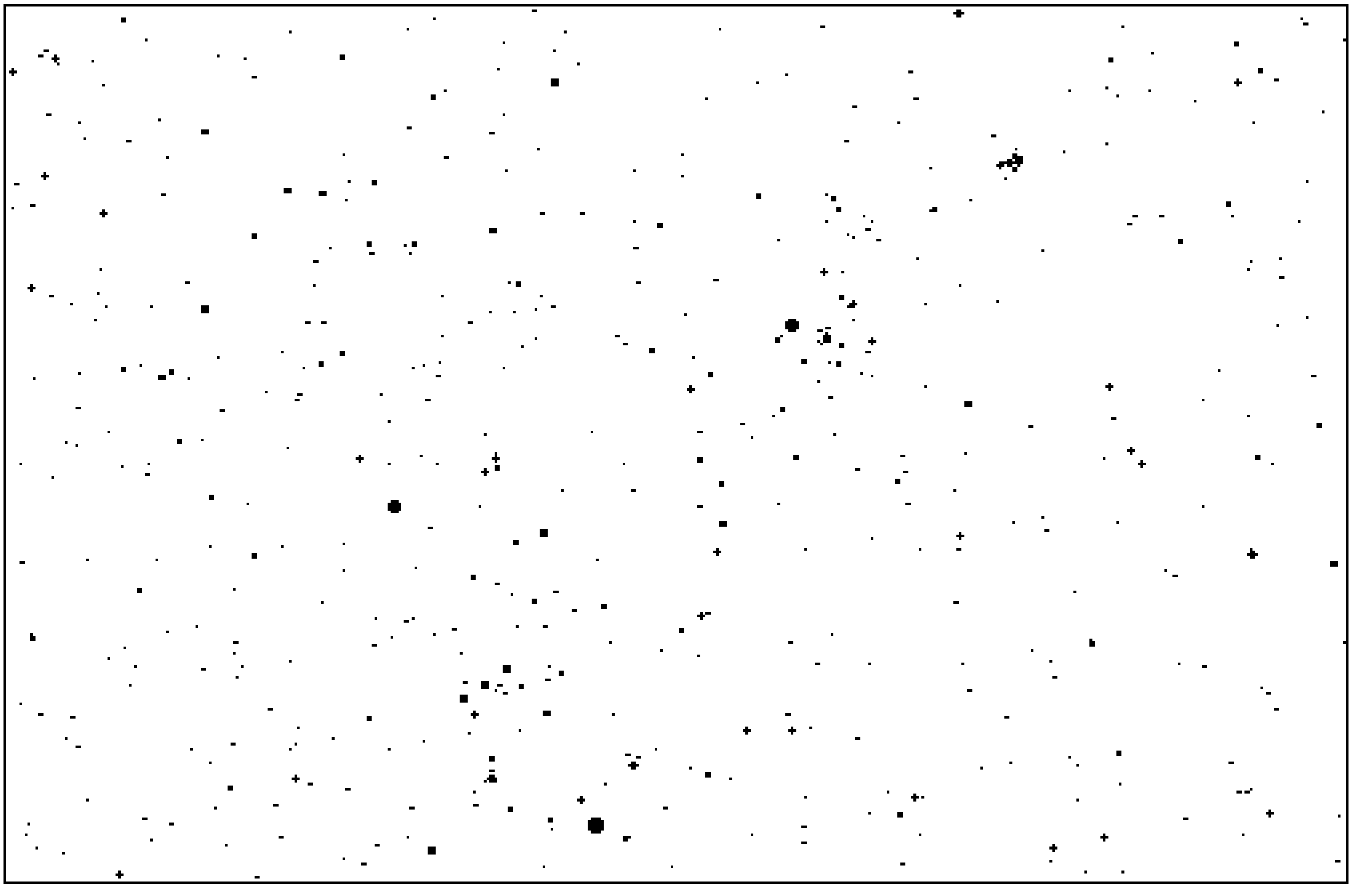
-- WIlliam Shakespeare, *Julius Caesar*

2.1 The Stars

(Discovering the Universe, 5th ed., §1-0, §1-1)

- The human eye can see about 6000 stars without aid.

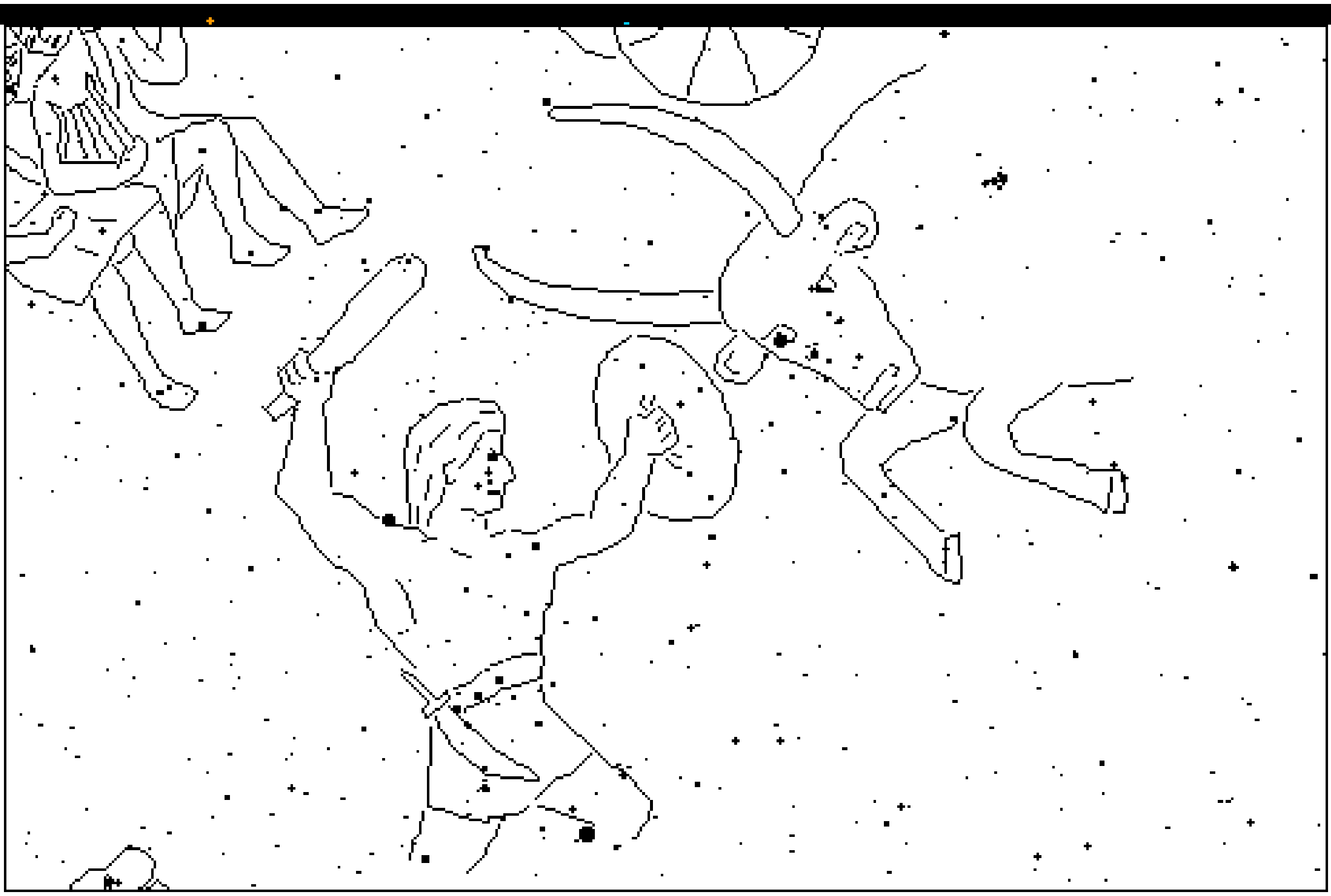
  The picture below covers a field of view of about 70° x 46°, roughly 5% of the entire sky.



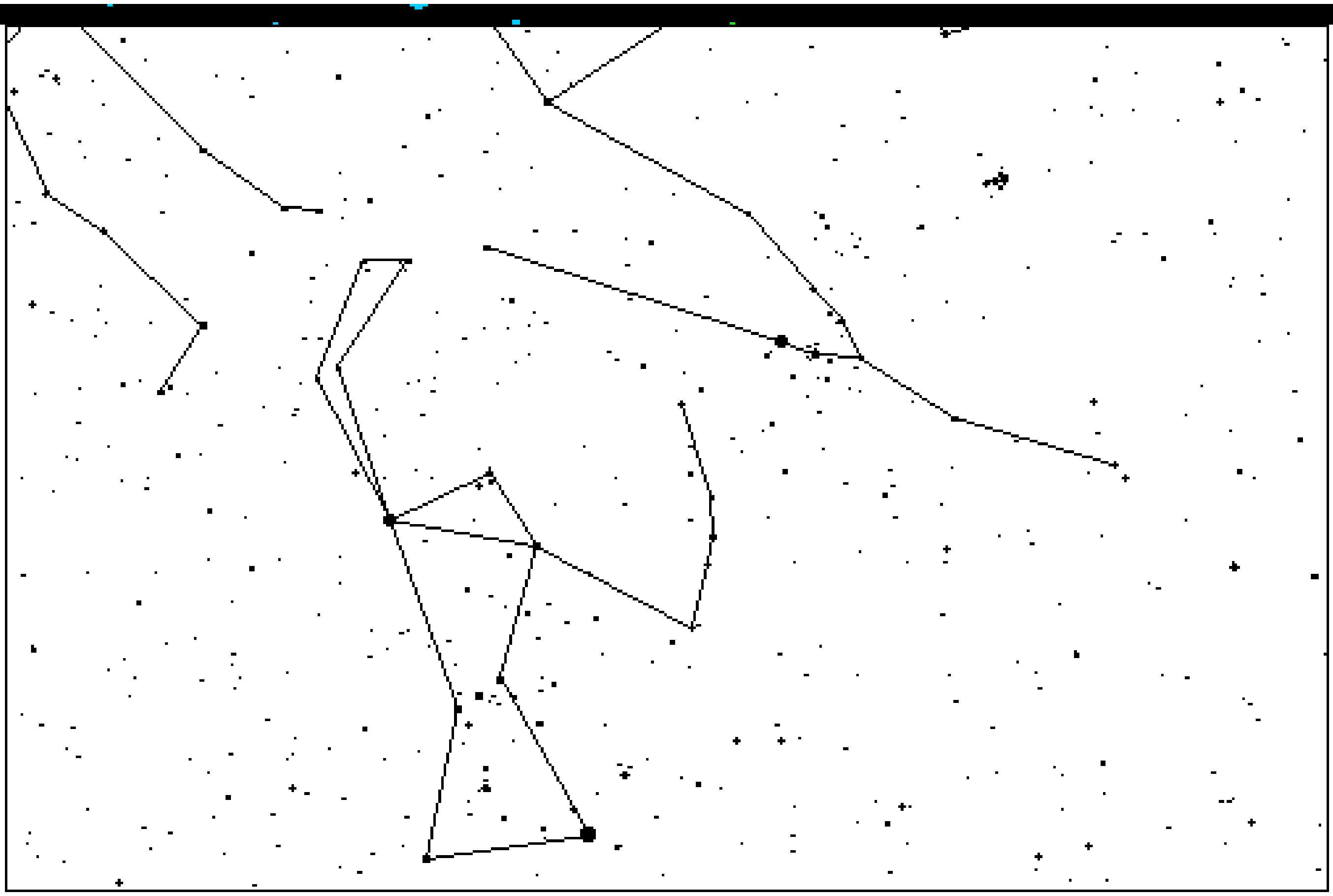
- The stars are grouped into **constellations**.

  Most of these are the same ones described by the ancient Greeks and Babylonians, although the southern hemisphere has many that were "created" by European explorers a few centuries ago.

  The ancients thought of the constellations as representing mythical figures such as Orion the Hunter and Taurus the Bull.



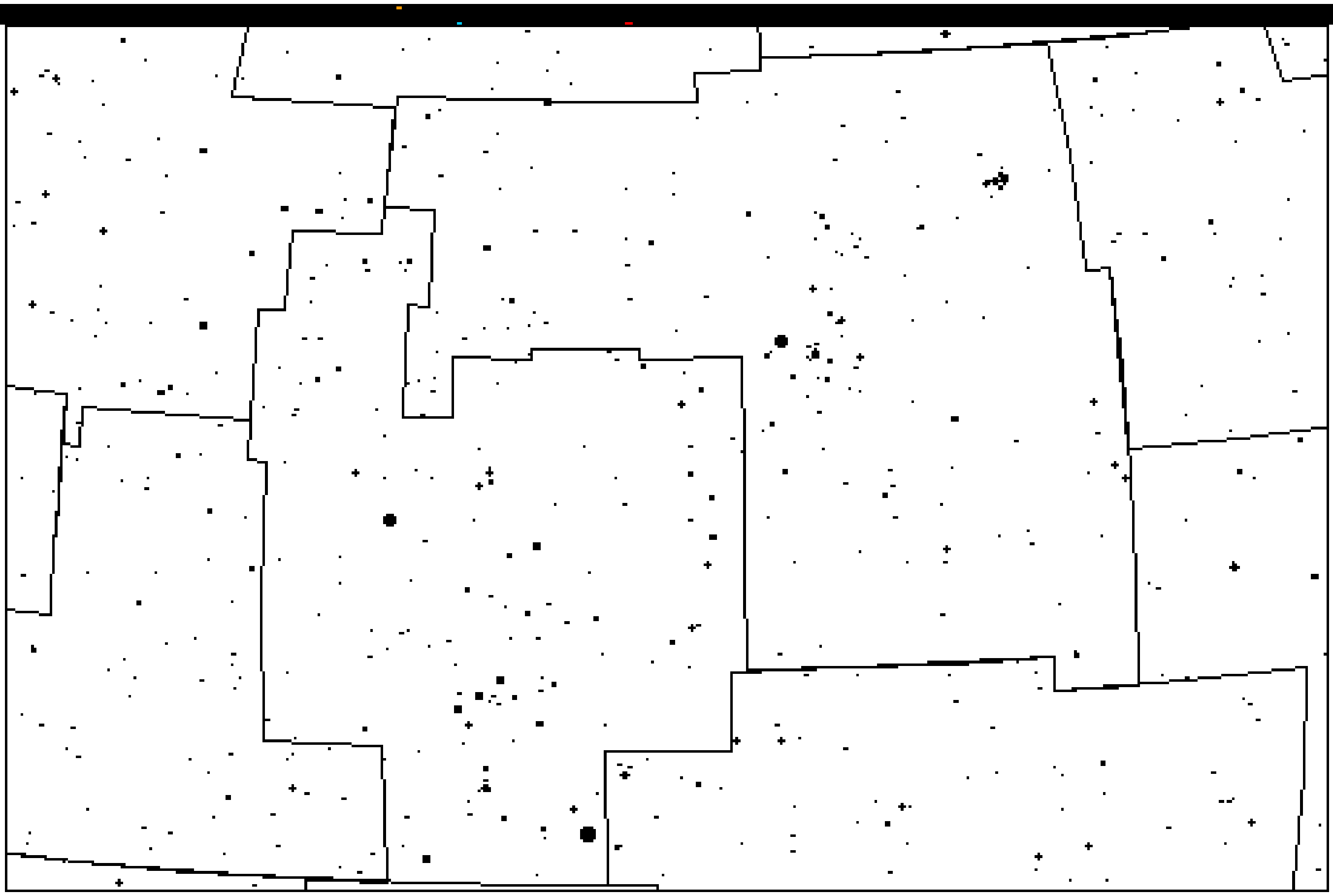
- Nowadays we often think of constellations as "stick figures", consisting of lines connecting the major stars.



- These figures leave out many stars and other objects, including those that require telescopes to be seen.

  So, astronomers now think of a constellation as one of 88 *regions* that divide up the sky and completely cover it.

  Any object can now be said to lie in one constellation or another.



- Many stars have names from Arabic or Greek, e.g. Betelgeuse means "armpit" in Arabic.

  The stars are also given names such as "Alpha Orionis", using letters from the Greek alphabet followed by the constellation name.

  After that, numbers are typically used, e.g. "37 Orionis".

  This ordering is typically (but not always) according to brightness.

  Extra: an extensive listing of common Star Names and their meanings.

  Extra: purchased star names are not recognized by any scientific organization. See the Naming Stars statement by the International Astronomical Union for more information on how astronomical names are actually selected.

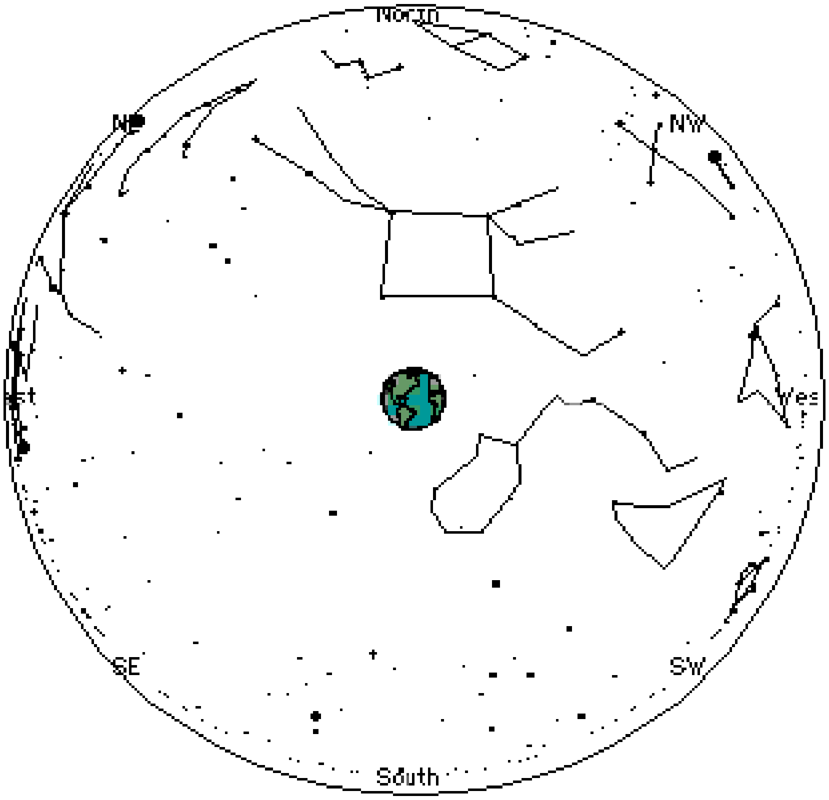
2.2 The Celestial Sphere

(Discovering the Universe, 5th ed., §1-3)

- An important characteristic of the stars is that they have relatively fixed positions with respect to each other, i.e. the constellations do not change with time.
  - The stars do actually move, but this motion is only noticeable to the unaided eye after a long time, tens of thousands of years or more.
  - Nearby stars also exhibit parallax, but this is only visible in a telescope.

- Although the stars have many different distances from the Earth, this is not distinguishable with the naked eye (again, it requires a telescope).

- It is therefore useful to think of the stars as being "painted" on the interior surface of a large sphere centered on the Earth, called the **celestial sphere**.



- As you are no doubt aware, the Earth rotates once a day.

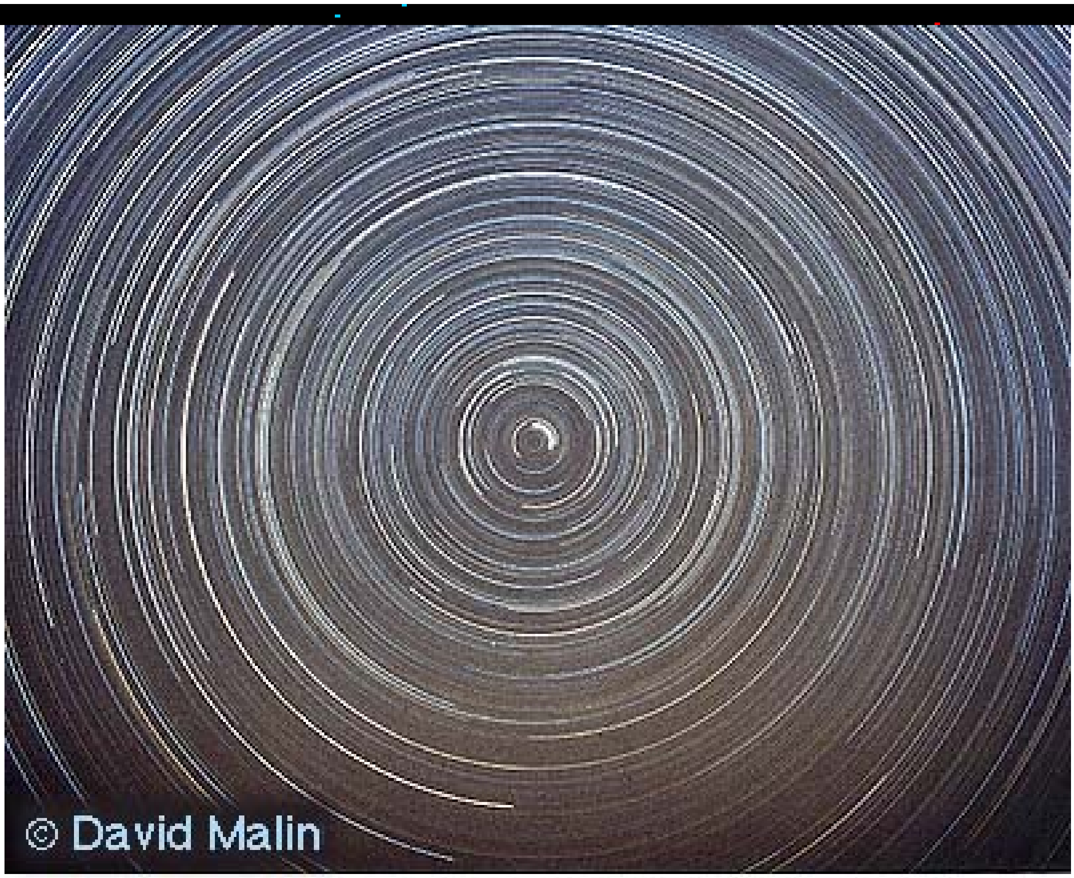
  We cannot detect this motion, however, so it appears to us as if the stars (and Sun and Moon and planets) are rotating around *us*: they rise in the east and set in the west, once a day.

  This is called **diurnal motion**.

- We can imagine diurnal motion as being due to the "rotation" of the celestial sphere around the Earth.

Picture Information

- This motion can be seen in the time-lapse photograph at the right, centered on the north pole of the celestial sphere.



2.3 Latitude and Longitude

(Discovering the Universe, 5th ed., §1-4)

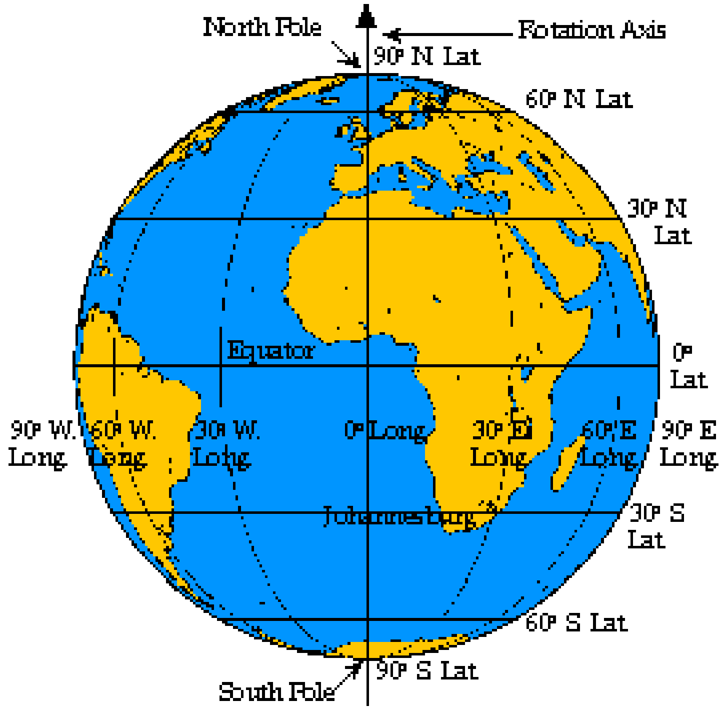
- It is useful to be able to precisely specify positions on the celestial sphere.

  So, a set of coordinates is used that is similar to latitude and longitude on the Earth.

  The system of latitude and longitude was first suggested by Hipparchus, a Greek astronomer in the 2nd C. B.C.

- Recall that the Earth's **rotation axis** is a line that passes through the **geographic poles** (the **North** and **South Poles**), and the center of the Earth.

  The Earth rotates around this axis, leaving the poles fixed.



- The **equator** is a circle on the Earth's surface that is perpendicular to the axis and equidistant from the poles.

  It is a **great circle** because it is centered on the Earth's center, making it as large as possible.

  The **northern hemisphere** is the half of the Earth north of the equator, and the **southern hemisphere** is the half south of the equator

- Any circle parallel to the equator is called a circle of **latitude**.

  The angle (with vertex at the center of the Earth) between a given circle of latitude and the equator describes that circle and any point on it.

  So, the North Pole is at 90° north latitude, the equator itself is 0° latitude, and Johannesburg, South Africa is roughly 30° south latitude.

- Any semicircle passing through the poles is called a **meridian of longitude**.

  One of these is designated as the **prime meridian**, namely the one passing through the Royal Observatory in Greenwich, England (just outside London).

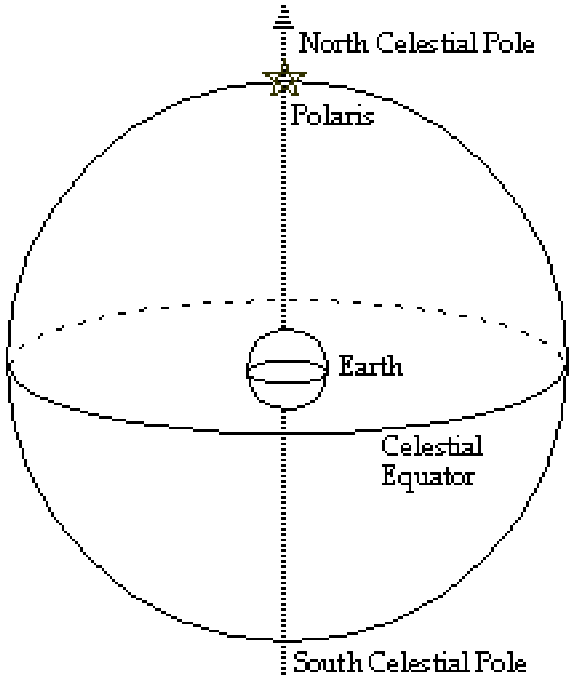
  The angle (with vertex at the center of the Earth) between a given meridian and the prime meridian describes that meridian and any point on it.

  So, Johannesburg is at 30° east longitude.

  Note that 180° west longitude is the same meridian as 180° east longitude.

2.4 Celestial Coordinates

(Discovering the Universe, 5th ed., §1-2)



- We describe the celestial sphere using a similar geographical notation:
  - The **North Celestial Pole** is the point on the celestial sphere directly above the Earth's North Pole.

    Similarly, the **South Celestial Pole** is directly above the Earth's South Pole.
  - The star Polaris, in the constellation Ursa Minor, is located very close to the North Celestial Pole.

    Polaris is therefore also called the **North Star**.

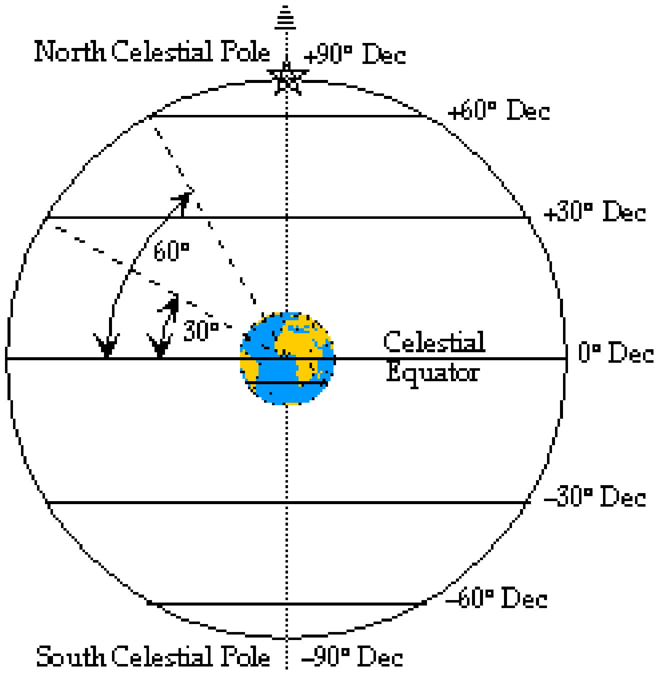
    Question: can you identify Polaris in the photo of the polar sky above?
  - The **celestial equator** is directly above the Earth's equator.

- Positions on the celestial sphere can also be measured relative to these markings, although different names are used besides latitude and longitude.

- **Declination** corresponds to latitude, and is measured in the same way, but relative to the celestial equator (0° dec).

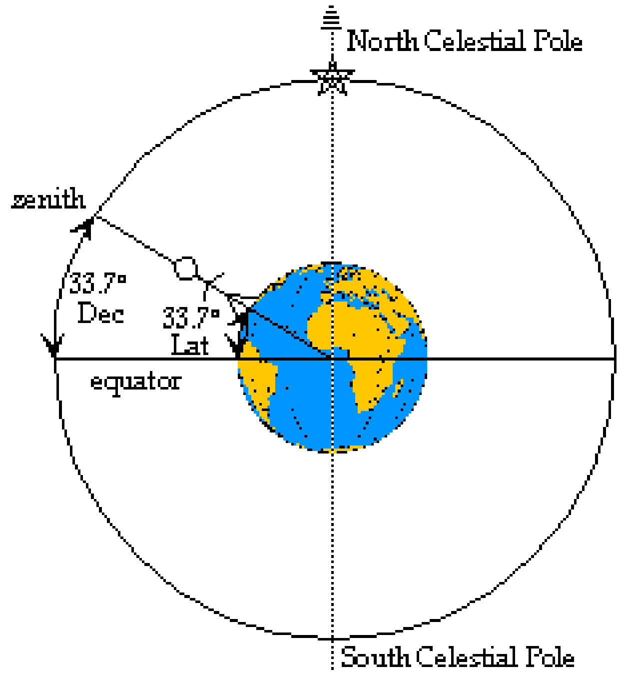
  The north celestial pole is at 90° north declination (+90° dec). The south celestial pole is at 90° south declination (-90° dec).

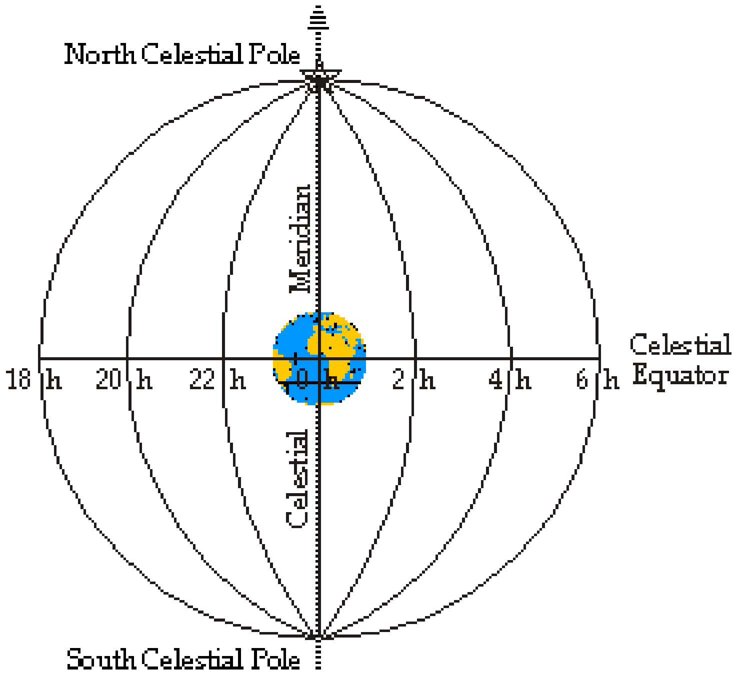
  Circles of constant declination are all parallel to the celestial equator.



- For any position on the surface of the Earth, the point on the celestial sphere that is directly overhead is called the **zenith**.

  Since the Earth and the celestial sphere are concentric, simple geometry shows that the zenith will always have a declination equal to the latitude of the observer (such as for Atlanta in the picture).





- A star's position along a circle of constant declination is described by a second number called **right ascension**.

  Right ascension corresponds to longitude, but different units are used.

  Instead of 360°, a circle is broken into 24 hours of right ascension.

  So, 360° = 24 h R.A., 15° = 1 h R.A., and 1° = 4 min R.A.

  Note that hours of right ascension is a unit of *angle*, not time, although there is an obvious connection due to the daily rotation of the celestial sphere.

- Right ascension is measured from the **celestial meridian**, chosen to be 0 h R.A. (which is also the same as 24 h R.A.)

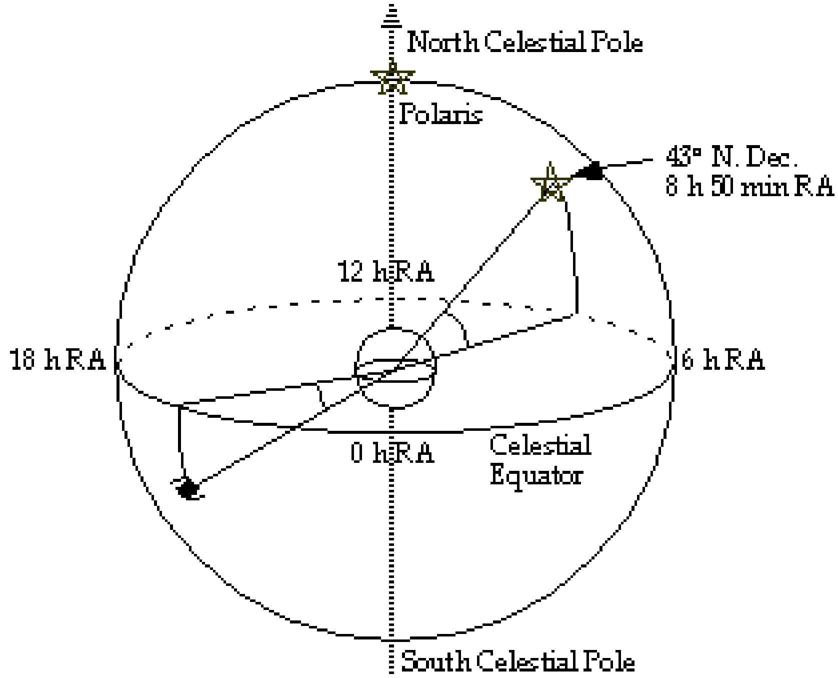
  The celestial meridian is a semicircle connecting the celestial poles and passing through a particular point on the celestial equator called the **vernal equinox** (defined below).

  Question: to what position on Earth is the vernal equinox analogous?

  Right ascension increases from west to east (note that we are looking at the *exterior* of the celestial sphere in the above picture).

- With the two numbers of declination and right ascension, the position of any object in the sky can be precisely described.

  Question: what is the approximate position of the galaxy shown?



2.5 The Motion of the Sun

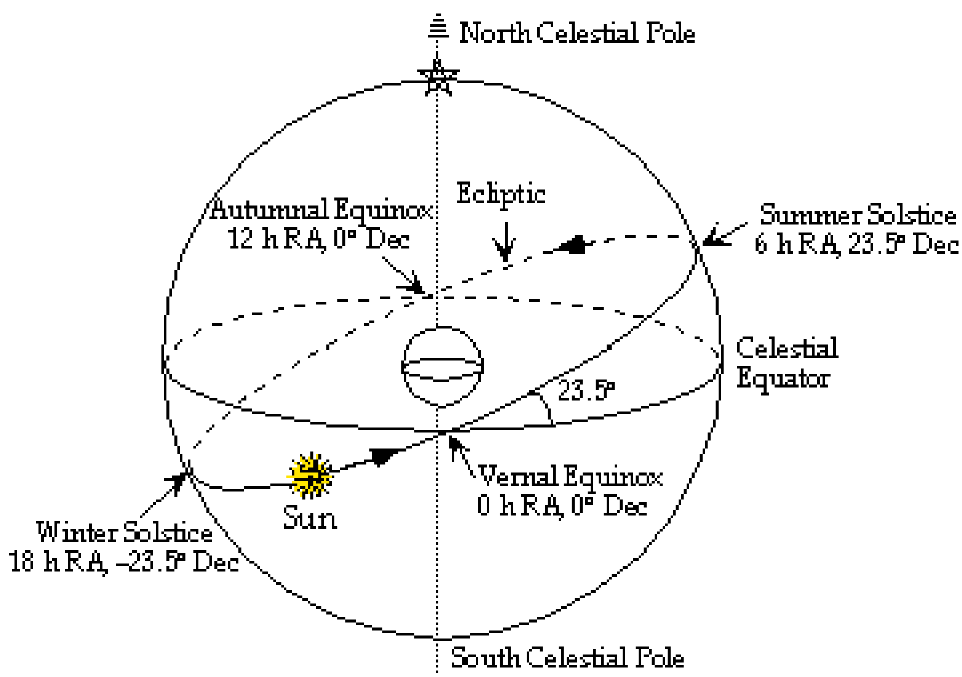
(Discovering the Universe, 5th ed., §1-6)

- Although the stars are fixed relative to each other, the Sun moves relative to the stars.

  Once a year, the Sun traces out a circle on the celestial sphere called the **ecliptic**.

  The ecliptic is tilted at an angle of 23.5° with respect to the celestial equator.

  (The Moon and planets also move near the ecliptic.)



- The Sun crosses the celestial equator at exactly two points, called **equinoxes**, from the

Latin for "equal nights" (for reasons we'll see later).

- The equinox where the Sun ascends from the southern to the northern hemisphere is called the **spring** or **vernal equinox** because the Sun is there on March 21.

  The vernal equinox is chosen to be 0 h R.A.

- The Sun again crosses the celestial equator halfway around, at 12 h R.A.

  This position is called the **autumnal equinox** because the Sun is there on September 23.

- The positions where the Sun reaches its highest and lowest points are called **solstices**, from the Latin for "the Sun stops" as it changes direction.

- The Sun is highest in the sky (in the northern hemisphere) when it is at 6 h R.A.

  This position is called the **summer solstice** because the Sun is there on June 21.

  The Sun then has a declination of +23.5°.

- The Sun is lowest in the sky (in the northern hemisphere) when it is at 18 h R.A.

  This position is called the **winter solstice** because the Sun is there on December 21.

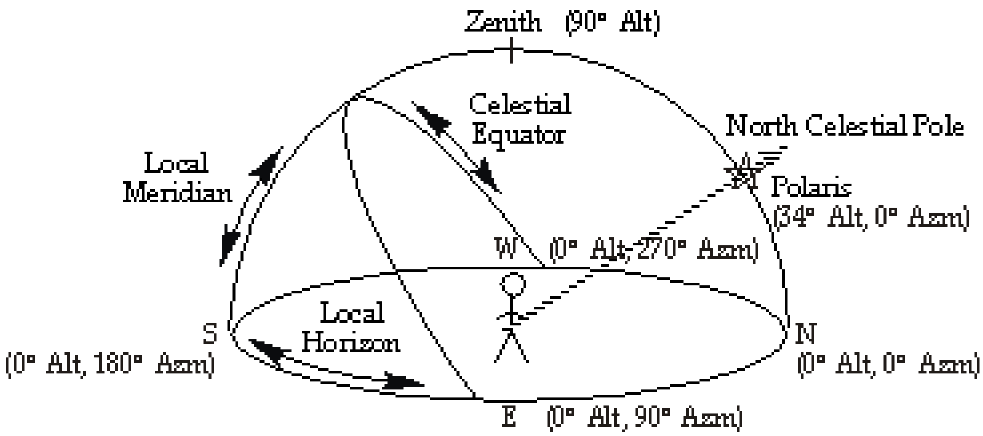
  The Sun then has a declination of -23.5°.

2.6 The Local Horizon

(Discovering the Universe, 5th ed., §1-6)

- To an observer on the Earth, only one half of the celestial sphere can be observed at a time.

  As a result, in Atlanta the sky appears roughly as shown at the right.



- The **local horizon**, often just called *the* **horizon**, is the circle that divides the Earth and the sky from each other.

  The compass directions north, south, east, and west are marked along the horizon.

  North will be underneath the north celestial pole.

  When we face north, east is on our right and west is on our left.

- Another coordinate system that is commonly used to locate objects in the sky is the **altazimuth** system, which is based on the local horizon.

  The **altitude** of an object is the angle between it and the horizon.

  The horizon has an altitude of 0° and the zenith has an altitude of 90°.

  The **azimuth** of an object is the angle between it and north, measured clockwise along the horizon.

  North has an azimuth of 0°, east has an azimuth of 90°, south has an azimuth of 180°, and west has an azimuth of 270°.

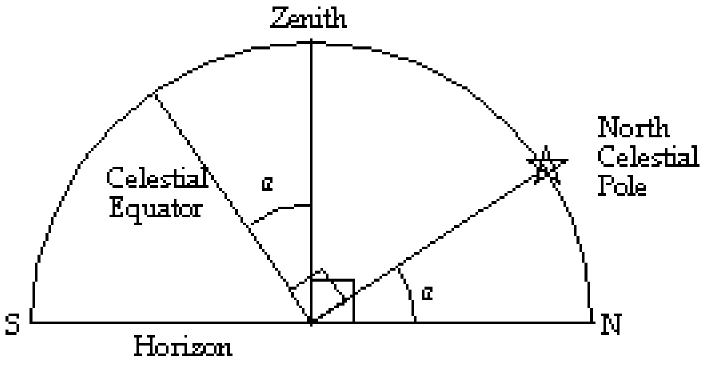
- The **local meridian**, often just called *the* **meridian**, is a semicircle that passes through the celestial poles and the zenith.

  Question: the local meridian is a projection onto the celestial sphere of what previously described item on the Earth?

- Note that the horizon, zenith, and meridian are fixed relative to the observer; hence the stars and sun will move past them with time.

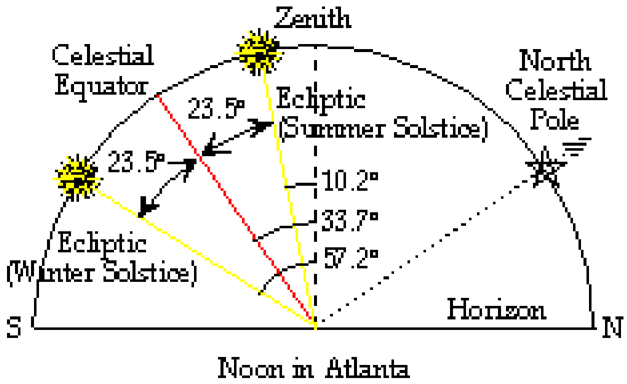
  Question: what happens to these items when the observer moves to a different location on the Earth?

- Simple geometry shows that the angle between the zenith and the celestial equator (i.e. the zenith's declination) must also be the angle between the north celestial pole and the north horizon.

  Since the zenith's declination is equal to one's latitude, Columbus was always able to determine his latitude when he crossed the Atlantic Ocean by measuring the altitude of Polaris.

- During the summer, the Sun is located near the summer solstice, north of the celestial equator.

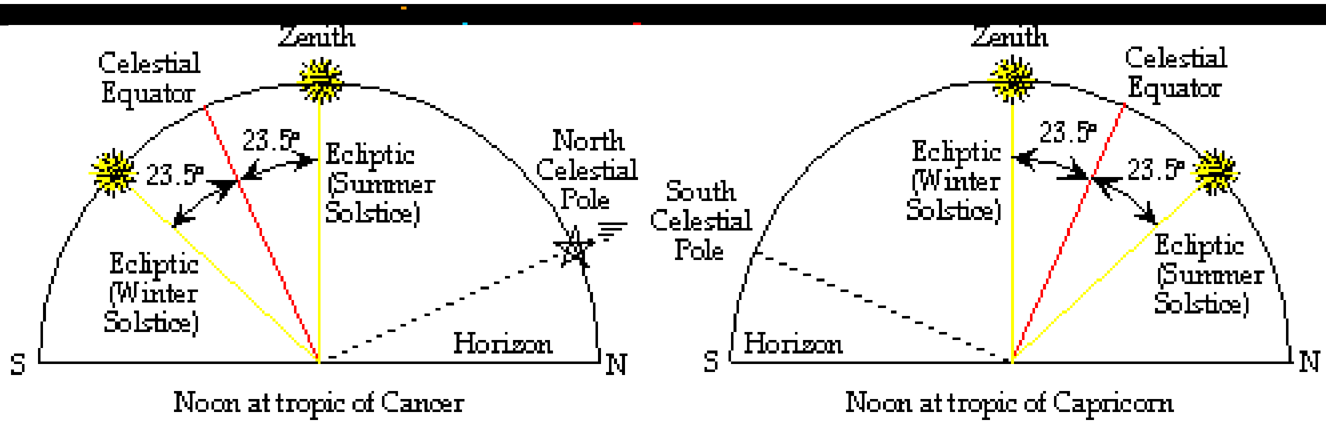
  In Atlanta, it therefore appears high in the sky at transit, 33.7° - 23.5° = 10.2° away from the zenith.

- During the winter the Sun is near the winter solstice, south of the celestial equator.

  In Atlanta, it therefore appears low in the sky at transit, 33.7° + 23.5° = 57.2° away from the zenith.

- At a latitude of 23.5° N, the **tropic of Cancer**, the Sun just reaches the zenith on the summer solstice.

  At 23.5° S, the **tropic of Capricorn**, it just reaches the zenith on the winter solstice.



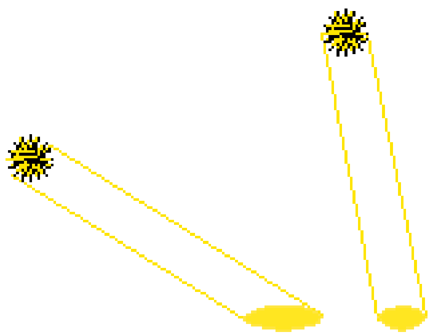
Between these latitudes (the **tropics**), the Sun crosses the zenith twice during the year.

Tropic is from the Greek for "turning", again describing the Sun's motion at the solstice.

Cancer and Capricorn are the constellations where the Sun is located at the solstices (or rather where it was located in 500 B.C...).

- The closer the Sun is to the zenith, the more concentrated its light is on the Earth's surface, so the more energy it transfers.

  This is why summer is warmer and winter is colder, and why the tropics are warm year round.



2.7 Day and Night

(Discovering the Universe, 5th ed., §1-4)

- We define the **synodic day** as the time for the Sun to transit *twice*.

  The synodic day is defined to be exactly 24 hours long, i.e. it is the "day" you are familiar with.

- When the Sun is at transit we say it is 12 **noon**.

  Since this can only happen at one longitude at a time, it used to be that every town had its own "time zone".

This was a nightmare for the railroads to keep track of, so in the 19th century they convinced Congress to implement time zones, breaking up the country into four broad areas that shared the same clock time.

This meant that, for most places, noon no longer occurred when the Sun was at transit, but it simplified scheduling, especially when broadcast radio and TV came along.

Atlanta is on the western edge of the Eastern Time Zone, so the Sun doesn't transit until 12:40 P.M. EST (1:40 P.M. EDT).

- As the Sun rises and approaches the meridian, it is "before the meridian" or **ante meridian** (A.M.).

  As the Sun sets toward the horizon, it is "after the meridian" or **post meridian** (P.M.).

- Because the Sun is so bright, we can only see the stars at night.

  These are the stars on the *opposite* side of the celestial sphere from the location of the Sun.

  But *which* stars we see depends on the time of the year, because the Sun moves along the ecliptic!

  The Sun moves about one degree, or 4 minutes of RA, along the ecliptic every day (360°/365 d).

  This solar motion means that a particular star will rise (or transit, or set) about 4 min earlier on each subsequent night.

  The **sidereal day** is defined as the time for a star to cross the meridian twice.

  The sidereal day is equal to 23 h 56 min 14 s.

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Thanks to Martin Weinelt and his Online Map Creation web page, which generated most of the images of the Earth used in this document.

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Introduction to Astronomy

Lecture 3: The Motion of the Earth

Look in the calendar, and bring me word.

-- Shakespeare, *Julius Caesar*

3.1 The Solar System Viewpoint

(Discovering the Universe, 5th ed., §1-4, §1-6)

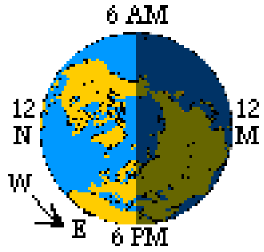
- We now know that the diurnal motion of the stars and the Sun is due to the Earth's rotation.

  In addition, the movement of the Sun along the ecliptic is actually because of the Earth's revolution around the Sun.

- Let's now consider the point of view where we are fixed with respect to the stars, located above (north of) the Earth, looking down on it and observing these motions.

- First we notice that, looking down on the Earth's north pole, it is **rotating** *counterclockwise*.

  Such a rotation is essentially a definition of a "north pole".



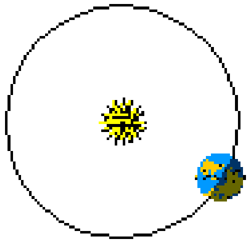
- The side of the Earth facing the Sun is in daylight, and the side away from the Sun is at night.

  Twelve noon would be halfway through the daylight portion, and twelve midnight would be on the opposite side of the Earth, halfway through the night portion.

- The Sun sets around 6 P.M. as we are carried into the dark side, and rises around 6 A.M. as we are carried back into daylight.

- Since the Sun rises in the east and sets in the west, these directions must be defined in terms of the rotation: east is in the direction of rotation and west is opposite to that direction, no matter where we stand on the surface of the Earth.

- Continuing further "north", we are able to see the Earth's orbit around the Sun.



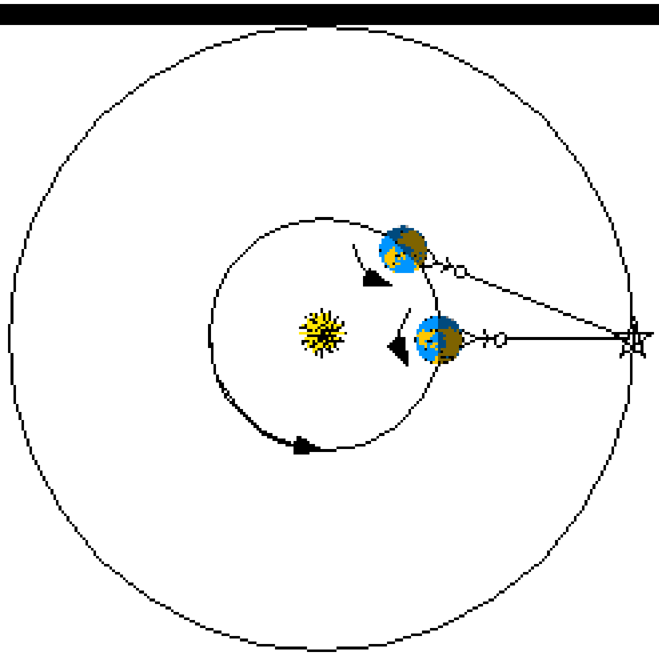
  The Earth's orbit is very nearly circular, and it defines a plane in space called the **plane of the ecliptic**.

  As the Earth moves around the orbit, we say that the Earth **revolves** around the Sun (to distinguish this motion from rotation).

  The Earth's revolution is in the *same* counterclockwise direction as its rotation.

- Because of the revolution of the Earth, stars shift their position relative to the Sun.

  For example, in the picture at the right (representing the passage of about two months' time), a star which was overhead at midnight (i.e. directly opposite the Sun) is now overhead at a different time.

  Question: about what time is it in the second position?

  As a result of the Earth's revolution, from day to day a particular star will transit (or rise, or set) at earlier and earlier times.

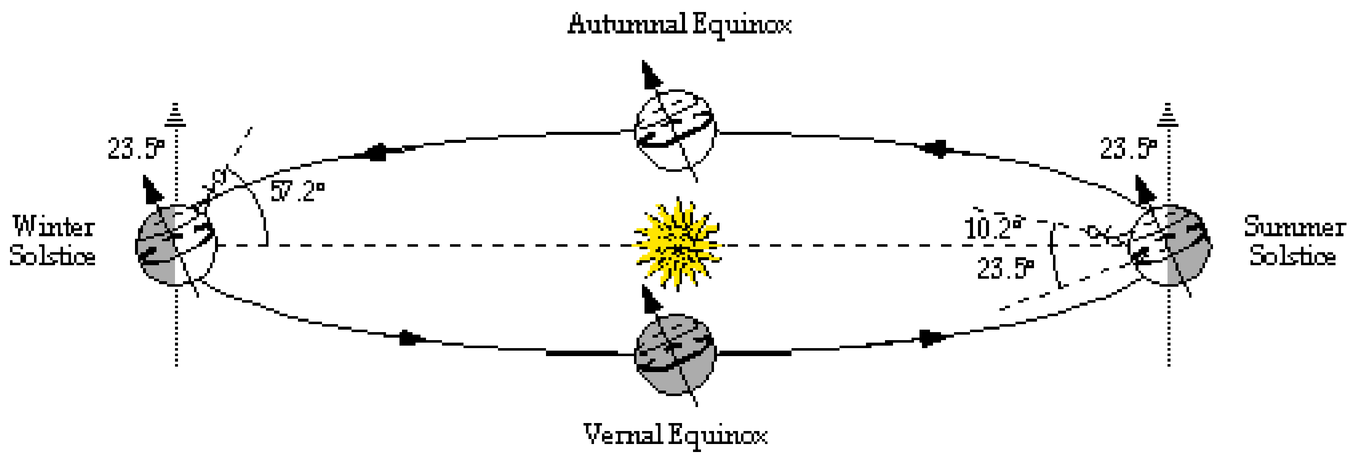
  This is the same 4 min/day differentiating the sidereal day from the synodic day.

3.2 The Tilt of the Earth's Axis

(Discovering the Universe, 5th ed., §1-6)

- Moving from directly above the Earth's orbit down outside one edge of the orbit, we can get a perspective view.

  We then observe that, with respect to the perpendicular to the ecliptic plane (which points to **orbital north**), the Earth's axis is tilted at an angle of 23.5°:

  Equivalently, we can say that the Earth's equator is at an angle of 23.5° to the ecliptic plane.

The tilt angle is fixed, so the Earth's axis maintains the same orientation with respect to the stars as the Earth revolves around the Sun.

- When the Earth's north pole is tilted directly towards the Sun, the latter is highest in the sky (in the northern hemisphere), which is what we called the summer solstice.

  Here in Atlanta, the Sun is 33.4° - 23.5° = 10.2° away from the zenith at the summer solstice.

- When the north pole is tilted directly away from the Sun, the latter is lowest in the sky (in the northern hemisphere), which is the winter solstice.

  Here in Atlanta, the Sun is 33.4° + 23.5° = 57.2° away from the zenith at the winter solstice.

- As before, the intermediate positions are the vernal and autumnal equinoxes.

  Here in Atlanta, the Sun is 33.7° away from the zenith at the equinoxes.

- Note that (in the northern hemisphere) daytime (the light part of the circle the person is standing on) is longest at the summer solstice, and it is shortest at the winter solstice.

  Question: what effect will this have on daily temperature?

  Daytime and nighttime have roughly equal length at the equinoxes, hence the name,which means "equal night".

3.3 Precession

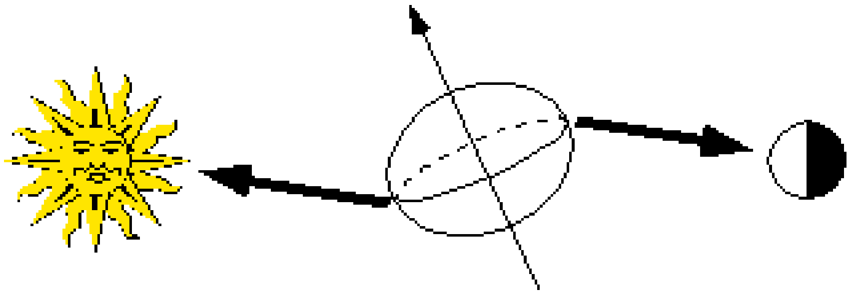
(Discovering the Universe, 5th ed., §1-7)

- The Earth is not a perfect sphere; instead, it is slightly **oblate**, i.e. it bulges in the middle along the equator.

  This bulge is due to its rotation and the fact that it is not completely rigid.

  As a result, the equatorial diameter is 43 Km greater than the polar diameter, a difference of 0.34%.

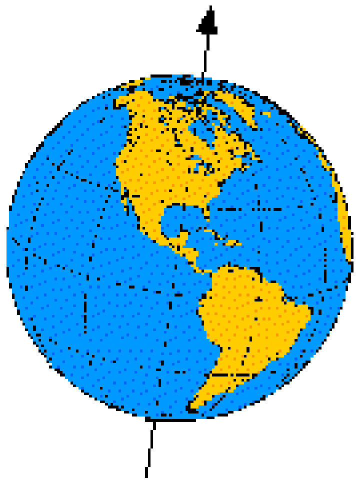
- Because the force of gravity weakens with distance, the Sun and Moon have non-uniform gravitational forces on the Earth, pulling harder on the near side of the bulge than on the far side.

  This differential gravitational force is called a **tidal force**.

  Basically, the Sun and Moon try to "straighten" the rotation axis to bring it in line with the orbital axis.

- However, instead of straightening, the Earth's rotation axis **precesses**, i.e. it exhibits a slow, conical motion around the orbital axis.

  Precession is the same effect you see with a top.

  As long as it is spinning, the top does not fall over, and likewise the Earth's axis won't straighten.

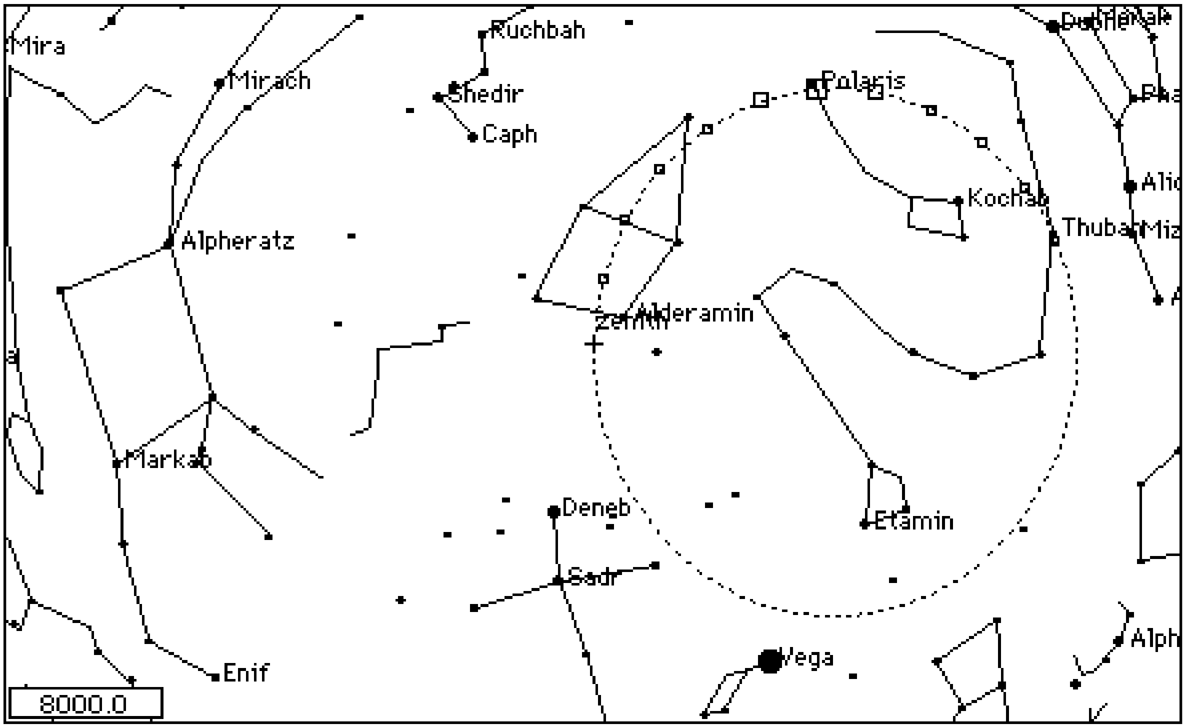
- The Earth's precession is a very small effect; it takes 26,000 years for the axis to make one full circle!

  Currently the Earth's axis points within a degree of the star Polaris, and it will slowly get closer until around the year 2100, when it reaches a minimum separation of 27 minutes of arc.

  Almost 5000 years ago the Earth's axis pointed towards the star Thuban in the constellation of Draco, and this star was used by the ancient Egyptians as their pole star.

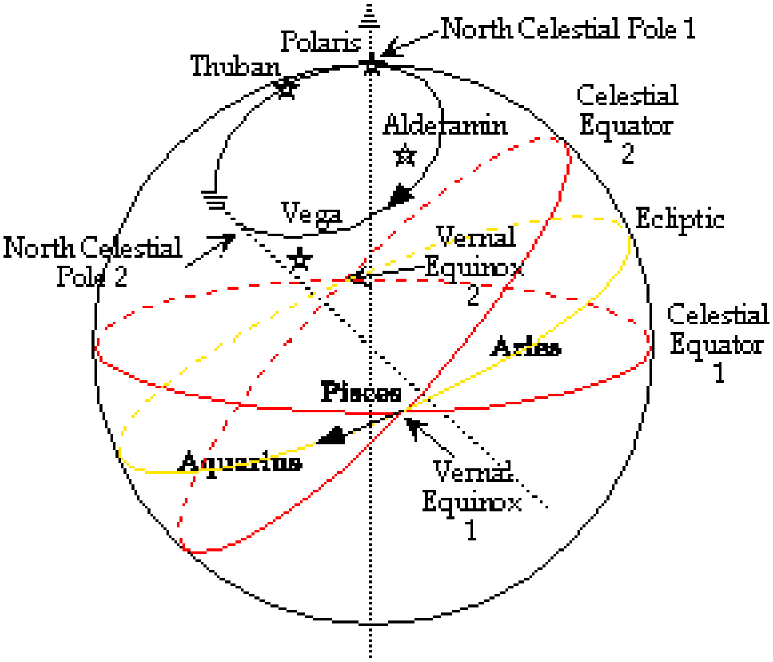
In 6,000 years the Earth's axis will point towards the star Alderamin in Cepheus, and in 12,000 years it will be near Vega in Lyra.

The Earth's precession can be easily observed by standing at the Earth's north pole, where the north celestial pole is at the zenith, and watching how that point changes over time (note the year in the lower-left corner):



- The circle traced out by the north celestial pole can also be observed on the celestial sphere.

  Two different positions, now and 13,000 years in the future, are noted in the picture at the right.



- As the precession of the axis occurs, the orientation of the celestial equator will also change, since it is necessarily perpendicular to the axis.

- However, the ecliptic is fixed on the sphere.

As a result, the intersections between the celestial equator and the ecliptic, the equinoxes, move along the ecliptic 50 arc sec (3.3 sec R.A.) per year.

The vernal equinox moves in the direction shown.

Currently, the vernal equinox is in Pisces; 2000 years ago it was in Aries; in another 1000 years, it will move into Aquarius.

- This movement of the celestial equator relative to the ecliptic is called **precession of the equinoxes**.

  Obviously, this effect is so slow that it is only observable over many years.

  Precession was discovered by the Greek astronomer Hipparchus, who had access to several centuries of Greek and Babylonian records.

3.4 The Calendar

(Discovering the Universe, 5th ed., §1-5)

- The **sidereal year** is defined to be the time for the Sun to return to the same position against the stars.

  The sidereal year is equal to 365.25 d + 9 min 10s.

- The **tropical year** is the time for the Sun to return to the same position relative to the Earth's axis, e.g. summer solstice to summer solstice.

  Because of precession, the tropical year is 20 min 24 s shorter than the sidereal year, equal to 365.25 d - 11 min 14 s.

- Neither of these is an integer number of days.

  The early Roman calendar (~300 B.C.) had 365 days per year, so it was short by roughly one day every four years.

  As a result, the date of the equinoxes and solstices moved *forward* on the calendar.

- In the original Roman calendar the vernal equinox was on March 24.

  By 45 B.C. it had moved into late May, so the first Roman Emperor Julius Caesar subtracted 63 days from the calendar to bring the equinoxes back to their traditional dates (more than two months were therefore "redone").

- To keep the equinoxes fixed, Caesar decreed that every four years an extra **leap day** would be added to the calendar, at the end of the year (February).

  A year with a leap day added is called a **leap year**, and this calendar is known as the **Julian Calendar**.

- Then, the calendar was *too long* by 11 min 14 s /year.

  Even this small amount can build up with time, and the vernal equinox began to move *backward* on the calendar, about 1 day every 128 years.

- By 325 A.D. the vernal equinox had moved three days to its current location on March 21.

  At this time the Roman Emperor Constantine I convened the Council of Nicaea, to establish dates for the Christian holidays.

  Easter, in particular, was based on the date of the vernal equinox.

- The vernal equinox continued to move backward on the calendar.

  By 1582 the vernal equinox had moved another ten days.

  On the advice of astronomers, Pope Gregory established a new calendar system which accounted for the extra 11 min 14 s.

  In the Julian calendar, century years had always been leap years; in the new calendar, that would no longer be true, *except* in years divisible by 400:

  1600 leap year
  1700 not a leap year
  1800 not a leap year
  1900 not a leap year

2000 leap year
2100 not a leap year
....

- This arrangement is known as the **Gregorian Calendar.**

  Since there is still not a perfect match with the tropical year, even further corrections will eventually be necessary.

- Gregory also added ten days to the calendar to bring the vernal equinox back in alignment with the dates established by the Council of Nicaea.

  Ten days were therefore "lost" when October 5, 1582 was decreed to be October 15, 1582.

  Now the vernal equinox always occurs on or near March 21.

- Despite its scientific merit, the Gregorian Calendar was widely distrusted in northern Europe, which had only recently broken away from the Catholic church in the Reformation, and in the Eastern Orthodox countries of eastern Europe.

  So, it wasn't until 1752 that the Gregorian Calendar was finally adopted by England and its colonies.

  Most eastern European countries didn't adopt the Gregorian Calendar until the early 20th century!

- **Extra:** you can learn more details about calendars, including non-western calendars, at the [Calendars and their History](#) web site.

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Last update: 2002 February 13
Please send questions, comments, suggestions, or corrections to srca@mindspring.com.

Introduction to Astronomy

Lecture 4: The Motion of the Moon

O dark, dark, dark, amid the blaze of noon,
Irrecoverably dark, total eclipse
Without all hope of day!

-- John Milton, *Samson Agonistes*, 1671

4.1 The Phases of the Moon

(Discovering the Universe, 5th ed., §1-8)

- The Moon orbits the Earth roughly once a month.

  Looking down on the Earth and Moon from above the Earth's north pole, we see that its revolution is in the *same* direction as the Earth's rotation (and also the Earth's revolution around the Sun).

- The Moon shines by reflected sunlight.

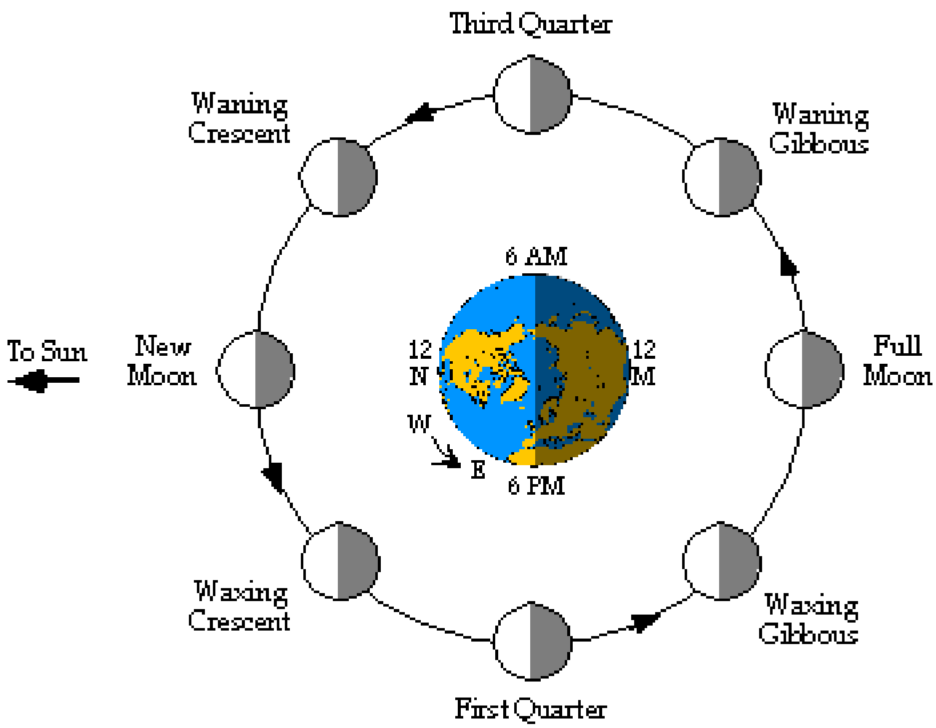
Therefore, at any time only one half of the Moon, the side facing the Sun, is illuminated.

The dividing circle between the light side and the dark side is called the **terminator**.

- The illuminated side of the Moon is *not* necessarily the half which faces the Earth.

  Depending on the relative positions of the Sun, Moon, and Earth, we see different fractions of the Moon illuminated.

  These are called the **phases** of the Moon.



- At **new moon**, we can't see any of the illuminated half of the Moon; at **full moon** we can see all of it.

- Halfway in between new and full moon, we see *half* of the illuminated half of the Moon, or a **quarter** of the Moon.

  First quarter occurs as the Moon moves from new to full; **third** or **last quarter** occurs as the Moon moves from full to new.

- Between the new and quarter moons, only a small fraction of the Moon is illuminated; we call this a **crescent moon**.

  Between the quarter and full moons a larger fraction of the Moon is illuminated; we call this a **gibbous moon**.

  When the Moon moves from new to full, it becomes more illuminated, and we say that it is **waxing**. When it moves from full to new, it becomes less illuminated, and we say that it is **waning**.

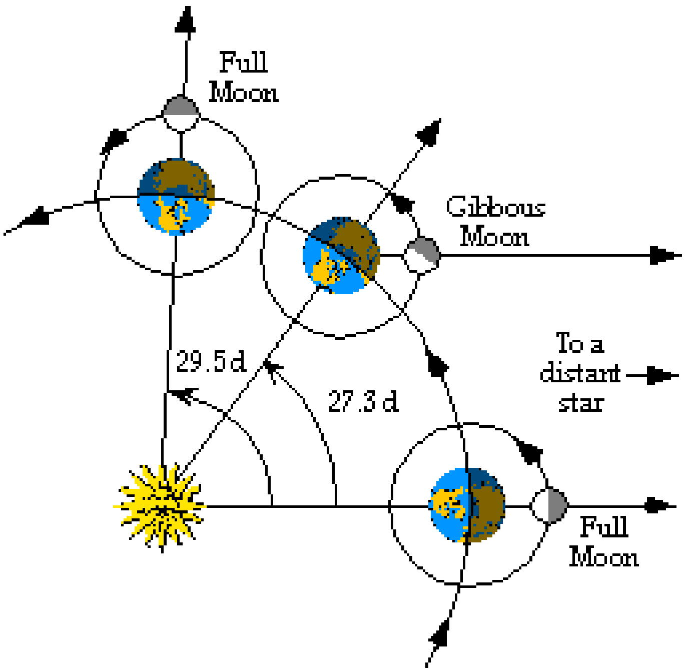
- On any particular night, the Moon will essentially be motionless.

  As can be seen from the diagram above, a full moon must therefore rise around 6 P.M., be overhead at midnight, and set around 6 A.M.

  A first quarter moon must rise around noon, be overhead around 6 P.M., and set around midnight.

  Crescent moons are overhead during the day, but they are generally only visible near sunrise/sunset (both because of their small illumination *and* the brighter light from the Sun).

  Question: if it's 3 A.M. and the Moon is rising, what phase is it?



- The **synodic month** is defined as the time it takes for the Moon to return to the same position relative to the Sun, e.g. from full moon to full moon.

  The synodic month is equal to 29.5 days.

- The **sidereal month** is defined as the time it takes for the Moon to return to the same position relative to the stars; it is equal to 27.3 days.

  The sidereal month is shorter than the synodic month because of the revolution of the Earth around the Sun, as can be seen at the right.

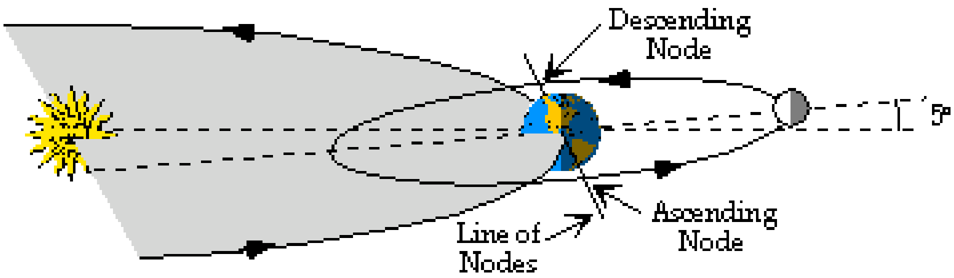
  The Moon doesn't have to travel as far around its orbit to line up with the same distant star.

  (Note: the motion of the Earth around the Sun is exagerated in this picture to clarify the positions.)

4.2 Eclipses

(Discovering the Universe, 5th ed., §1-9)

- The Moon's orbit is inclined at an angle of 5° to the Earth's, so it is usually either above or below the plane of the ecliptic.



- The points where it crosses the ecliptic are called the **ascending** and **descending nodes**, depending on whether it is moving north or south, respectively.

- The line connecting the two nodes is called the **line of nodes**.

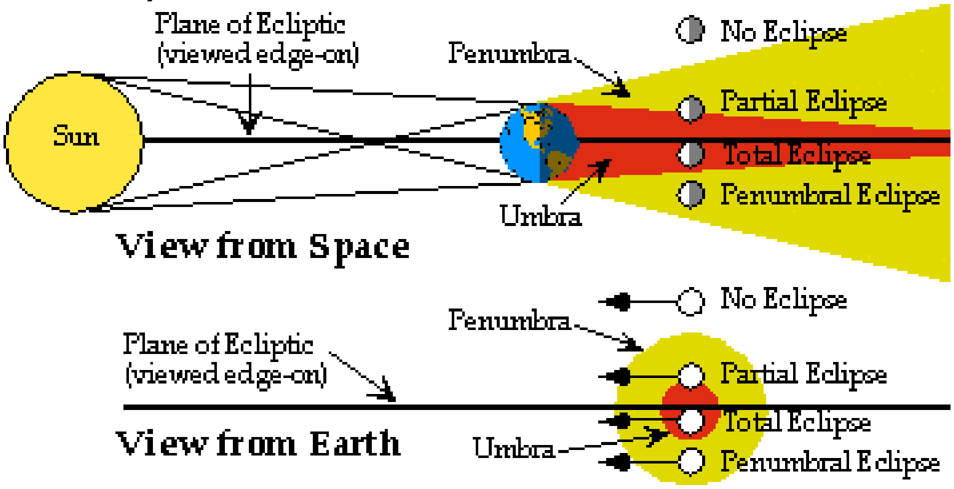
  Question: a line is also the intersection of two planes; what are those two planes for the line of nodes?

- Sometimes, when the Moon passes through the ecliptic, it will happen to be full (directly opposite the Sun) or new (directly towards the Sun).

  At these positions and phases, an **eclipse** will occur, when the Moon or Sun "fails to appear", which is the Greek meaning of the word (this is also the origin of the name *ecliptic*).

4.3 Lunar Eclipses

(Discovering the Universe, 5th ed., §1-10)



- A **lunar eclipse** occurs when the Moon is full and it is close enough to the ecliptic that it passes partially or completely through the Earth's shadow.

  A lunar eclipse can be observed from anywhere on the night side of the Earth.

- The darkest part of the Earth's shadow is called the **umbra**; it is where the Sun's light is completely blocked out.

  The umbra is not totally dark, however, because the Earth's atmosphere scatters red light into it.

- The Earth's partial shadow is called the **penumbra**; it is where the Sun is only partially blocked by the Earth.

Photo information

- When the Moon completely enters the umbra, a **total lunar eclipse** occurs as the Moon almost disappears from view.

  The long-exposure photograph at the right shows the entire span of a total eclipse.

  Because of the scattered light in the umbra, the Moon does not completely disappear but takes on a dull red hue which brightens toward the edge of the umbra.

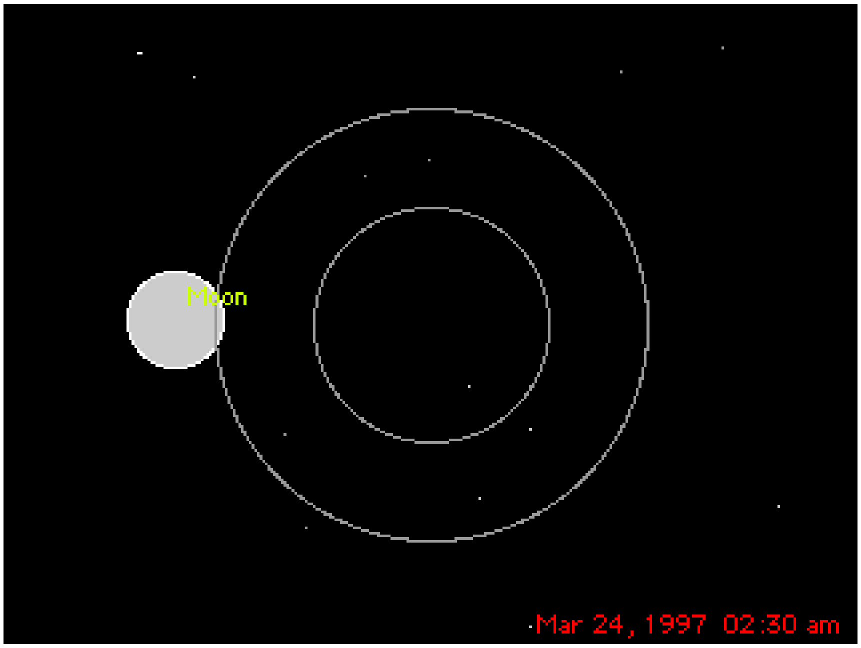
Photo information

- A total lunar eclipse can last as long as 1 h 42 min, depending on how close to the center of the umbra the Moon passes and its distance from the Earth.

  The total lunar eclipse shown above right lasted 1 h 18 min.

- A **partial lunar eclipse** occurs when the Moon only passes partway through the umbra.

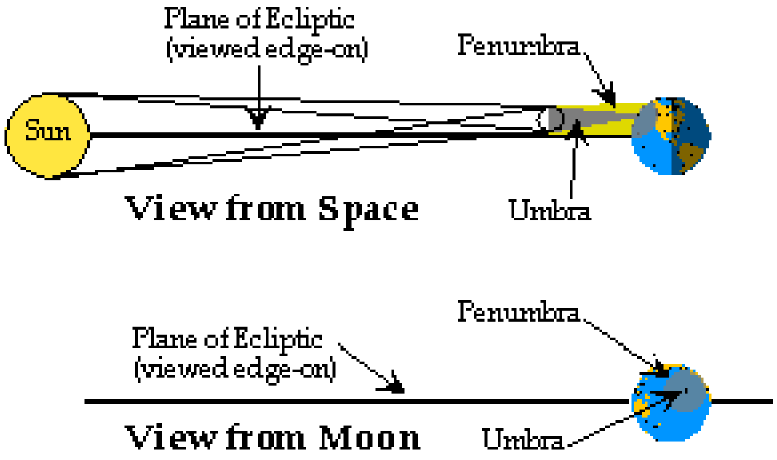
  The eclipse at the right was 92% total (more details).



- A **penumbral lunar eclipse** occurs when the Moon only passes through the penumbra.

4.4 Solar Eclipses

(Discovering the Universe, 5th ed., §1-11)



- A different kind of eclipse, a **solar eclipse**, occurs when the Moon is new and it is close enough to the ecliptic that its shadow partially or completely reaches the Earth.

- The Moon's **umbra** forms a circular region on the surface of the Earth, and if you are in that shadow the Sun is blocked out.

  This is a **total solar eclipse**.

Photo information

- The Moon's umbra has a maximum diameter on the surface of the Earth of 270 Km.

  The umbra of the eclipse of August 11, 1999 can be seen at the right.

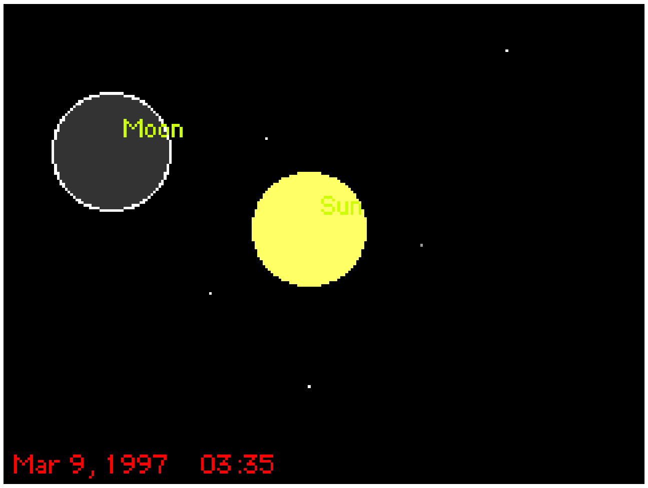
Photo information

- A total solar eclipse is dark enough that animals will actually begin their nocturnal habits, e.g. birds will stop chirping.

  Once again, however, a total solar eclipse is not completely dark, because the dim glow of the Sun's atmosphere can be observed around the edge of the Moon.

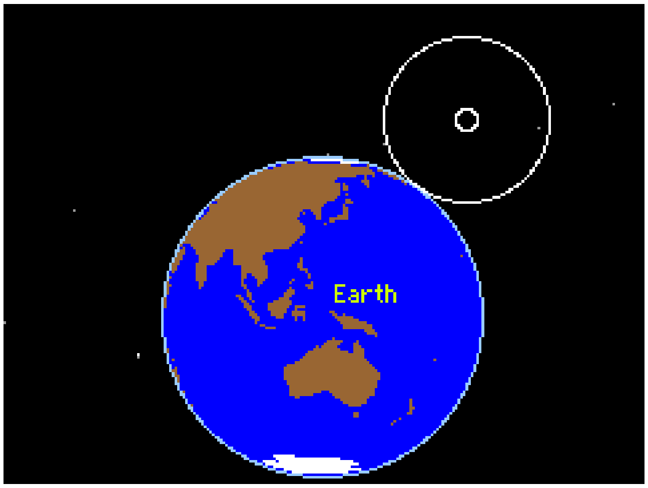
More details

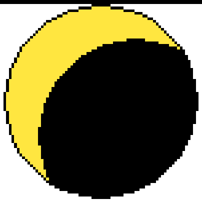
- As the Moon moves in its orbit, we see the Moon pass across the face of the Sun:



- The shadow moves rapidly across the surface of the Earth, sweeping out a narrow path as it speeds by at about 0.5 Km per second.

  As a result, the maximum time that a total solar eclipse can last is 7.5 min, depending on the shadow's size and speed.

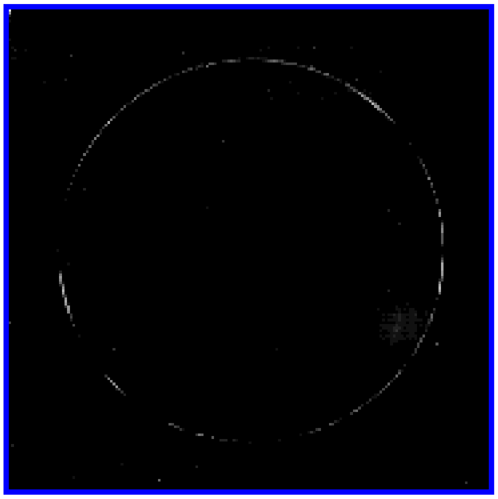




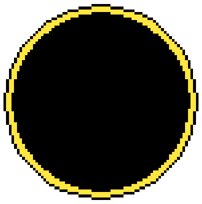
- If you are located in the Moon's **penumbra**, which is much larger than the umbra, the Sun is only partially blocked out.

  This incomplete covering of the Sun is called a **partial solar eclipse**.

Photo information



- When the Moon is farthest from us, the tip of the umbra doesn't quite reach the Earth.

  From our point of view here on the Earth, the Moon does not quite cover the Sun, so a ring of sunlight will surround it.

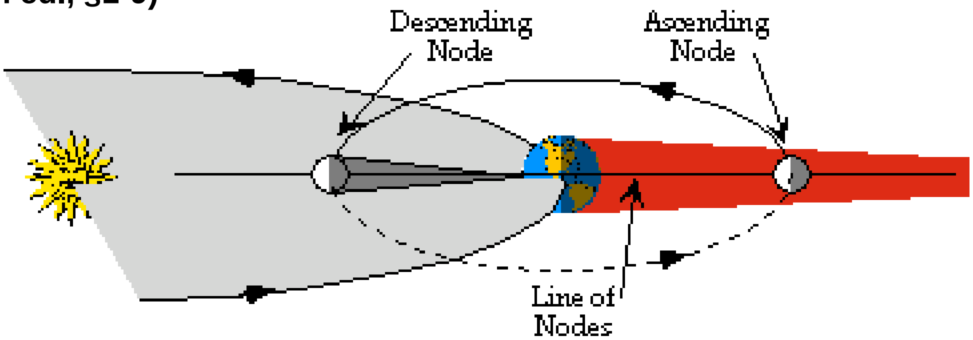
  This type of partial eclipse is called an **annular eclipse**.

  The eclipse at the right is just barely annular.

4.5 The Frequency of Eclipses

(Discovering the Universe, 5th ed., §1-9)

- As mentioned above, eclipses can only occur when the Moon is close to a node and it is also either full or new.

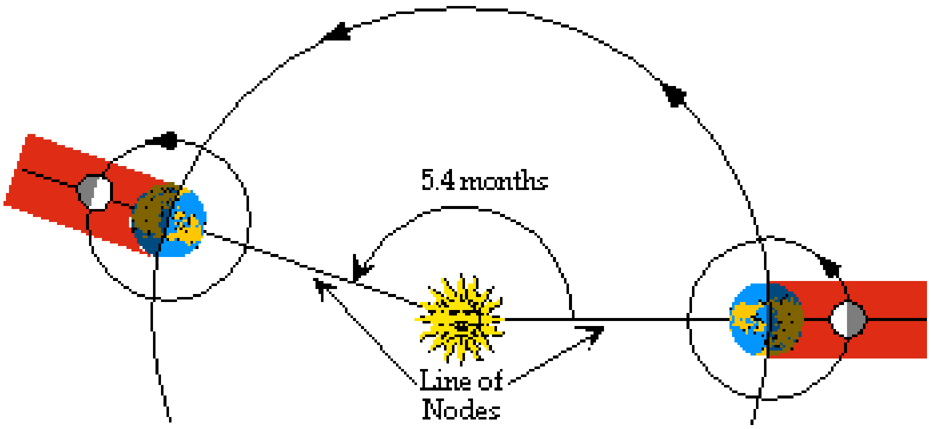


  For this alignment to happen, the line of nodes must point near the Sun.

- Just like the Earth's axis, the line of nodes is relatively fixed in space.

  With no other forces acting, the line of nodes would therefore be in line with the Sun every six months.

- However, also like the Earth's axis, the gravitational force of the Sun on the Moon causes the line of nodes to precess.

  This precession is a much more noticeable effect than the Earth's precession, with one every 19 years.

  As a result, the time between alignments is decreased to about 5.4 months.

- Because of the finite size of the Earth, Moon, and their shadows, multiple eclipses can occur whenever the line of nodes points near the Sun.

  So, eclipses are actually very common!

  During a one-year period, there can be between two and five eclipses of each kind (solar and lunar), with a total of between four and seven.

  This includes partial and penumbral lunar eclipses, and partial and annular solar eclipses.

- Lunar eclipses are much more likely to be observed, since anyone on the night side of the Earth can see them.

  Solar eclipses, on the other hand, cover only a small fraction of the Earth, and often occur over unpopulated locations such as the polar regions or the oceans.

- The table below lists upcoming eclipses for the next several years:

Eclipses for 1997 - 2002
(Dates and Times are Atlanta Local)

Date (Peak)	**Time (Peak)**	**Type**	**Fraction of Totality**	**Duration of Totality**	**Where Visible**
1997 Mar 8	8:24 PM	Solar, Total	100%	2 min 50 s	East Asia, Alaska

1997 Mar 23	11:39 PM	Lunar, Partial	92%	---	Americas
1997 Sep 1	8:04 PM	Solar, Partial	90%	---	Australia, Antarctica
1997 Sep 16	2:47 PM	Lunar, Total	100%	1 h 2 min	Europe, Africa, Asia, Australia
1998 Feb 26	12:28 PM	Solar, Total	100%	4 min 9 s	Americas
1998 Mar 12	11:20 PM	Lunar, Penumbral	0%	---	Americas
1998 Aug 7	10:25 PM	Lunar, Penumbral	0%	---	Americas, Europe, Africa
1998 Aug 21	10:06 PM	Solar, Annular	97%	---	Southeast Asia, Australia
1998 Sep 6	7:10 PM	Lunar, Penumbral	0%	---	East Asia, Australia, Americas
1999 Jan 31	11:17 AM	Lunar, Penumbral	0%	---	Asia, Australia, Hawaii, Alaska
1999 Feb 16	1:34 AM	Solar, Annular	99%	---	South Africa, Antarctica, Australia
1999 Jul 28	7:34 AM	Lunar, Partial	40%	---	Australia, Hawaii, North America
1999 Aug 11	7:03 AM	Solar, Total	100%	2 min 23 s	Europe, North Africa, Middle East
2000 Jan 20	11:43 PM	Lunar, Total	100%	1 h 18 min	Americas
2000 Feb 5	7:49 AM	Solar, Partial	58%	---	Antarctica
2000 Jul 1	2:32 PM	Solar, Partial	48%	---	South Pacific
2000 Jul 16	9:56 AM	Lunar, Total	100%	1 h 48 min	Asia, Australia, Hawaii, Alaska
2000 Jul 30	10:13 PM	Solar, Partial	60%	---	Siberia, Alaska
2000 Dec 25	12:35 PM	Solar, Partial	72%	---	North America
2001 Jan 9	3:20 PM	Lunar, Total	100%	1 h 2 min	Eastern Americas, Eurasia, Africa, Australia
2001 Jun 21	8:04 AM	Solar, Total	100%	4 min 57 s	Southern Africa
2001 Jul 5	10:55 AM	Lunar, Partial	50%	---	Eastern Africa, Asia, Australia
2001 Dec 14	3:52 PM	Solar, Annular	97%	3 min 53 s	Central America
2001 Dec 30	5:29 A.M.	Lunar, Penumbral	0%	---	Asia, Australia, Americas

2002 May 26	8:03 AM	Lunar, Penumbral	0%	---	Eastern Asia, Australia, Western Americas
2002 Jun 10	7:44 PM	Solar, Annular	99.6%	23 s	Pacific
2002 Jun 24	5:27 PM	Lunar, Penumbral	0%	---	South America, Africa, Europe, Asia, Australia
2002 Nov 19	8:46 PM	Lunar, Penumbral	0%	---	Americas, Africa, Eurasia
2002 Dec 4	2:31 AM	Solar, Total	100%	2 min 4 s	Southern Africa, Australia

The information in this table is derived from NASA's The Eclipse Home Page, where you can find lots more information about eclipss..

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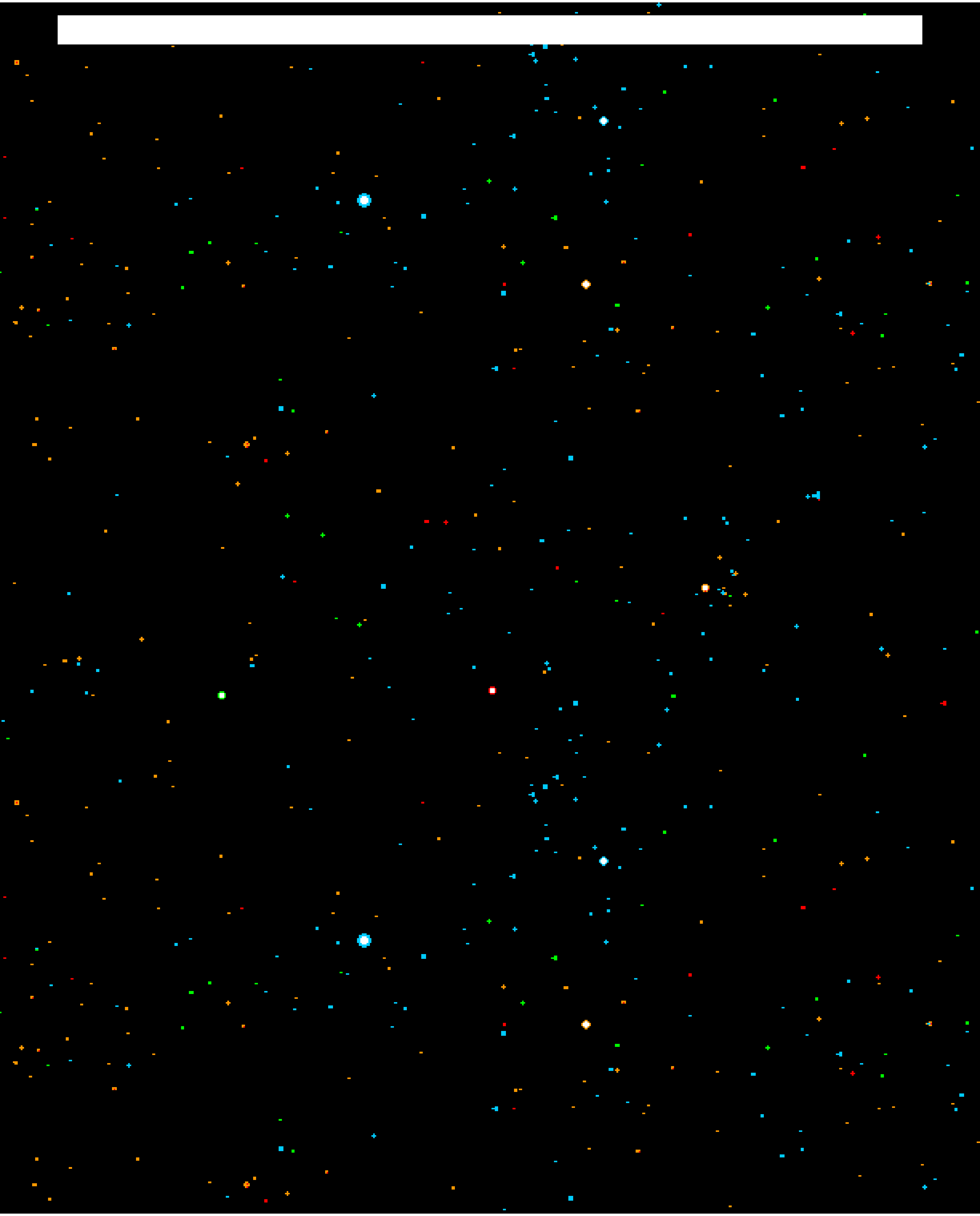


Introduction to Astronomy

Lecture 5: The Motion of the Planets

**The heavens themselves, the planets, and this centre
Observe degree, priority, and place,
Insisture, course, proportion, season, form,
Office, and custom, in all line of order:**

-- William Shakespeare, *Troilus and Cressida*, 1609

5.1 Direct and Retrograde Motion

(Discovering the Universe, 5th ed., §2-0)

- In addition to the stars, the Sun, and the Moon, there are several other objects in the sky which are easily visible at night.

  From the ancient perspective, a **planet** is a point of light in the sky that moves relative to the stars, much as the Sun and Moon do.

  The name comes from the Greek for "wanderer".

Photo Information

- With the naked eye, one can see five planets: **Mercury**, **Venus**, **Mars**, **Jupiter**, and **Saturn**.

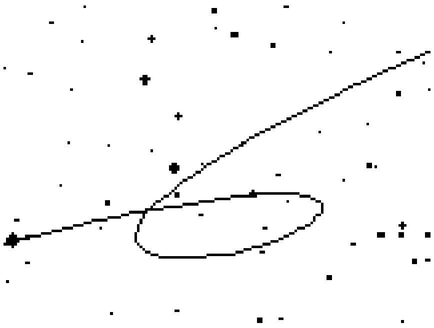
  Extra: the Sun, Moon, and planets are associated with ancient gods, and their number is the basis of our seven-day week.

- Like the Sun and the Moon, the planets all move near the ecliptic, never being more than a few degrees away.

  In the photo at the right, you can see (from top to bottom) Saturn, Venus, Jupiter, and Mercury in alignment with the recently set Sun.

- The planets move slowly enough that their positions change only slightly from night to night.

  They therefore rise in the east and set in the west as part of the sky's diurnal motion.



- Relative to the *stars*, however, the planets generally move from *west* to *east* , like the Sun and Moon.

  Their speeds vary, but Mercury is the fastest, followed by Venus, Mars, Jupiter, and then Saturn, the slowest.

  This motion is called **direct motion**.

- What distinguishes the planets from the Sun and Moon is that they will also sometimes *reverse* their motion, travelling from *east* to *west* relative to the stars.

  This reverse motion is known as **retrograde motion**.

  Retrograde motion can last from weeks (Mercury) to months (Saturn).

- The image below displays the actual retrograde motion of Jupiter (brighter) and Saturn (dimmer) over eleven months:

Photo Information

5.2 Geocentric Cosmology

(Discovering the Universe, 5th ed., §2-0)

- According to the laws of physics, there is no preference between saying that the Sun revolves around the Earth or the Earth revolves around the Sun.

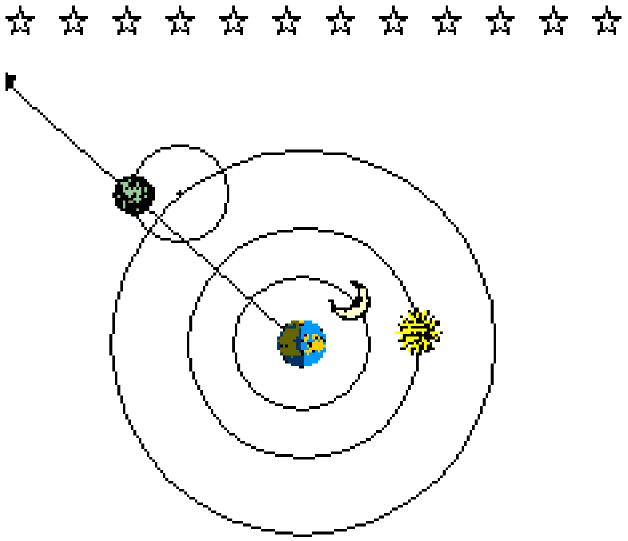
  Each are equally true, although one perspective may be more useful than the other for a particular purpose, as we have seen.

- When it comes to the planets, however, the principles of science forces one to make a distinction between an Earth-based view and a Sun-based view.

- Given that the motion of the Earth cannot be perceived, it is natural to assume the planets revolve around it. This is known as a **geocentric cosmology**, and it was widely accepted until just a few hundred years ago.

- A good scientist, however, must try and make sense out of retrograde motion, which cannot be simply explained in an Earth-centered perspective.

- The Greek astronomer Hipparchus described a model for retrograde motion which placed each planet in motion around a circle called an **epicycle**, which in turn revolved around a circle centered on the Earth called a **deferent**.

  The former produces the retrograde motion, while the latter is primarily responsible for the direct motion.

  In the adjacent animation, the arrow points towards the stars we see behind the planet; watch where the arrow points as the planet moves around its epicycle.

- In the 1st C. A.D., Ptolemy, an astronomer at the Alexandria observatory in Egypt, took Hipparchus' model and fit it to the several centuries of observational data that was available to him.

  For each planet, Ptolemy determined the sizes of its deferent and epicycle, and the speed of revolution of its epicycle and the planet itself.

  By projecting his model forward in time, Ptolemy was then able to correctly predict where the planets would be located centuries into the future.

  Because of the success of his model, Ptolemy's treatise on the subject, which became known as the *Almagest* ("the Greatest"), was the bible of astronomers through the Middle Ages.

- After a millenium, however, the Ptolemaic model increasingly deviated from the planets' observed motions.

  Other astronomers tried to correct it by adding additional levels of epicycles, but the result was exceedingly complex.

  It was clear that something was not quite right with this model.

5.3 Heliocentric Cosmology

(Discovering the Universe, 5th ed., §2-1)

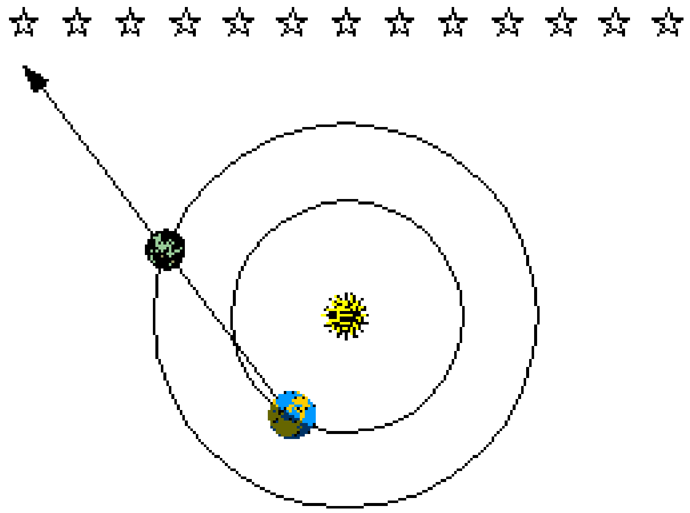
- An alternative to the geocentric cosmology was actually suggested a century before Hipparchus by Aristarchus (3rd C. B.C.).

- In the **heliocentric cosmology**, the planets orbit the Sun rather than the Earth.

  The Earth also orbits the Sun, but the Moon still orbits the Earth.

  Mercury and Venus (the **inner planets**) have smaller orbits than the Earth, while Mars, Jupiter, and Saturn (the **outer planets**) have larger orbits.

- The heliocentric cosmology also explains retrograde motion, by relying on the fact that the planets move at different speeds; in particular, inner planets move faster and outer planets move more slowly.

  As a result, the Earth will regularly overtake and pass the outer planets, and the inner planets will do the same to the Earth.

  Like one car passing another on the highway, the second car will appear to "move backward".

  This is another example of parallax.

- Although the heliocentric cosmology had a simpler geometry than the geocentric cosmology, it never achieved acceptance in ancient Greece because it required that the Earth move.

  The heliocentric cosmology was forgotten for almost 2000 years, until the 16th century, when the Polish astronomer Nicolaus Copernicus rediscovered it.

- Copernicus performed his own calculations using this model (assuming circular orbits), and found that he could describe the planets' observed motions to an accuracy similar to that of the geocentric model.

He was also able to make very accurate predictions of the planets' relative distances from Sun (see the table below).

- Although Copernicus was convinced that his heliocentric model was a well-founded improvement to astronomy, he delayed publication of his results until near the end of his life, presumably because he was concerned that his work was so radical that it would be rejected or lead to censure.

  Finally, in 1543, Copernicus' book *On the Revolutions of the Celestial Spheres* appeared, shortly before he died.

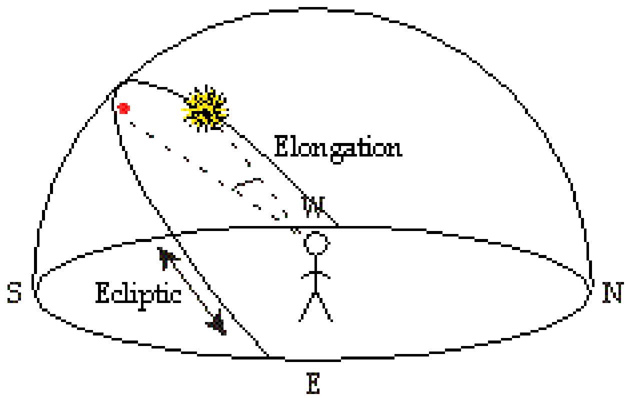
  The book was widely read in Europe, and gained enough support that it seriously threatened the geocentric model, which was virtually an article of faith in the Catholic Church.

  In 1616 the Church banned Copernicus' book (and the ban was not lifted until the end of the 18th century!).

5.4 Planetary Configurations

(Discovering the Universe, 5th ed., §2-1)

- For millenia, observational astronomers have described the positions of planets and other celestial bodies using several special configurations, which can be easily understood in terms of the Copernican model.



- The configuration between two celestial bodies can be described using the angle between them (measured along the ecliptic), which is called their **elongation**.

  Question: what other type of celestial angular measurement is elongation similar to?

- When two or more celestial bodies pass each other along the ecliptic, they have an elongation of 0°, and they are said to be in **conjunction**.

  At the right, the Sun and the red planet are in conjunction.

  Question: what is the phase of the Moon when it is in conjunction with the Sun?

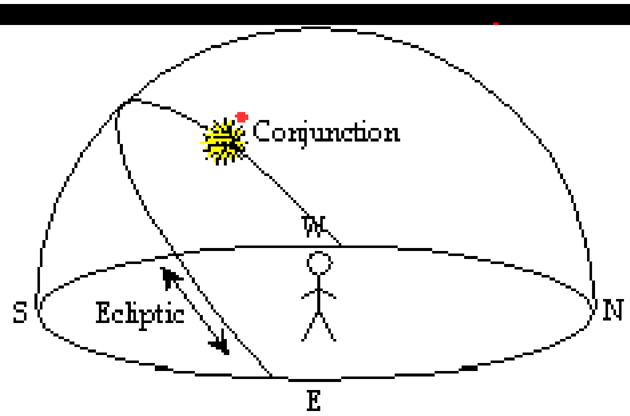


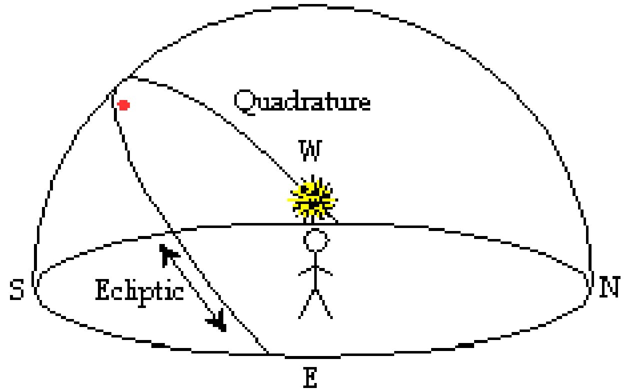
Photo Information

The image at the right shows a "triple" conjunction that occurred on April 23, 1998, between the Moon,Venus, and Jupiter.

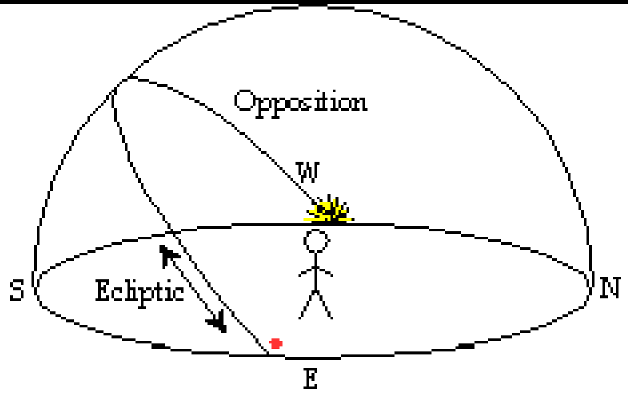
- When two celestial bodies are at right angles in the sky, they have an elongation of 90°, and they are said to be in **quadrature**.

  At the right, the Sun near the western horizon and the red planet near the meridian are in quadrature.

  Question: what is the phase of the Moon when it is in quadrature with the Sun?



- When two celestial bodies are directly opposite each other, they have an elongation of 180°, and they are said to be in **opposition**.

  At the right, the Sun near the western horizon and the red planet near the eastern horizon are in opposition.

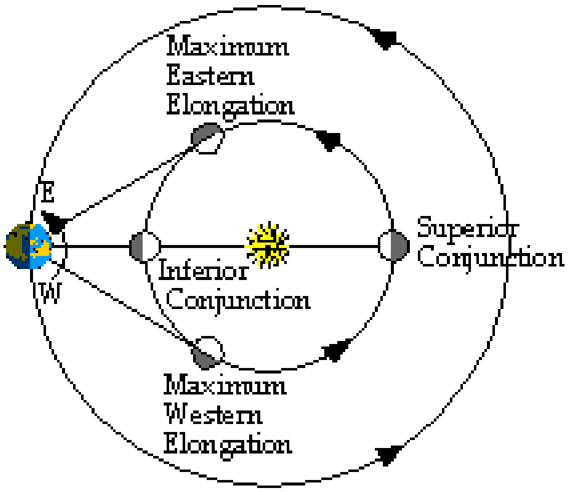
  Question: what is the phase of the Moon when it is in opposition to the Sun?

- Mercury and Venus differ from the other planets in that they never appear far from the Sun.

  Mercury is at most 23° away from the Sun, while Venus is at most 46° away; this is their **maximum elongation**.

  Maximum elongation of a planet is not readily explained using the geocentric model, but it arises naturally out of the heliocentric model, simply by assuming that the orbits of Mercury and Venus lie *inside* the Earth's orbit.

- Maximum elongation of an inner planet from the Sun can be seen from the geometry of the picture at the right; it is determined by the tangent line from the Earth to the planet's orbit.

  From the rotation of the Earth we can determine the relative directions of the planet and the Sun, allowing us to distinguish the two sides of the planet's orbit as **eastern** and **western**.

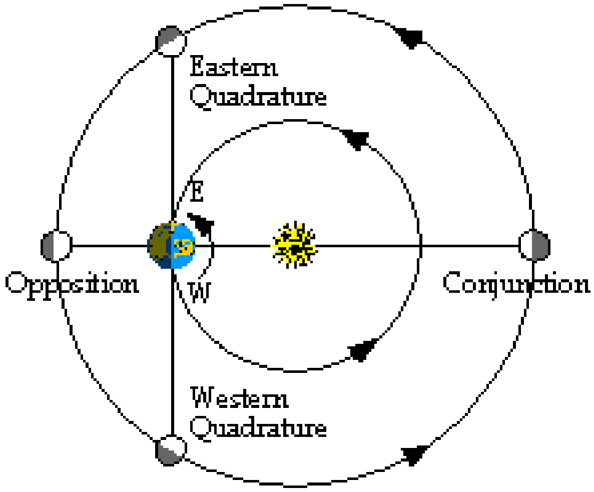
  When an inner planet is at maximum eastern elongation it will only be visible shortly after sunset (an "evening star"); when it is at maximum western elongation it will only be visible shortly before sunrise (a "morning star").

- Note that an inner planet can never be in opposition to (180° away from) the Sun, or even in quadrature (90° away).

- For the planet and the Sun to be in conjunction, they must be along the same line of sight from the Earth.

From the picture above we can see that there are two different ways in which an inner planet can be in conjunction with the Sun, one in between the Sun and the Earth (called **inferior conjunction**) and the other on the opposite side of the Sun from the Earth (called **superior conjunction**).

Question: as observed from Earth, what is the phase of the inner planet at each of the four positions in the picture?



- Unlike Mercury and Venus, Mars, Jupiter, and Saturn can appear in opposition to the Sun (180° away).

  In the heliocentric model, their orbits must therefore lie *outside* the Earth's orbit.

- An outer planet can be in opposition with the Sun, in quadrature with it (both **eastern** and **western quadrature**), and in conjunction with it (but only one way, corresponding to an inner planet's superior conjunction).

  Question: as observed from Earth, what is the phase of the outer planet at each of the four positions in the picture?

- It can be shown that an outer planet is least illuminated at quadrature.

  Question: when will an outer planet be brightest?

5.5 Orbital Period

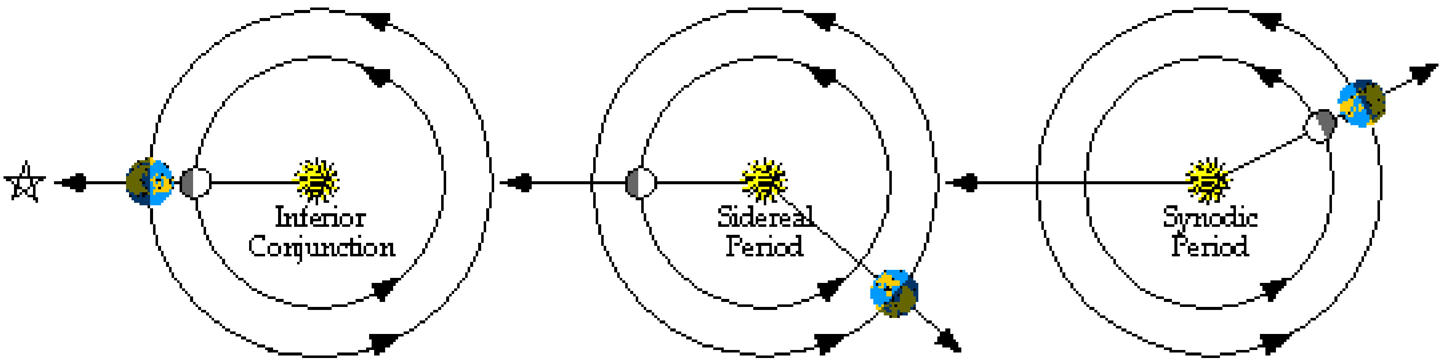
(Discovering the Universe, 5th ed., §2-1)

- The time it takes for a planet to complete one orbit is called the **orbital period of revolution**, often simplified to "orbital period" or just "period".

  As with the Moon, we must distinguish between star-relative and sun-relative positions when determining the period:

  The **sidereal period** of a planet refers to the time it takes for the planet to return to the same position with respect to the stars, e.g. from one position on its orbit back to the same position.

  The **synodic period** of a planet refers to the time it takes for the planet to return to the same position with respect to the Sun, e.g. from inferior conjunction to inferior conjunction, or from opposition to opposition.



- As can be seen in the table at the right, the farther a planet is from the Sun, the longer is its sidereal period.

  The synodic period doesn't have a simple behavior, however; it initially increases, and then decreases until it is slightly larger than one year.

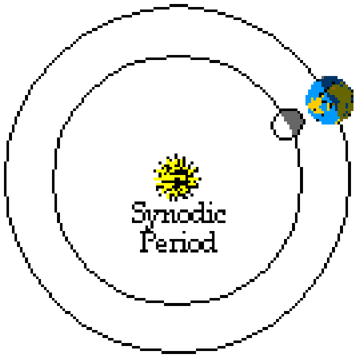
  This complicated behavior is due to the relative motion of both the planet and the Earth.

Planet	Average Distance	Sidereal Period	Synodic Period
Mercury	0.3871 AU	0.2408 y = 87.97 d	115.88 d
Venus	0.7233 AU	0.6152 y = 224.70 d	583.92 d
Earth	1.0000 AU	1.0000 y = 365.26 d	----
Mars	1.5237 AU	1.8809 y = 686.98 d	779.94 d
Jupiter	5.2028 AU	11.862 y	398.9 d
Saturn	9.5388 AU	29.458 y	378.1 d
Uranus	19.1914 AU	84.01 y	369.7 d
Neptune	30.0611 AU	164.79 y	367.5 d

Pluto	39.5294 AU	248.5 y	366.7 d

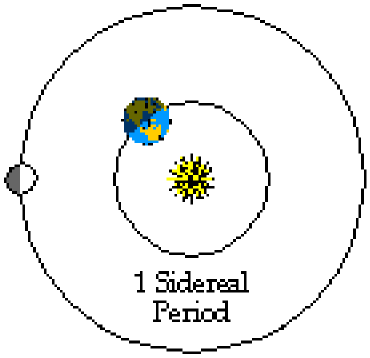
- For an inner planet, the sidereal period is shorter than the synodic period, because when the planet returns to its original position the Earth has moved in *its* orbit, so the planet must travel further to catch up to the Earth.

  In the animation at the right, Venus actually completes two sidereal periods (225 d) before it finally catches up with the Earth after the synodic period (584 d).



- For an outer planet, the sidereal period is (usually)*longer* than the synodic period, because when the Earth returns to its original position (one year) the planet has only moved slightly in *its* orbit, and the Earth doesn't have to travel very far to catch up to the planet.

  Mars is an exception to this because it is so close to the Earth; after one year it has already traveled more than half an orbit, so the Earth has to complete two orbits before it can finally catch up to Mars.



5.6 Tests of the Heliocentric Model

(Discovering the Universe, 5th ed., §2-2, §2-4)

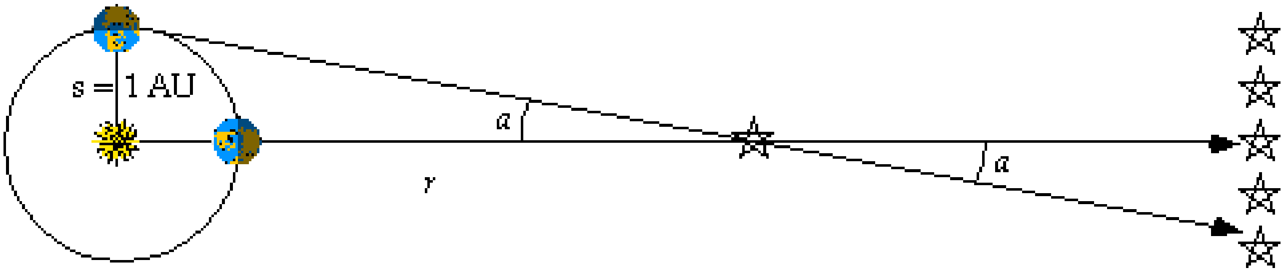
[Portrait Information]

- Tycho Brahe (1546 - 1601), a Danish nobleman, was renowned for his development of astronomical instruments and his use of them to make measurements of the positions of stars and planets.

  His data were the most accurate available prior to the introduction of the telescope into astronomy, shortly after his death.

  Amongst other discoveries, he made accurate measurements of a supernova in 1572, and showed that it was in the realm of the stars, which was believed to be unchanging.

- Tycho noted that the Copernican model predicts that stars should appear to shift their position as the Earth moves around the Sun, due to parallax:



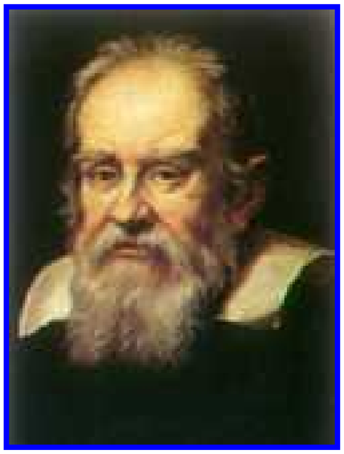
  Tycho attempted to measure this parallax, but he was unable to do so, and therefore concluded that the premise that the Earth moves around the Sun was wrong.

  Actually, it was Tycho's confidence in his own measurements which was ill-founded!

  As we have already seen, the stars do exhibit parallax, but because they are so far away, a telescope is required to observe it!

  However, this is still a good example of the scientific method in action: a prediction is made, and then tested by subsequent observations.

Painting Information



- The telescope was invented by a Dutch optician late in the 16th century.

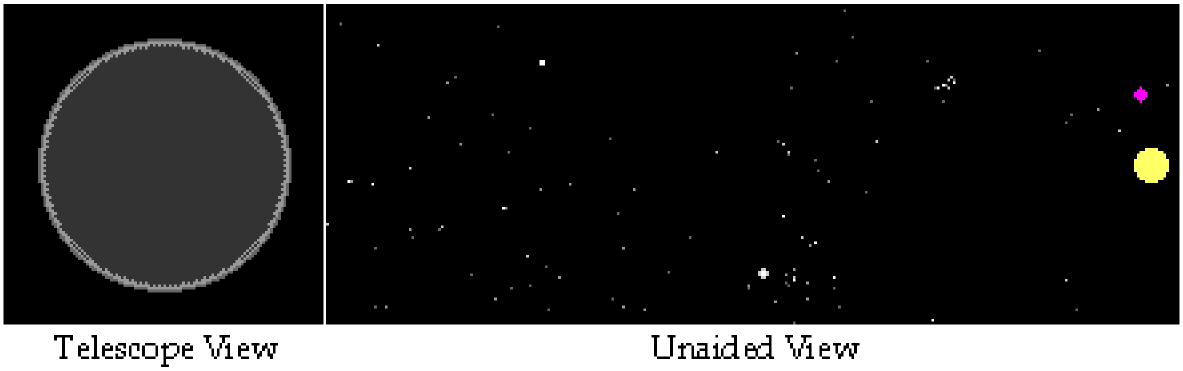
  Galileo Galilei (1561-1642), a professor of mathematics at the University of Padua, heard about the telescope in 1609.

  Recognizing the telescope's possibilities, Galileo immediately built one of his own, based only the sketchy details he had heard.

Galileo then improved the design of the telescope to the point where it could be used for astronomy.

Galileo quickly made several important astronomical discoveries, which were published in 1610 in his book *The Starry Messenger*.

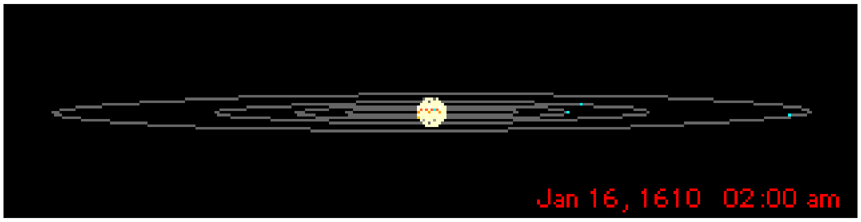
- One of Galileo's observations was that Venus exhibited phases similar to the Moon's:



Galileo noticed that Venus' phases were related to its angular diameter and elongation: it is smaller (farther away from us) at the gibbous phase and larger (closer to us) at the crescent phase, with the extremes occurring at small elongations.

These observations were strong confirmations of the heliocentric model.

- Galileo also saw the four large moons of Jupiter, now called the **Galilean satellites**.



The Galilean satellites were obviously orbiting Jupiter, which was contrary to a basic assumption of the geocentric model, viz. everything in the heavens orbited the Earth.

- In 1616, when Copernicus' book was banned, Galileo was instructed by the Vatican that he could only discuss the heliocentric model as a "mathematical supposition" because anything else would "restrict God's omnipotence".

Nevertheless, in 1632 Galileo published *Dialogue Concerning the Two Chief World Systems--Ptolemaic and Copernican*, which was such a masterpiece of exposition of the heliocentric model that readers ignored the ordained conclusion.

Galileo was then brought before the Inquisition and forced to publicly recant; his *Dialogue* was banned, and he spent the last eight years of his life under house arrest.

The ban on Galileo's *Dialogue* wasn't lifted until 1822, and the Vatican's censure of

Galileo himself wasn't removed until 1992!

Extra: you can find out much more about Galileo at PBS/Nova's website, [Galileo's Battle for the Heavens].

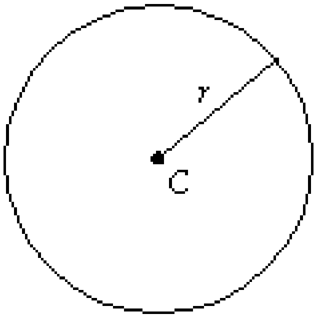
5.7 Kepler's Laws

(Discovering the Universe, 5th ed., §2-3)

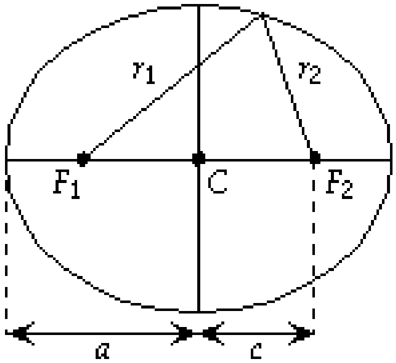
- Although the heliocentric model worked just as well as the geocentric model, to make it work over a millenium Copernicus still had to add epicycles.

- The German astronomer [Johannes Kepler] (1571-1630) had a different idea, however.

  Kepler didn't believe planetary orbits were necessarily circles, but could instead be other closed curves, such as the ellipse or oval.



- Recall that a **circle** is defined as the set of all points that are a constant distance r (the **radius**) from the **center** C.



- An **ellipse** is a generalization of a circle, involving *two* points F_1 and F_2(each called a **focus**, and together the **foci**) and two distances r_1 and r_2, whose *sum* is a constant:

  $r_1 + r_2 = 2a$

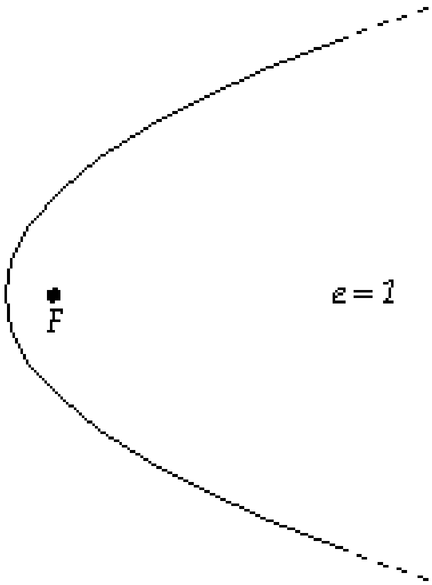
  When the foci coincide (coming together at the center), the result is a circle with a radius a.
- The constant $2a$ is equal to the length of the longer or "major" axis, so a is called the

semimajor axis.

The semimajor axis therefore describes the overall size of the ellipse.

It can be shown that *a* is the average distance of the ellipse from one focus.

- The constant *c* describes how far each focus is from the center, which determines how elongated the ellipse is (for a given value of *a*).

  However, it is more useful to use the **eccentricity**:

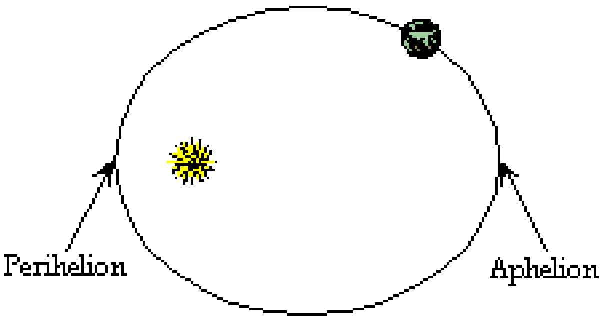
  $e = c/a$

  Because *c* is always less than *a*, the value of *e* varies between 0 and 1.

  When $e = 0$, $c = 0$, the foci coincide, and we have a circle.

  When $e = 1$, the foci approach the opposite ends of the ellipse; the result is so elongated that, from one focus, both the center and the other focus are infinitely far away, forming a curve called a **parabola**.

- Kepler came to work with Tycho in 1600, and the latter's astronomical records provided Kepler with the data he needed to test his hypothesis.

  After many years of laborious calculations, Kepler was able to demonstrate what is now known as **Kepler's First Law**:

  Planetary orbits are ellipses, with the Sun at one focus.

- Because the Sun is off-center, we can describe two special positions on a planet's orbit, both on the major axis:

  The **perihelion** is the point of closest approach to the Sun; it is a distance $a(1 - e)$ from the Sun.

  The **aphelion** is the point where the planet is farthest from the Sun; it is a distance $a(1 + e)$ from the Sun.

- As can be seen in the table at the right, the eccentricity of the planets' orbits is generally quite small, except for Mercury and Pluto, whose orbits are noticeably elongated.

  This is why circles initially worked well in describing planetary orbits.

- The table also shows the **orbital inclination**, or tilt, of the planets' orbits relative to the ecliptic plane.

Planet	Semimajor Axis ***a***	Sidereal Period ***P***	Eccen-tricity ***e***	Orbital Inclination
Mercury	0.3871 AU	0.2408 y	0.206	7.00°
Venus	0.7233 AU	0.6152 y	0.007	3.39°
Earth	1.0000 AU	1.0000 y	0.017	0.00°
Mars	1.5237 AU	1.8809 y	0.093	1.85°
Jupiter	5.2028 AU	11.862 y	0.048	1.31°
Saturn	9.5388 AU	29.458 y	0.056	2.49°
Uranus	19.1914 AU	84.01 y	0.046	0.77°
Neptune	30.0611 AU	164.79 y	0.010	1.77°
Pluto	39.5294 AU	248.5 y	0.248	17.15°

The orbital inclination is usually quite small, except for Pluto.

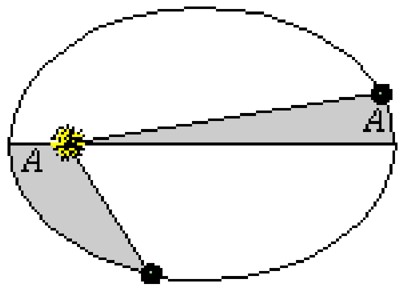
Question: where did we see orbital inclination previously?

Question: why doesn't a planet usually disappear behind the Sun when they are in conjunction?

- Kepler also noticed another characteristic of planetary motion: planets move fastest at perihelion, and slowest at aphelion.

  Kepler was able to quantify these varying speeds in what is known as **Kepler's Second Law**:

  Planets sweep out equal areas in equal times.



- Kepler published his First and Second Laws in 1609 in a book entitled *New Astronomy*.

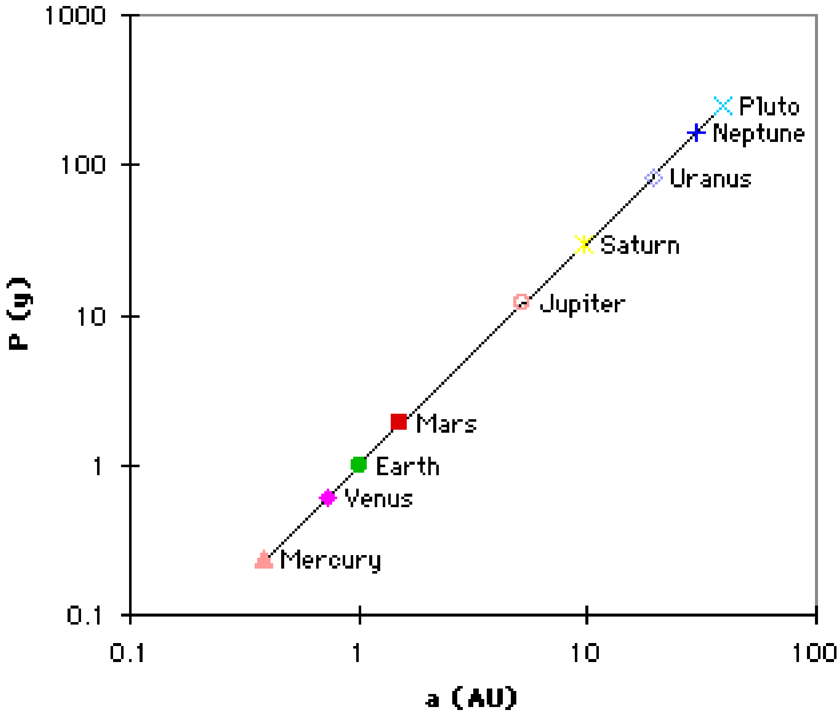
- Ten years later, in 1619, Kepler discovered and published an additional relationship.

  Kepler's Third Law quantifies the observation that more distant orbits have longer periods:

  $a^3 = P^2$

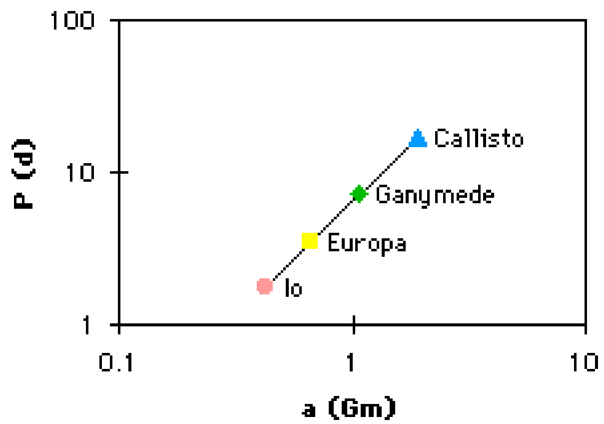
  Here, the semimajor axis *a* is measured in A.U. and the orbital period *P* is measured in years.

  The graph at the right shows log *P* vs. log *a*; the data falls along a straight line, with a slope of 3/2.



- Kepler also noticed that the Galilean satellites obeyed the Third Law, as can be seen by the same 3/2 slope in the graph at the right.

  This implied that Kepler's Third Law was a general principle.



- Galileo himself refused to accept Kepler's ideas, clinging to the notion that planetary orbits must be circular, though his reasons were based on his studies of motion rather than on tradition.

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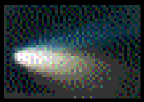
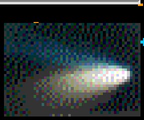
[Open Course Info]

 [Contents] [Index] 

[Prior: §5] [Bottom §6] [Next: §7]

Introduction to Astronomy

Lecture 6: The Laws of Motion and Gravity

Nature and Nature's laws lay hid in night.
God said, "Let Newton be!" and all was light.

-- Alexander Pope, *Epitaph intended for Sir Isaac Newton*

6.1 Isaac Newton

(Discovering the Universe, 5th ed., §2-5)

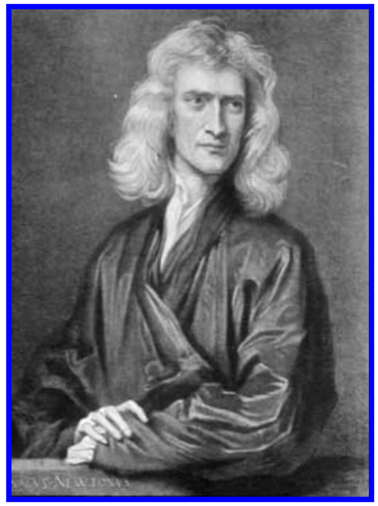
- The Copernican/Keplerian model for the motions of planets was based on direct observations, and provided a unified framework for explaining their past motions and predicting future ones.

- As is often the case in science, however, this explanation immediately lead to additional, more basic questions:

  - Why are the orbits elliptical?
  - Why is the Sun at one focus?
  - Why do the planets move faster at perihelion?

    etc.

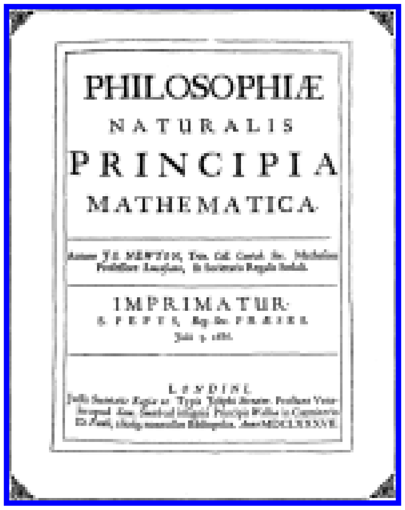
Picture Information



- These questions were addressed by the English scientist and mathematician Isaac Newton (1642 - 1727)

  Newton had a fundamental belief that guided his work: "As below, so above".

  In other words, by understanding why objects move the way they do here on Earth, we should also be able to understand the motions of the planets.



PHILOSOPHIÆ NATURALIS PRINCIPIA MATHEMATICA

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- Newton therefore studied motion in detail, making many new observations.

  Newton formulated his new observations (as well as those of others) in three fundamental **Laws of Motion** which govern all objects, including the planets.

  These laws of motion were published in 1687 in Newton's monumental work *Mathematical Principles of Natural Philosophy*.

- When Newton talked about the **motion** of an object, he was referring to two general characteristics: speed and direction.

Together, these are also known as the **linear momentum** of the object.

An object at rest is simply a special case of motion, with zero speed.

6.2 Newton's Laws of Motion

(Discovering the Universe, 5th ed., §2-5)

- **Newton's First Law of Motion** states:

The motion of an object will remain unchanged unless a force acts on it.

  In other words, an object will never change its speed or direction unless something comes along and forces it to do so.

  This is an example of the principle of **Conservation of Linear Momentum**.

  An object's resistance to changes in motion is known as **inertia**

- The First Law was actually stated a century earlier by Galileo (and even many centuries earlier than that by several others).

  However, the First Law was in direct contradiction to the still-dominant teachings of Aristotle, who thought that all objects in motion will eventually come to rest of their own accord.

  Newton therefore felt it necessary to make a forceful contradiction.

- **Newton's Second Law of Motion** describes *how* a force changes the motion of an object:

$$\boxed{F = ma}$$

Here, *F* describes the **force** acting, *m* is the mass of the object, and *a* is its **acceleration**, the change in its motion.

- Like motion, force has both a value or "strength", and a direction in which it acts.

  We commonly think of "acceleration" as a speeding up, but in physics it can also include a slowing down ("deceleration") as well as a change in direction.

- In the metric system, the unit of force is called a **Newton**, whose abbreviation is "N".

  A Newton is equal to 1 kg•m/s^2.

  In the English system, the unit of force is the pound; it is equal to 4.45 N.

- We can deduce several things about moving objects by considering Newton's Second Law, *F = ma:*
  - For example, the larger the force is, the larger the acceleration:
  - Second, the Second Law actually includes the First Law within it.

    Question: why is this?
  - Third, for an equal force, a larger mass must have a *smaller* acceleration, and vice versa:

In other words, a larger mass has greater inertia than a smaller mass.

This is one way that we can measure an object's mass.

- **Newton's Third Law of Motion** describes two additional characteristics of forces:

The force on an object is always due to *another* object, and that other object always feels an *equal* and *opposite* force.

You are familiar with this law from striking an object with your hand: the object moves as a result, but your hand also feels a force, and bounces back:

Question: if the forces are equal, why does the smaller object bounce back faster?

6.3 Forces in Nature

(Discovering the Universe, 5th ed., §2-5)

- Physicists have identified four fundamental forces in nature, all of which are consistent with Newton's Laws (or its subsequent generalizations):
  - **Gravity**: an attractive force between objects with mass.

    Gravity holds the Sun and planets together in the solar system, and holds stars together in galaxies.

    You should be personally familiar with the effects of gravity, which holds you to the Earth and in general makes things "fall down".

    We will discuss the gravitational force in more detail below.

  - **Electromagnetism**: a force between objects with electric charge.

    Electromagnetism holds atoms together, makes compasses point north, and is the source of starlight and auroras.

    You should also be personally familiar with electromagnetism, via common devices such as electric appliances, refrigerator magnets, and the innumerable sources of light surrounding you.

    We will discuss electromagnetism in more detail later on, in the contexts of electricity, magnetism, and light.

  - **Strong nuclear force**: an attractive force between some subatomic particles.

    The strong nuclear force holds atomic nuclei together, and we will talk about it more in that context.

    The strong nuclear force is involved in the generation of energy in stars and in their explosive destruction known as type I supernovae.

    Although this is probably not a force with which you have personal familiarity, it has been harnessed in nuclear power plants to provide electricity, and in various medical applications.

  - **Weak nuclear force**: another force between some subatomic particles.

    The weak nuclear force can change one type of subatomic particle into another in some situations such as radioactive decay, the generation of energy in stars, and in type II supernovae.

The weak nuclear force's other effects, observable in free particle collisions, are usually masked by the strong nuclear force, as its name implies.

The weak nuclear force shows up in the same sorts of technologies described above for the strong nuclear force.

We will consider the weak nuclear force in more detail in our discussion of radioactive decay.

- You are also personally familiar with **contact forces**, the result of electromagnetic forces acting within solids, liquids, and gasses:
  - **Normal Force**: a repulsive force that opposes compression and prevents objects from passing through each other.

    The normal force prevents planets and stars from collapsing down to zero size under the force of their own gravity (though not always!).
  - **Tension (Cohesion)**: an attractive force that holds objects together.

    Cohesion prevents moons and planets from being torn apart by tidal forces (though not always!).
  - **Friction**: an attractive force that opposes the sliding of objects past each other.

    Friction between molecules in a gas falling into a black hole will cause it to heat up and emit radiation.

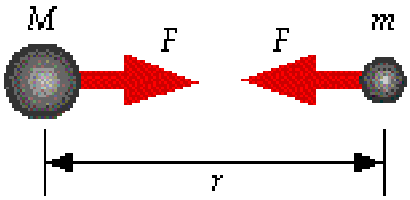
Question: if the force of gravity is pulling you downward, what force counteracts it to keep you in place while you are sitting or standing?

6.4 The Universal Law of Gravity

(Discovering the Universe, 5th ed., §2-5)

- In order to complete his study of the motion of the planets, Newton had to combine his general Laws of Motion with a specific description of the force of gravity.

- Knowing the basic behavior of the planets from Kepler's Laws, Newton was able to determine an appropriate force law, the **Universal Law of Gravitation**:



$$F = G\frac{Mm}{r^2}$$

Here, *G* is a constant, *M* and *m* are two masses, and *r* is the separation between them.

- Gravity is an attractive force, and in accordance with Newton's Third Law, the two masses feel equal and opposite forces.

- Gravity is relatively weak because of the small value of the gravitation constant *G*; in metric units,

$G = 6.7 \times 10^{-11}$ N•m^2/kg^2 .

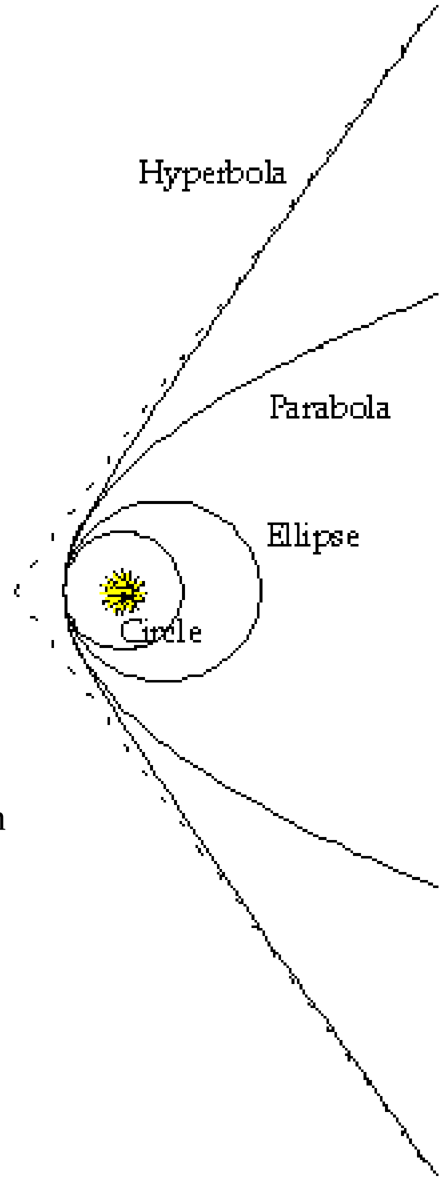
Therefore, large masses are required to provide an appreciable force, e.g. the mass of the Earth is 6.0×10^{24} kg.

- Despite the Earth's large mass, the gravitational force holding you to the surface of the Earth, your **weight**, is still only a few hundred Newtons.

(Note: the distance *r* in the force law is the radius of the Earth, 6378 Km, as if all of its mass is concentrated at its center.)

6.5 Gravity and Kepler's Laws

(Discovering the Universe, 5th ed., §2-6)



- By combining the Law of Gravitation with his Laws of Motion, Newton was able to mathematically derive all three of Kepler's Laws!

  (In the process Newton also had to invent the mathematics of calculus!)

- Because the Sun is so much more massive than any of the planets, it has a very small gravitational acceleration, and can be taken as essentially motionless.

  As described by Kepler, Newton found that all of the planets move around the Sun in circular and elliptical orbits, with the Sun located at a focus of each planet's orbit.

  Objects with circular and elliptical orbits move around the Sun with a definite period, always between their perihelion and aphelion distances, and sweeping out equal areas in equal times.

- Newton also showed that Kepler's 3rd Law, relating semimajor axis and period, depends on the mass of whatever is being orbited:

  $$a^3 = P^2\left(\frac{M}{M_{Sun}}\right)$$

  As before, *a* is measured in AU and *P* is measured in years.

  But now the mass *M* appears, and here is measured as multiples of the mass of the Sun.

  This result provides a powerful tool for determining the mass of the Sun, as well any planet being orbited by a moon, simply by measuring *a* and *P*.

  Question: Newton could immediately calculate the mass of which planets?

- **Circular and elliptical orbits** describe objects which are **bound** to the Sun.

  Newton also demonstrated that there could be parabolic and hyperbolic orbits!

- A **parabolic orbit** describes an object which is **marginally bound**.

  Such an object can escape from the Sun's gravity, but it will just barely reach an infinite distance.

  Recall that a parabolic orbit has an eccentricity $e = 1$. Therefore, highly elliptical orbits ($e > 0.9$) approach a parabolic shape.

- An object in a **hyperbolic orbit** travels in a straight line until it nears the Sun and has its path deflected by gravity.

  Such an object is not part of our solar system, but is instead simply passing through, and can be infinitely far from the Sun while still moving at high speed.

  An object with a hyperbolic orbit is therefore said to be **unbound**.

  A hyperbola has an eccentricity $e > 1$.

6.6 Energy

(Discovering the Universe, 5th ed., §2-6)

- An important concept that arises from Newton's Laws of Motion is **energy**.

  We all have an intuitive idea of what this means.

  For example, when something moves very fast we say it "has a lot of energy".

  We might also recognize that heat, electricity, and light have energy as well.

- Energy of motion is called **kinetic energy**.

  Based on Newton's Laws, kinetic energy can be defined as:

$$KE = \frac{1}{2} m v^2$$

This expression satisfies our intuition, which tells us that kinetic energy should depend not only on the object's speed *v*, but also on its mass *m*.

For example, a car travelling at 90 mph has much more energy than a baseball travelling at 90 mph.

- In the metric system, the unit of energy is the **Joule**, whose abbreviation is "J".

  One Joule is equal to 1 $kg \cdot m^2/s^2$, or equivalently 1 $N \cdot m$.

  A unit of energy you may be more familiar with is the food calorie, which is equal to 4184 J.

- You are probably more familiar with **power**, the rate of energy production or use (energy per unit time).

  The metric unit of power is called a **Watt**, whose abbreviation is "W". One Watt is equal to 1 J/s.

  Question: where have you seen the Watt appear in everyday usage?

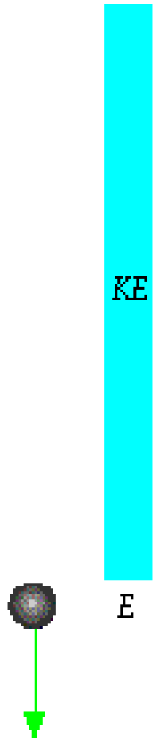
6.7 Potential Energy and Energy Conservation

(Discovering the Universe, 5th ed., §2-6)

- Consider an object which experiences a gravitational force.

  If the object is thrown upward, it will have some initial speed but it will immediately begin to slow down and eventually stop, i.e. its kinetic energy *decreases*.

  The object will then begin to move back downward, rapidly gaining speed as it is accelerated by gravity, and its kinetic energy *increases*.



- We intuitively think of an object with greater height as having, "potentially", more energy, because it will be moving faster when it reaches us.

  We can therefore think of there being a **potential energy** associated with the object's height, which *increases* as it rises, and *decreases* as it falls, the opposite of kinetic energy.

- If we define the **total energy** *E* as the sum of the kinetic and potential energies,

  $E = KE + PE$,

  then *E* will not change, i.e. it is **conserved**.

  If kinetic energy increases, potential energy must decrease by an equal amount, and vice versa, so that *E* remains a constant value.

  We can think of this as one kind of energy being *converted* into another.

- The potential energy described above is basically another way to characterize the force of gravity.

  We can define potential energy for *all* of the fundamental forces, in such a way that energy is, in general, conserved.

  As a result, energy conservation and conversion from one form to another are extremely important concepts in physics and astronomy, and we will see many applications, such as planet formation and solar thermal equilibrium.

6.8 Gravitational Potential Energy

(Discovering the Universe, 5th ed., §2-6)

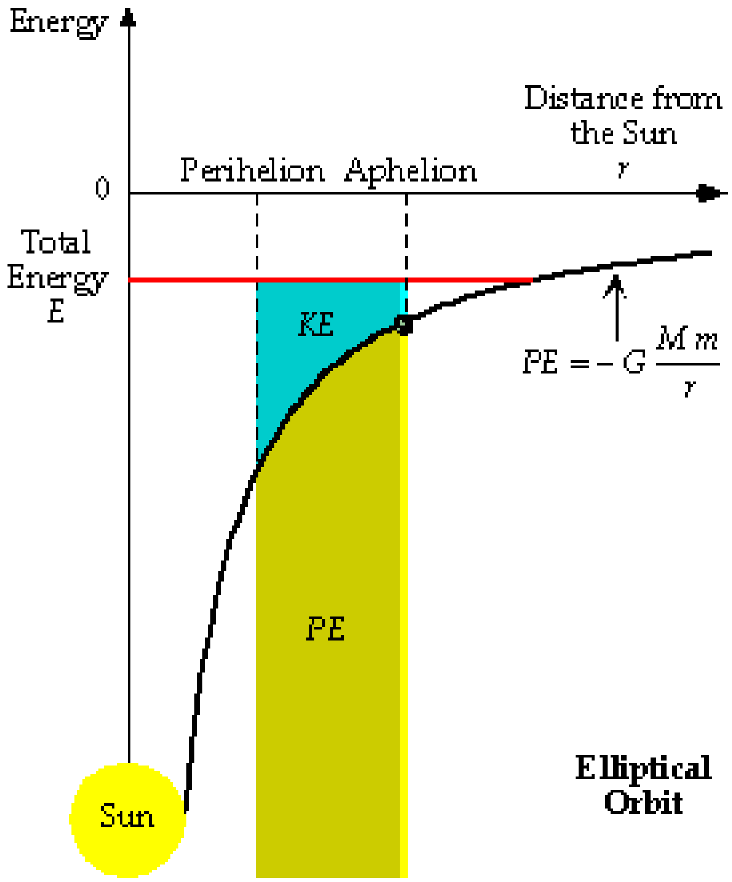
- The mathematical form of **gravitational potential energy** is very similar to the force law:

  $$PE = -G\frac{Mm}{r}$$

  Note that the potential energy is always a *negative* number, and reaches its *maximum* value of zero when the two masses are an infinite distance *r* apart.

- For planetary orbits, we can take the Sun to be fixed at position zero, and a planet to be a distance *r* away from it.

  The potential energy of a planet in an elliptical orbit ($e \sim 0.36$) can then be plotted as shown in the picture at the right.



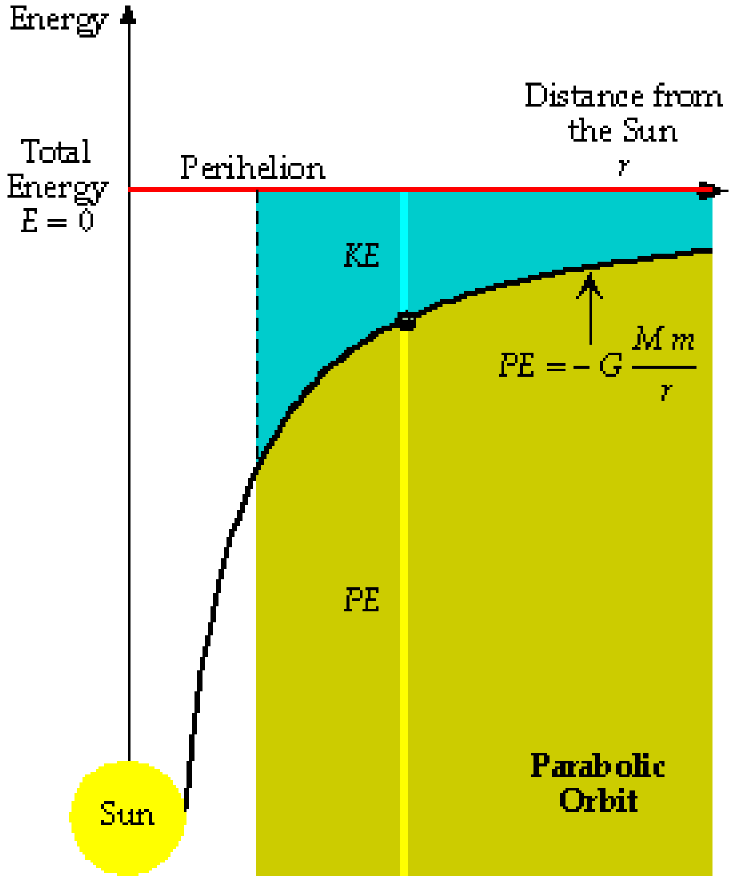
With each orbit around the Sun, the planet will move between its perihelion and its aphelion, and as it does so its energy will convert back and forth between potential and kinetic.

At perihelion, kinetic energy is a maximum and potential energy is a minimum; at aphelion, kinetic energy is a minimum and potential energy is a maximum.

Question: given that kinetic energy is closely related to speed, where was this characteristic of a planet's motion previously described?

Question: what can you say about the speed of a planet in a circular orbit?

- Notice that, for the elliptical orbit above the total energy is negative ($E < 0$). This is true for all bound objects (those in circular or elliptical orbits).

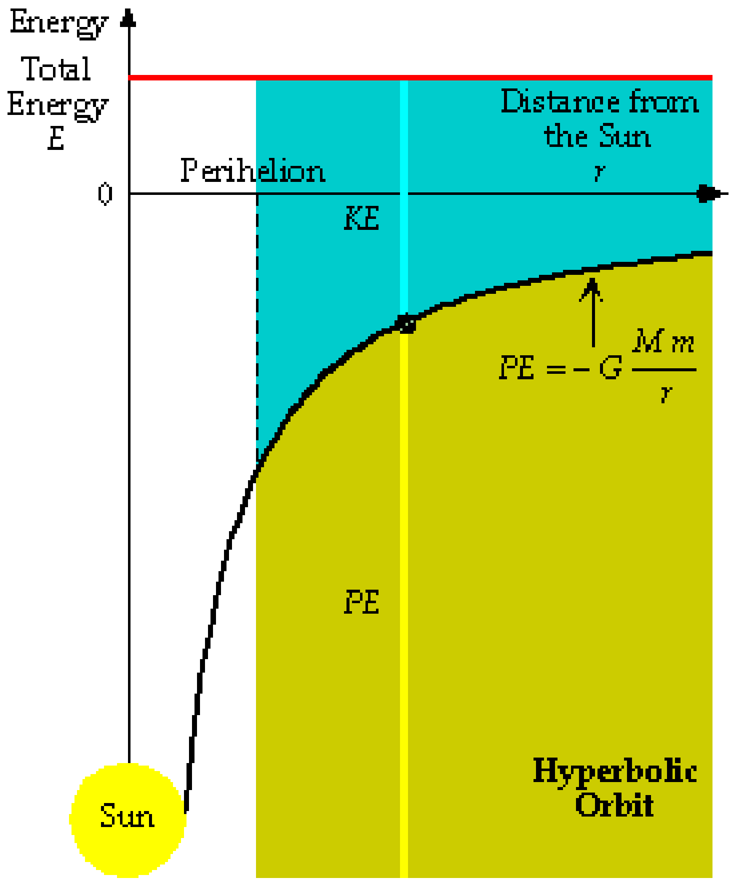


- For marginally bound objects (those in parabolic orbits), the total energy is zero ($E = 0$).

  Question: what is the speed of a marginally bound object which has moved an infinite distance from the Sun?

- For unbound objects (those in hyperbolic orbits), the total energy is positive ($E > 0$).

  Question: what can you say about the speed of an unbound object at all times?



- You can further explore planetary motion and energy using this Java applet.

- We can get an intuitive feel for potential energy by "revolving" the potential energy curve into three dimensions.

  Potential energy then forms a two-dimensional surface called a **gravity well**, with the Sun at the bottom and planetary orbits forming curves along it.

  Imagine walking around the edge of a valley: as you walk higher you slow down, and as you descend you speed up; a planet does the same thing!

  Question: in the image above you can see three types of orbits; can you tell what they are?

6.9 Escape Velocity

(Discovering the Universe, 5th ed., Appendix)

- The **escape velocity** of an object such as a rocket is the speed required to depart from some point in a gravity well (such as the Earth's surface) and reach an infinite distance away.

  This means that the object must be marginally bound or unbound, and so have at least zero total energy:

$$E_{escape} \geq 0$$

$$KE_{escape} + PE_{start} \geq 0$$

$$\frac{1}{2}mv_{escape}^2 - G\frac{Mm}{r_{start}} \geq 0$$

$$\boxed{v_{escape} \geq \sqrt{\frac{2GM}{r_{start}}}}$$

- For the surface of the Earth, v_{escape} = 11.2 Km/s ~ 40,000 Km/h.

  For comparison, at the surface of the Sun, v_{escape} = 618 Km/s, since its mass is 333,000 times that of the Earth!

- Newton knew about escape velocity, and used the idea in his *Mathematical Principles* to illustrate how gravity works; you can explore this yourself with this Java applet from the University of Virginia.

6.10 Conservation of Angular Momentum

(Discovering the Universe, 5th ed., §2-5)

- Another important conservation law arises out of Newton's Laws of Motion, having to do with objects which rotate or revolve.

  Much like linear momentum, objects have a tendency to keep rotating in the absence of external forces.

  This "rotational inertia" is characterized by **angular momentum**, which can be loosely defined as:

  $AM \sim mr^2/P$

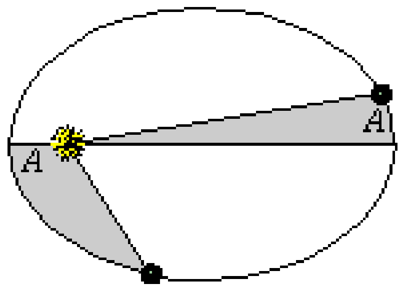
  where m is the mass of the object, P is its period of rotation or revolution, and r is the distance from the center of rotation or revolution.

- The "direction" of angular momentum is also important; two rotating objects with the same mass and speed, but different axes of rotation, have different angular momenta.

- For many forces, including gravity, the angular momentum of a rotating or revolving object will be conserved, i.e. it will be constant.

  Conservation of angular momentum is why the Earth always rotates once every 24 hours, and why its rotation axis remains (relatively) fixed in space as it orbits the Sun.

- Kepler's Second Law, which states that planets sweep out equal areas in equal times, is a consequence of conservation of angular momentum.

  This can be seen from the above expression for angular momentum by recognizing that area $A \sim r^2$ and time $\sim P$.

  So, if $AM \sim A/P$ is conserved, equal areas require equal times.

  Question: where else have you seen conservation of angular momentum?

6.11 Confirmations of Newton's Laws

(Discovering the Universe, 5th ed., §)

- A contemporary of Newton, Edmond Halley (1656-1742), had been studying comets, bright objects that appear briefly in the sky from time to time and move relative to the stars, like planets (though much faster).

  Halley noticed that the comets of 1531, 1607, and 1682 had similar characteristics, and were separated by the same period of 76 years.

  In 1684, Halley visited Newton in Cambridge, and told him about his suspicion that they were the *same* comet moving in a periodic orbit around the Sun.

  It was only then that Halley learned of Newton's unpublished work on planetary motion.

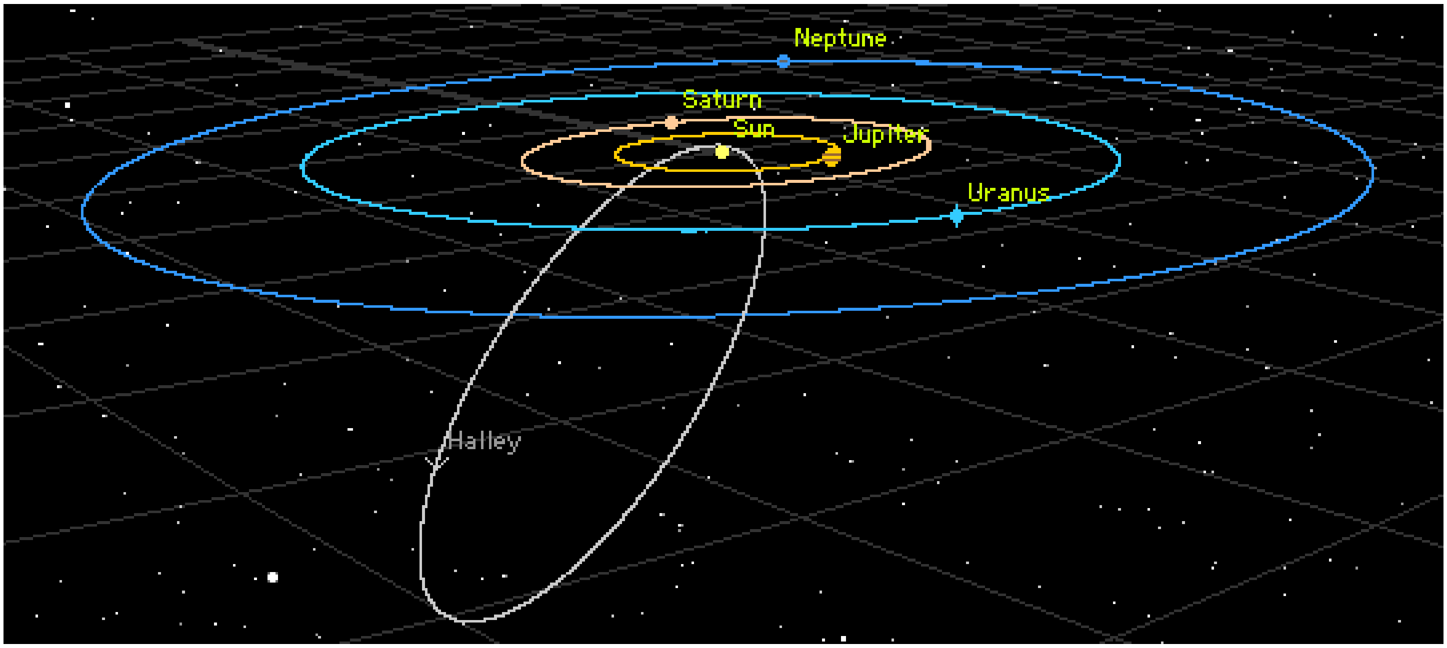
  Newton advised Halley that the comet's orbit must be elliptical, though much more elongated than a planet's.

Photo Information

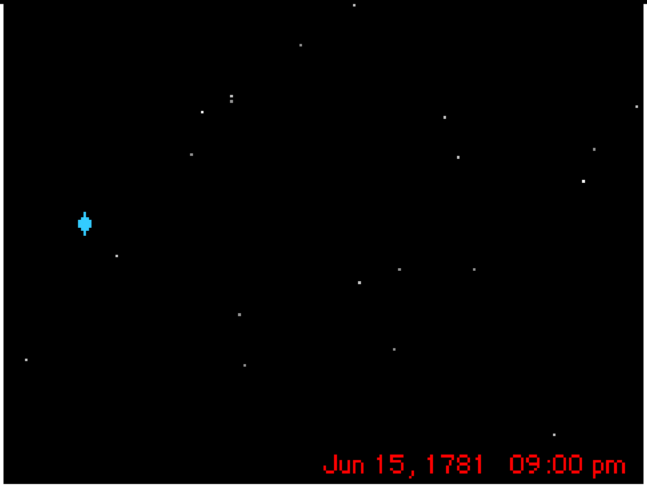
- Halley applied Newton's laws to correctly predict the date and location of the comet's reappearance in 1758.

  That comet is now known as **Halley's Comet**; its most recent passage was in 1986.

  Halley's comet has an orbit with an eccentricity of 0.9673 and a semimajor axis of 17.9 AU (its aphelion of 35.3 AU takes it out beyond the planet Neptune!).



- It wasn't long before astronomers had applied Newton's Laws to determine the masses of the known planets, by observing their interaction with their moons and with each other.



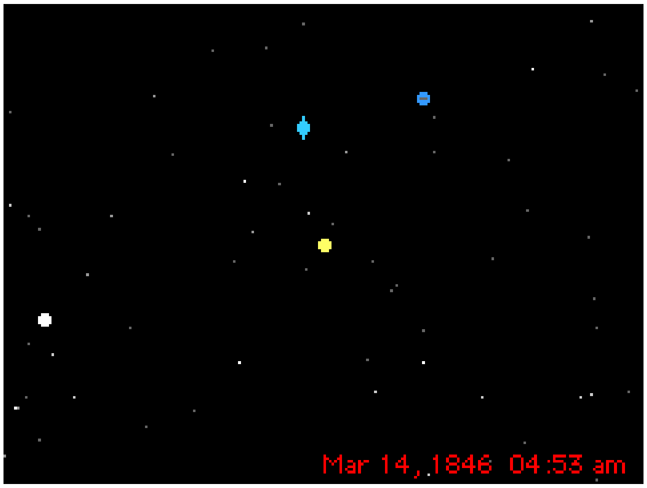
- In 1781, an amateur astronomer named William Herschel, who had built one of the most powerful telescopes of the time, noticed "a curious either nebulous star or perhaps a comet".

  Subsequent observations revealed that this object moved relative to the stars, although more slowly than a comet.

  Herschel soon realized that he had discovered a seventh planet, **Uranus** (and the first in recorded history!).

  At its brightest, Uranus is barely visible to the naked eye in a dark sky.

  Because of its slow motion, however, Uranus was always mistaken for a star by earlier observers.



- Uranus has an orbital period of 84 years, but after 50 years it was clear that it wasn't following its predicted orbit.

  Astronomers applied Newton's Laws to account for the gravitational pulls of Jupiter and Saturn, but that still did not remove all of the discrepancies.

  John Couch Adams and Urbain-Jean-Joseph Le Verrier independently realized that a new planet beyond Uranus might cause these deviations.

  In 1843 and 1845, respectively, they applied Newton's Laws to determine its position.

  In 1846 Galle and d'Arrest at the Berlin Observatory followed up on Le Verrier's prediction, and quickly identified the eighth planet, **Neptune**.

  Neptune moves even more slowly than Uranus, and it has an orbital period of 165 years.

  Question: in the picture shown, looking down on the solar system, what effect would the gravity of the outer planet (Neptune) have on the speed of the inner planet (Uranus)?

- After some years, positional errors in Neptune's predicted orbit again suggested the presence of another large planet further out.

In 1905, another amateur astronomer, Percival Lowell, who had built his own observatory in Arizona, began a search for this planet, which he called **Planet X**.

After Lowell died in 1916, his successors at the Lowell Observatory continued the search.

Finally, in 1930, Clyde Tombaugh discovered **Pluto**, but its observation was fortuitous because its mass is so small that it doesn't have a significant effect on Neptune.

Better measurements of the outer planets' masses (by the Voyager spacecraft in 1970s and 1980s) have now removed the errors in Neptune's position.

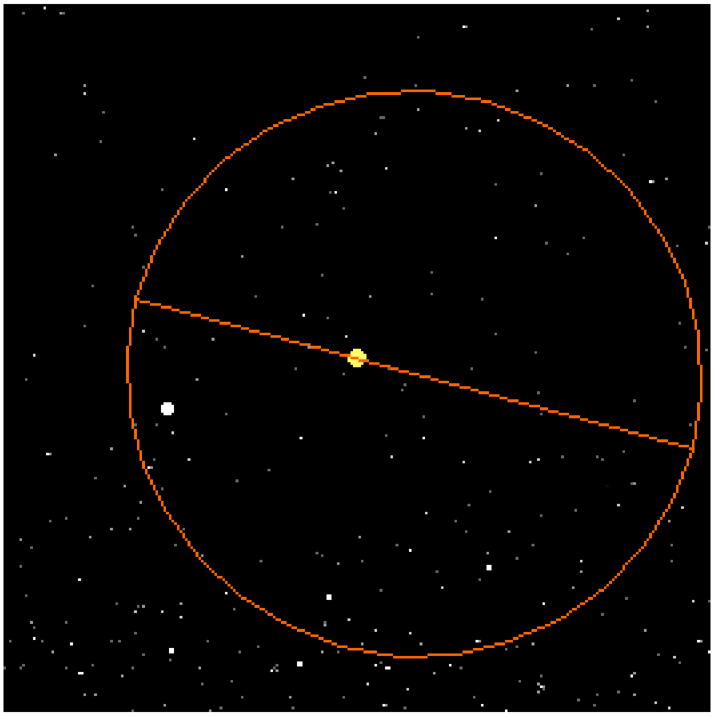
- Generally speaking, a planetary orbit should be fixed in space.

  Question: what physical principle requires this?

  However, another planet's gravitational pull can make a planet's orbit precess around the Sun.

  Question: where have we already seen an example of a precessing orbit?

  In 1845, Le Verrier discovered that Mercury's orbit also precesses around the Sun (note the changing orientation of the semimajor axis in the picture).



  This is a *very* small effect, only 0.10 seconds of arc per orbit (43" per century), but even so it could not be explained by the other planets.

  Le Verrier hypothesized that there might be another planet inside of Mercury's orbit, so close to the Sun that it was difficult to observe.

  This planet, which Le Verrier called **Vulcan**, has never been found.

  So, there was no good explanation for Mercury's precession using Newton's laws, but, like Neptune, the effect was small enough to attribute to measurement errors, and was largely ignored.

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The Halley's orbit, Uranus Motion, Uranus Passes Neptune, and Mercury's Precession animations, as well as the star chart background,were produced on a Macintosh with the Voyager II program, and are ©1988-93 Carina Software, 830 Williams St., San Leandro, CA 94577, (510) 352-7328. Used under license.

Open Course Info

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Introduction to Astronomy

Lecture 7: The Nature of Matter

The ignorant man marvels at the exceptional; the wise man marvels at the common; the greatest wonder of all is the regularity of nature.

-- George Dana Boardman

7.1 The Constituents of Matter

(Discovering the Universe, 5th ed., §4-5)

- Newton's laws are completely general, and apply not only to the motion of planets but also to the motion of the tiniest objects in the Universe such as **protons**, **neutrons**, and **electrons**.

- These three **subatomic particles** are the basic constituents of **matter**, the stuff which makes up stars, planets, the Earth, and you and me.

It is therefore important to have an understanding of their basic behavior.

- Another fundamental particle, the **neutrino**, does not show up in ordinary material objects, but its interaction with the other three particles has great importance in astronomy.

- The electron was the first to be discovered, by J. J. Thomson in 1897.

  Wilhelm Wien discovered the proton shortly thereafter in 1898.

  The neutron was discovered much later, in 1932, by James Chadwick.

  The neutrino followed in 1949, discovered by Chalmers Sherwin.

- The most fundamental characteristic of these particles is their mass.

  Protons and neutrons have roughly the same mass.

  They are both much more massive than the electron, which in turn is much more massive than the neutrino (whose exact mass is unknown):

  $m_{\text{proton}} = 1.7 \times 10^{-27}$ kg
  $m_{\text{neutron}} = 1.0016 \times m_{\text{proton}}$
  $m_{\text{electron}} = 0.00054 \times m_{\text{proton}}$
  $10^{-7} \times m_{\text{electron}} < m_{\text{neutrino}} < 10^{-4} \times m_{\text{electron}}$

- Another basic characteristic is their size; protons and neutrons have roughly the same diameter, while electrons and neutrinos have no measureable extent:

  $D_{\text{proton}} \sim 2 \times 10^{-15}$ m
  $D_{\text{neutron}} \sim 2 \times 10^{-15}$ m
  $D_{\text{electron}} \sim 0$
  $D_{\text{neutrino}} \sim 0$

7.2 Electricity

(Discovering the Universe, 5th ed., not!)

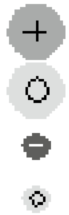
- In addition to their mass and size, these particles also have electric charge:

  $q_{\mathrm{proton}} = +e$

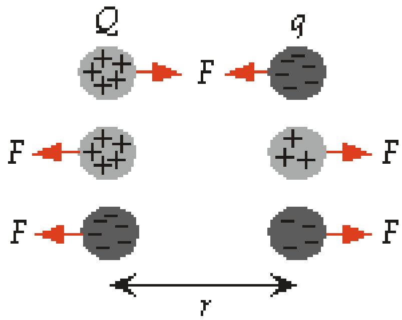
  $q_{\mathrm{neutron}} = 0$

  $q_{\mathrm{electron}} = -e$

  $q_{\mathrm{neutrino}} = 0$



- Charged particles interact with each other via the **electric force**, which has the same form as the gravitational force:



$$F = k\frac{Qq}{r^2}$$

  Here, k is a constant, Q and q are two electric charges, and r is the separation between them.

- Because charges can be both positive and negative, the electric force can be both attractive (between unlike charges) and repulsive (between like charges).

- Although the form of the force laws are the same, the electric constant $k \sim 10^{+10}$ (in metric units) is much larger than the gravitation constant $G \sim 10^{-10}$, so electricity is a *much* stronger force.

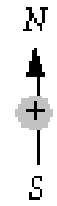
- In nature, there is an equal amount of positive and negative charge.

  As a result, an isolated charged particle will usually attract the opposite charge from its surrounding environment to quickly form a neutral system.

7.3 Magnetism

(Discovering the Universe, 5th ed., not!)

- In addition to electric charge, protons, neutrons, electrons, and neutrinos also have an intrinsic **magnetic dipole moment**, which means that they act like tiny bar magnets.

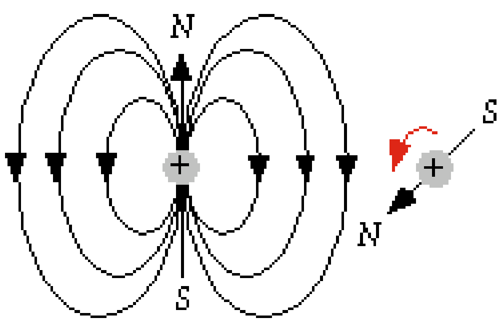
  They have a **magnetic axis** with a **north magnetic pole** at one end and a **south magnetic pole** at the other.

- Magnetic dipole moment is measured in units of A-m^2.

  While a typical bar magnet might have a few A-m^2, atomic dipoles are much smaller:

  μ_{proton} = 1.4 x 10^{-26} A-m^2
  $\mu_{neutron}$ = 0.69 x μ_{proton}
  $\mu_{electron}$ = 660 x μ_{proton}
  $\mu_{neutrino}$ = ?

- To understand how magnetism works, it is helpful to think in terms of a **magnetic field**.

  Every magnet creates a magnetic field in the space around it.

  The field has a direction associated with it; it emanates from the north pole of the magnet and wraps around back into the south pole (the field lines are continuous, though, without beginning or end).

- When another magnet is placed in the field, it experiences a **magnetic force** which rotates it so that its magnetic dipole moment aligns with the field, i.e. its poles are *opposite* to the original magnet's.

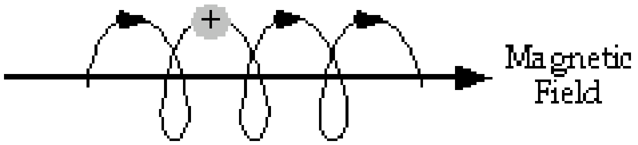
  This is why a compass needle turns towards the Earth's north pole, to align itself with the planet's magnetic field.

- Note that this alignment tends to cancel out the magnetic field far away, since the second magnet's field is opposite to the first's.

A bar magnet is formed from materials such as iron, which can hold the intrinsic magnetic dipoles of electrons so that they all align in the *same* direction.

They then add up to form a large total magnetic dipole moment.

- Magnetic fields also have a direct affect on moving electric charges (i.e. [electric current]), independent of their magnetic dipole moment.



If a charged particle is moving through a magnetic field, it is forced to *spiral* around the field.

- Moving electric charges also produce their *own* magnetic field!

As a result, the electric current in a wire can deflect a compass needle.

This might be expected from a magnetic field's effect on a moving charge and Newton's third law, which requires that there always be an equal and opposite effect.

- There are therefore two basic sources of magnetic fields, intrinsic magnetic dipole moments and motion of electric charges.

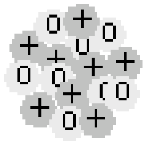
The former can be thought of as arising from the latter, *if* a subatomic particle is a rotating sphere of charge.

This "rotation" is called **intrinsic** or **spin angular momentum**, or **spin**, for short.

This is simply an analogy, though -- while spin is a very real characteristic of subatomic particles, its actual source is a mystery; there are great problems with describing these particles as rotating spheres (for example, remember that electrons have no measureable extent!).

7.4 Nuclei

(Discovering the Universe, 5th ed., §4-5, §17-4)



- Protons and neutrons like to join together to form a larger particle called a **nucleus**.

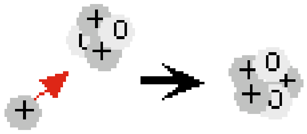
  Nuclei can have a diameter between 10^{-15} m and 10^{-14} m.

- Since protons are repulsed by their positive electric charge, there must be a stronger, attractive force at work which holds nuclei together.

  This force is the strong nuclear force.

- The strong nuclear force affects protons and neutrons equally (they are therefore given a common name, **nucleons**).

  Electrons, on the other hand, are not affected by this force at all.



- The strong nuclear force has a very short range, extending only about 2 x 10^{-15} m.

  Two nuclei that get at least this close together can then *join* to form a new, larger nucleus.

  This process is called **nuclear fusion**.

- All nuclei can be characterized by two numbers.

  Atomic number is the number of protons (amount of charge) a nucleus has.

  Atomic mass is the number of nucleons (protons + neutrons) a nucleus has.

- Electric charge, and therefore atomic number, determines the primary characteristics of materials made from nuclei.

  Materials made from nuclei all with a single atomic number are known as **chemical elements**, or simply **elements**.

  The names ascribed to these materials over the centuries are also used to designate the nuclei themselves.

The most common elements, along with one or two others we will run into in this class, are shown in the table below.

Element	Symbol	Atomic Number	Most Common Atomic Mass	Less Common Atomic Masses
Hydrogen	H	1	1	2
Helium	He	2	4	3
Carbon	C	6	12	13
Nitrogen	N	7	14	15
Oxygen	O	8	16	18, 17
Neon	Ne	10	20	22, 21
Magnesium	Mg	12	24	26, 25
Silicon	Si	14	28	29, 30
Sulfur	S	16	32	34, 33, 36
Iron	Fe	26	56	54, 57, 58
Uranium	U	92	238	235, 234, 233

- It is possible to have nuclei with the same atomic number but different atomic mass, i.e. the charge is the same but the number of neutrons is different.

  Such nuclei are called **isotopes** of each other.

  Differing isotopes are distinguished from each other in writing by preceding the element symbol with the atomic mass as a superscript, e.g. ^{56}Fe.

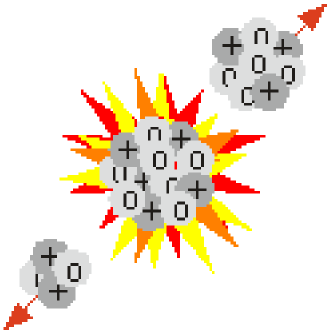
  Most nuclei have one isotope which is most common in nature, along with others with lower abundances.

  For example, hydrogen found in water on Earth is mostly ^{1}H (99.99%) and only a small part ^{2}H (0.01%).

  Extra: the National Institute of Standards and Technology provides a database of the isotopic compositions of the elements.

7.5 Radioactivity

(Discovering the Universe, 5th ed., §4-5, §17-4)



- Nuclei with an excess of protons over neutrons, or that have many protons, tend to be unstable, since large number of protons can produce a long-ranged electric repulsion which exceeds the attraction of the short-ranged strong nuclear force.

  Such nuclei may therefore *split* into two smaller nuclei with kinetic energy, a process called **spontaneous nuclear fission**.

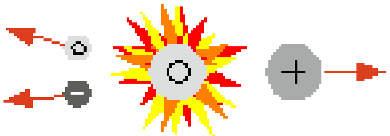
  Question: where does the kinetic energy come from?

  Spontaneous nuclear fission is a form of **radioactive decay**, and such unstable nuclei are said to be **radioactive**.

  Uranium (^{238}U), for example, naturally decays into thorium (^{234}Th) and helium (^{4}He).

  Question: what other radioactive materials have you heard of?

  Extra: the Saturn-bound Cassini spacecraft is so distant from the Sun that it must rely on radioactive decay to generate power.



- **Neutron decay** is another form of radioactivity in which a neutron spontaneously decays into a proton, an electron, and a neutrino:

  $n \rightarrow p + e + \nu + E$

  Neutron decay is a result of the fourth fundamental force in nature, the weak nuclear force.

  Neutron decay can occur both in isolated neutrons and also inside nuclei (generally those that have many more neutrons than protons).

  Question: after neutron decay in a nucleus, what happens to a nucleus' atomic number? its atomic mass?

- The rate at which a radioactive material decays is described by its **half-life**, the time it takes for half of the material to decay into its end products.

  The half-life of a radioactive material is independent of the beginning amount.

Half-life can be used to judge the age of, for example, a meteorite, by comparing the relative amounts of a radioactive material and its decay products.

For example, the half-life of uranium (^{238}U) is 4.5 Gy; rocks containing uranium commonly have an equal amount of its decay products, making them about 4.5 Gy old (assuming other sources of the decay products can be ruled out).

Question: what does that suggest about the age of our solar system?

- Many radioactive nuclei are isotopes of stable elements, with either an excess of protons or neutrons, and they commonly have half-lives of hours, days, or years.

  The neutron has a half-life of only 17 minutes.

  Because the Earth is very old, most of these materials have decayed away, and aren't generally found in nature.

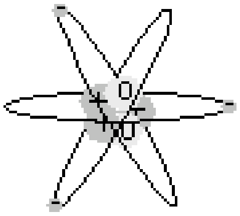
- For any element with an atomic number greater than 83 (bismuth), all isotopes are radioactive.

  Uranium, with an atomic number of 92, is the heaviest nucleus that exists in our solar system in large quantities, due to its long half-life.

  Most of the other high-mass elements, however, have extremely short half-lives.

7.6 Atoms

(Discovering the Universe, 5th ed., §4-5)



- Because positively charged nuclei and negatively charged electrons have an electric attraction, they routinely join together to form a stable structure called an **atom**.

  The experiments of Ernest Rutherford in 1910 demonstrated that atomic structure was much like the solar system, with light electrons orbiting the massive nucleus.

  Extra: You can explore Rutherford's experiments yourself with this Java applet from the University of Virginia.

- The electrons form a "cloud" around the nucleus which gives the atom a diameter of roughly 10^{-10} m, 10,000 times larger than the nucleus.

- Atoms usually have the same number of electrons as there are protons in their nucleus; the atom then has a neutral charge.

  Occasionally a neutral atom may lose or gain some electrons; it is then positively or negatively charged, respectively.

  Such an atom is called an **ion**, and it is said to be **ionized.**

  In astronomy, neutral atoms and positive ions are most common, and a roman numeral is used to indicate the degree of ionization.

  For example, Fe I is neutral, Fe II has one electron removed, Fe XIV has thirteen electrons removed, etc.

- Because atoms interact with their surroundings via their electron cloud, the number of electrons they have distinguishes them from each other.

  Since the number of electrons is usually the same as the number of protons, this is why atomic number characterizes the different elements that we see in nature.

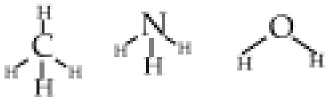
7.7 Molecules

(Discovering the Universe, 5th ed., §4-5)

- By sharing electrons, atoms can form strong bonds with each other.

  The resulting branched structures are called **molecules**.

  The molecules we will commonly run into are shown in the table at the right.

Molecule	Formula
Molecular Hydrogen	H_2
Molecular Nitrogen	N_2
Molecular Oxygen	O_2
Methane	CH_4
Ammonia	NH_3
Water	H_2O
Carbon Dioxide	CO_2
Sulfur Dioxide	SO_2

- Some atoms, such as helium and neon, do not easily join with others, usually remaining in their atomic form.

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a project of the U.S. Department of Education. The Introduction to Astronomy Webbook is catalogued in the Gateway, and Scott R. Anderson is a member of the GEM Consortium.

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Introduction to Astronomy

Lecture 8: The Phases of Matter

For a charm of powerful trouble,
Like a hell-broth boil and bubble.
Double, double toil and trouble;
Fire burn and cauldron bubble.

-- William Shakespeare, *Macbeth*

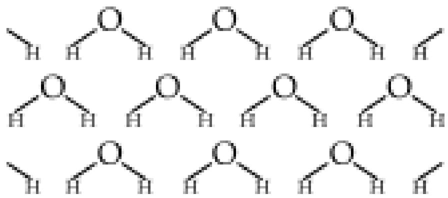
8.1 Solids, Liquids, Gases, and Plasmas

(Discovering the Universe, 5th ed., not!)

- Large quantities of molecules form the **phases of matter** you are familiar with: solids, liquids, and gases.

  A glass of water, for example, contains about 10^{25} molecules.

- **Solids** consist of closely packed molecules which form a rigid structure.

  Solids are held together by a residual electrostatic attraction which is generally weaker than a molecular bond.

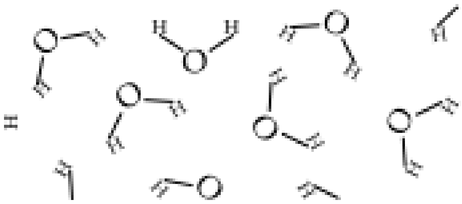
  Solids usually consist of a simple geometric pattern of atoms or molecules which is repeated over and over again in all directions, which is known as a **crystal**.

- Some crystals allow their electrons to freely move from atom to atom; they are called **metals**.

  Metals therefore conduct electricity very easily.

  Most metals consist of relatively massive atoms, for example iron, and these heavy elements are sometimes referred to as metals even when they aren't in solid form.

- **Liquids** also contain closely packed molecules, but they do not have a rigid orientation.

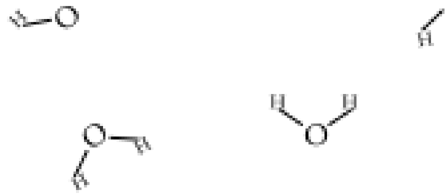
  

  They still feel an electrostatic attraction, and they regularly bump into each other, but they can move around with relative ease.

- Some liquids are extremely viscous, to the point where they appear solid; they are called **glasses**.

  Glasses can change their shape, but you might not notice it for years!

- **Gases** or **vapors** are the simplest phase: the molecules are widely spaced, and rarely bump into each other.



- A gas whose atoms have been ionized into a mixture of positive ions and electrons is called a **plasma**.

  Stars consist of plasmas.

  Question: where else have you seen the term plasma commonly used? How is it related to this definition?

- Liquids, gases, and plasmas are all referred to as **fluids**, because they can flow and take the shape of whatever container they are placed in.

  Gases and plasmas, in addition, will expand to fill their container.

- Generally, a solid is denser than a liquid, because it packs its molecules into a smaller volume.

  Similarly, liquids are denser than gases.

- **Extra:** in recent years, two more unusual phases of matter have been discovered, both a type of quantum-mechanical condensate.

8.2 Heat Energy

(Discovering the Universe, 5th ed., not!)

- The molecules which make up solids, liquids, and gases all move around to a lesser or greater extent.

  In rigid solids, the molecules can vibrate back and forth, and also rotate slightly.

  In liquids and gases the molecules are free not only to vibrate and rotate but also translate through space.

- Therefore, molecules in general have some amount of kinetic energy.

  As the molecules bump into each other, they may gain or lose energy, but the total amount is conserved.

  The total of all of the random kinetic energy of the molecules which make up an object is called its **heat energy**, or simply **heat**.

- A solid has the least amount of heat energy.

  As a solid is heated up, the electrostatic bonds which hold the molecules in their rigid positions begin to break, and the solid undergoes a **phase change** to become a liquid.

  This is what happens when ice **melts** to form liquid water.

  If energy is removed from a liquid, it will reverse the process, and **solidify** or **freeze**.

- If a liquid is heated, the remaining electrostatic forces holding the molecules close together will eventually be overcome, and the liquid will undergo another phase change to become a gas.

  This is what happens when liquid water **boils** to become water vapor.

  We also may say that the liquid **vaporizes** or **evaporates**.

  If energy is removed from a gas, it will **condense** back to a liquid.

- Some solids will change phase into a gas, without becoming a liquid first.

  For example, frozen carbon dioxide **sublimates** directly into a gas, hence its name **dry ice**.

  The reverse process, gas into solid, is also called condensation.

- If the gas is extremely hot, its molecules will be broken down into atoms, which will also become ionized as electrons are knocked loose by collisions.

  Such a gas has then become a plasma.

8.3 Temperature

(Discovering the Universe, 5th ed., Toolbox A-1)

- The amount of heat energy in a material is described by its **temperature**.

  For example, at room temperature, the oxygen molecules in air have a total kinetic energy of 10^{-23} J, which corresponds to an average translational speed of 480 m/s!

  Several different temperature scales are used for different purposes:

	Fahrenheit	Celsius	Kelvin
Water boils	212 °F	100 °C	373 K
Human body	99 °F	37 °C	310 K
Room Temperature	72 °F	22 °C	295 K
Water freezes	32 °F	0 °C	273 K
Salt water freezes	0 °F	-18 °C	255 K
Absolute zero	-460 °F	-273 °C	0 K

- The **Fahrenheit temperature scale** is commonly used in the United States, but nowhere else.

  The Fahrenheit scale ensures that most of the temperatures we experience are positive values, and it also places body temperature near 100 °F.

- The rest of the world uses the **Celsius temperature scale**, which is based on water, a convenient standard.

  Originally the Celsius scale was called the **centigrade scale** because there are 100 degrees between freezing and boiling.

  The Celsius scale is simply related to the Fahrenheit scale by the equation

  °F = °C (9/5) + 32 .

  Note that the degree Fahrenheit is roughly half the size of the degree Celsius.

- Scientists worldwide use the Celsius scale, as well as the **Kelvin temperature scale**, which is related to the Celsius scale by the equation

K = °C + 273 .

Note that the Kelvin is the same size as the degree Celsius.

Note also that we say simply "Kelvin" rather than "degree Kelvin".

- The Kelvin scale sets the zero point at **absolute zero**, the temperature at which all heat energy has been removed from an object.

  Absolute zero is therefore the lowest possible temperature.

  As a result, the Kelvin scale is sometimes also called the **absolute scale**.

8.4 Pressure

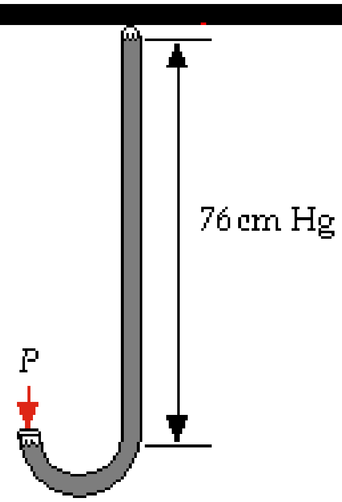
(Discovering the Universe, 5th ed., not!)

- As the molecules in a gas speed around, they will eventually bump into the walls of their container, applying a force to it.

  Because there are so many molecules bumping into the walls surrounding a gas, it is easiest to characterize their effect by the force per unit area, or **pressure**.

- A common metric unit for pressure is the **bar**, which is useful for describing planetary atmospheres:

  1 bar = 10^5 N/m^2 .



- At sea level, the average atmospheric pressure on Earth is called one **atmosphere**:

  1 atmosphere = 1 atm = 1.013 bar .

- Another unit of pressure that is still in common use is based on the original **barometers**, devices designed to measure pressure.

  Here, a column of liquid mercury (Hg) is supported by the pressure, and its height defines the value:

  1 atm = 76 cm Hg = 29.9 in Hg .

  Question: where have you seen the latter unit comonly used?

- A unit of pressure that you may be more familiar with is **pounds per square inch**:

  1 bar = 14.5 pounds per square inch = 14.5 psi .

  Question: where have you seen the latter unit comonly used?

- In a gas, the more molecules there are in a container, the greater the force they apply per unit area.

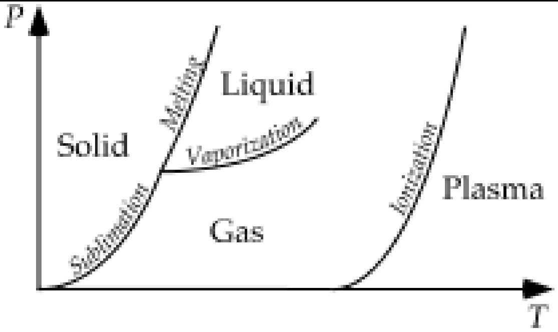
  The force will also be greater if the molecules have more energy.

  So, a simple relation between pressure, density, and temperature is given by:

  $P \sim dT$

  This relation only roughly describes the behavior of liquids.

  It is not applicable at all to solids, which don't change their density easily because of the electrostatic bonds between molecules.



- Just as temperature affects the phase of a material, so does pressure.

  For example, if a liquid has only a low pressure applied to it, its molecules have little external force holding them together, and they will vaporize more easily.

  Similarly, it is easier for a solid to liquify (or sublimate) if the pressure is low.

  These characteristics can be described by a **phase diagram** such as the one at the right.

  The phase diagrams of different materials will usually be similar to the above, but with different temperatures and pressures.

  For example, at atmospheric pressure water melts at 0 °C and boils at 100 °C (by definition), but methane melts at -182 °C and boils at -162 °C.

  Question: what would happen to the Earth's oceans if its atmosphere suddenly disappeared?

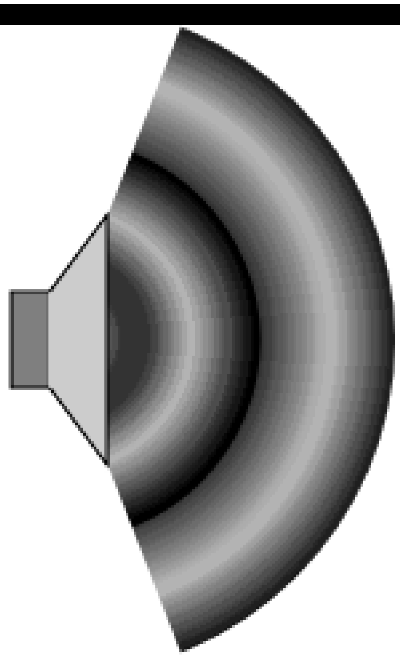
- Note that most solid materials will sublimate at a low enough pressure.

  For water that only occurs below 6.1 mbar, far below atmospheric pressure.

  Carbon dioxide, on the other hand, can only become a liquid above 5.2 bar.

8.5 Sound

(Discovering the Universe, 5th ed., not!)



- Solids, liquids, and gases can all carry directed, energetic disturbances through them, which are called **sound**.

  For example, when you speak, your vocal cords push against air molecules, which bump into other air molecules, etc.

  The sound moves through the air until it reaches a listener's ear and pushes against their ear drum, which is then interpreted by the brain.

- Sound is a type of **wave**, a natural phenomenon in which something oscillates back and forth, passing energy along as it does so.

  For sound waves, it is the molecules which move back and forth as they bump into their neighbors; the molecules themselves don't travel very far.

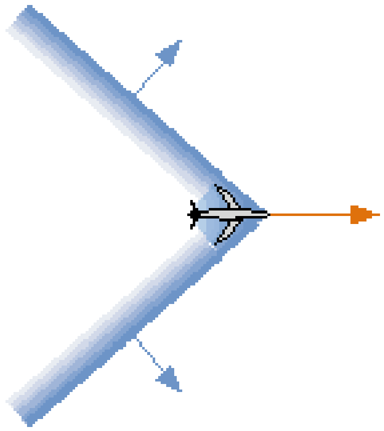
  Because the molecules alternately get closer together and farther apart, the density oscillates as well.

  In the picture at the right, the higher density regions are darker and the lower density regions are lighter.

  For this reason sound is also called a **density wave**.

- Sound waves travel at a particular speed, the **speed of sound**, that depends on the material, its density, and the temperature.

  In air, it is about 340 m/s; it is generally faster in a liquid and even faster in a solid, since the molecules don't have to travel as far to bump into each other.



- If an object travels through a fluid faster than its speed of sound, it pushes the fluid faster than it prefers to move.

  As a result, the fluid is compressed into a narrow, dense layer called a **shock wave**.

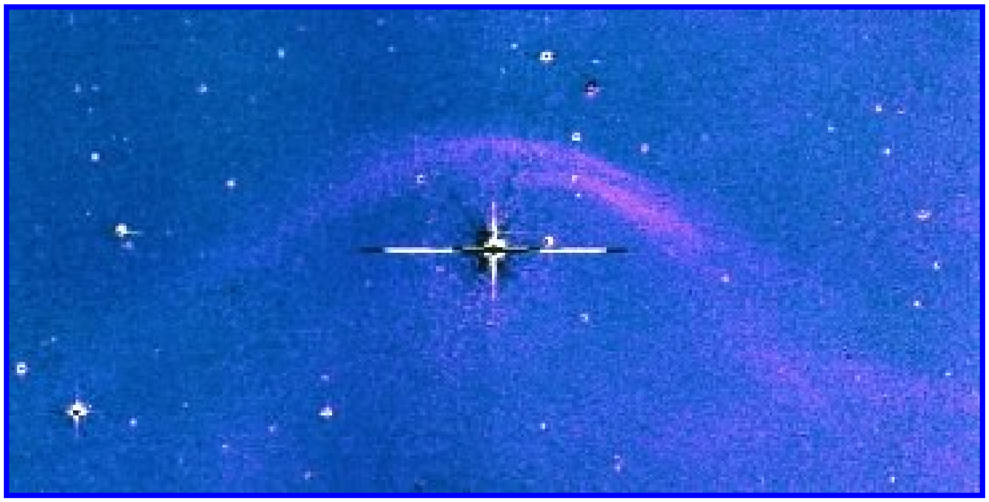
  When produced by high-speed jet planes in air, this is also known as a **sonic boom**.

  An example of a (non-sound) shock wave are the **bow waves** produced by a boat in water as it travels faster than the speed of water waves.

A shock wave travels at the speed of sound, and at an angle to the motion of the causal object.

Picture Information

In the picture at the right, the "runaway" star HD 77581 can be seen plowing through the interstellar medium at 80 Km/s, producing a highly visible bow shock.



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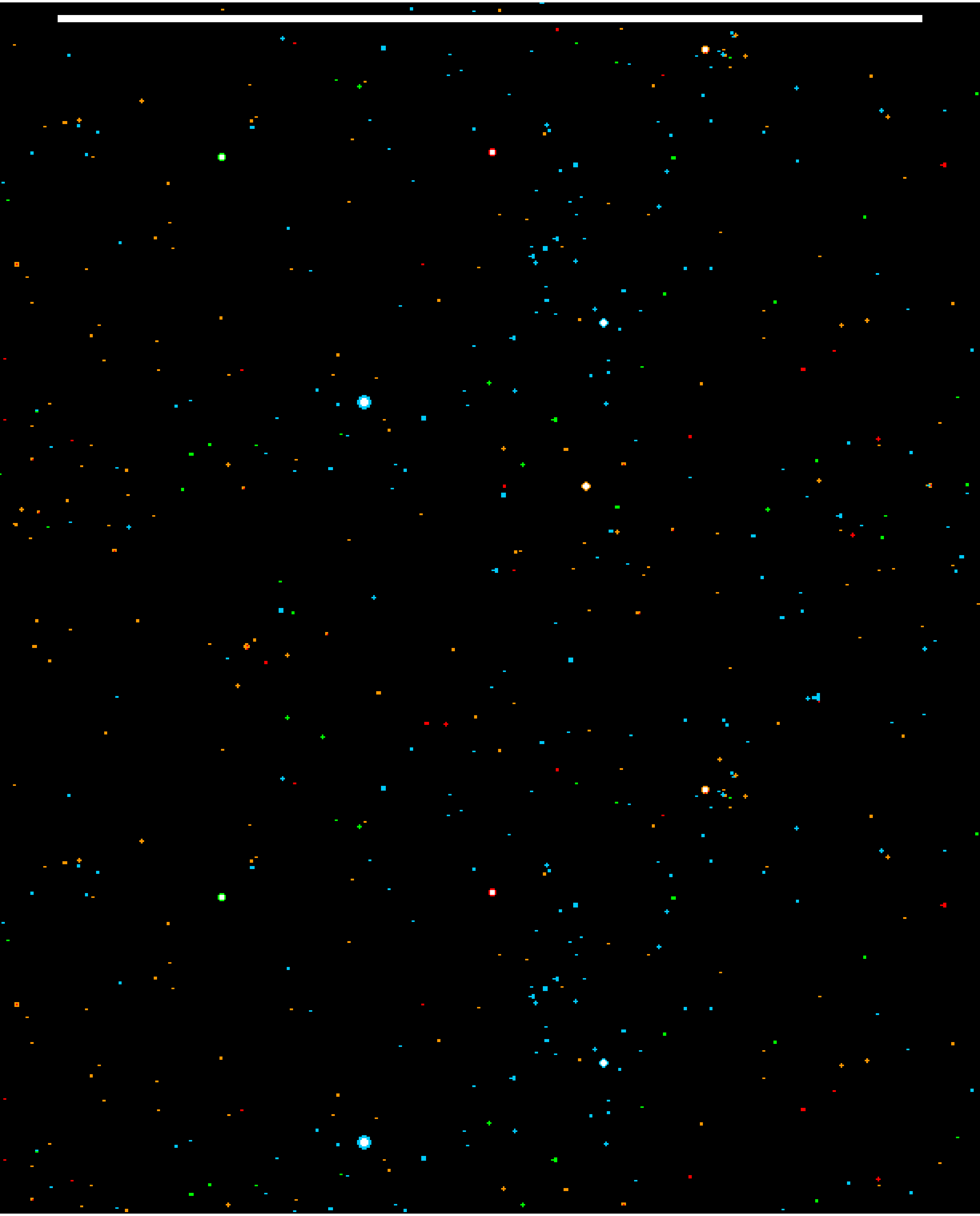

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Introduction to Astronomy

Lecture 9: The Speed of Light and Relativity

The lights of stars that were extinguished ages ago still reaches us. So it is with great men who died centuries ago, but still reach us with the radiations of their personalities.

-- Kahlil Gibran

9.1 The Speed of Light

(Discovering the Universe, 5th ed., §3.1)

- Everything we know about the stars and other objects in the universe comes to us through their release of some form of light, both visible and invisible.

  It is therefore important to understand light's basic properties to determine what that reveals about the stars.

- Although light appears to travel instantaneously from its emission to its detection, it does in fact have a finite speed, which must be very, very fast.

- The first person known to attempt a determination of the speed of light was Galileo.

  Galileo and an assistant each took a shrouded lantern and stood within site of each other on two widely-separated hilltops.

  Galileo opened his lantern, and when the assistant saw its light, he opened his, too.

  Galileo measured the time it took from when he opened his lantern to when he saw his assistant's lamp, which should be the time for light to travel back and forth between the two hilltops.

  Question: how would this information be used to determine light's speed?

  Unfortunately the time Galileo measured could not be distinguished from the time it took to open the lanterns, again due to light's high speed.

- The first determination of the speed of light was an astronomical one, since only in this circumstance will large distances result in a measurable travel time.

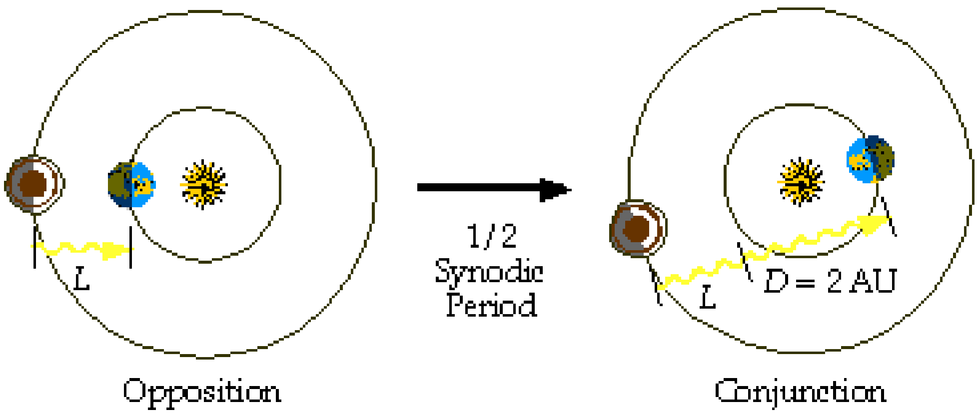
  In 1676, the Danish astronomer Ole Rømer (1644-1710) was studying the orbits of Jupiter's Galilean satellites.

  Over a period of many months, Rømer recorded the starting time of eclipses of these moons by Jupiter.

  These eclipses should occur periodically, so the *n*th eclipse should begin after a time nP.

  For example, the closest moon Io has an orbital period of P = 42.5 h, so the second eclipse takes place after $2P$ = 85.0 h, the third after $3P$ = 127.5 h, etc.

However, after a time equal to half of Jupiter's synodic period, the eclipses were occuring after a time nP + 16.6 minutes!



And after another half synodic period, the variation had disappeared, and the eclipses were again occuring after an integral number of periods.

This correlation with the relative position of Earth and Jupiter could only be due to the variation in their distance as they orbited the Sun.

Rømer realized that if light had a finite speed, the time to travel over an extra distance of two astronomical units would explain the variation.

The **speed of light** must then be:

$c = D/t$ = 2 AU/16.6 min = 7.2 AU/h

The size of the astronomical unit wasn't determined until the 19th century, but once it was the speed of light could be expressed in terrestrial units:

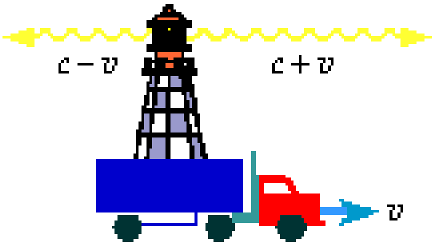
$c = 2.998 \times 10^5$ Km/s

Note the use of the special symbol c for the speed of light.

- By the middle of the 19th century improved technology allowed the measurement of the speed of light in the laboratory, verifying this value.

9.2 The Constancy of the Speed of Light

(Discovering the Universe, 5th ed., §3.1, §13.1)



- One prediction of Newtonian physics is that the speed of light *c* should depend on the speed of its source *v*.

  If light is emitted in the same direction that the source is moving, it should travel faster, at a speed *c* + *v*.

  If light is emitted in the direction opposite to the motion of the source, it should travel slower, at a speed *c* - *v*.

- But there was a problem: a series of precise experiments in the 1880s found that the speed of light was always the same, no matter how fast or in what direction the source was moving!

- Although physics is rooted in the scientific method, this conflict between experiment and an otherwise well-founded theory was very difficult for physicists to overcome.

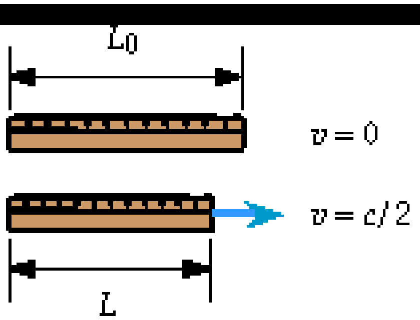
9.3 The Special Theory of Relativity

(Discovering the Universe, 5th ed., §13.1)

- While working in the Swiss Patent Office, Albert Einstein (1879-1955) developed what is now known as the **Special Theory of Relativity**, published in 1905.

  Einstein began with the experimental observation that light *always* has the same speed, and developed a number of unusual consequences:

1. *The faster an object moves, the shorter it becomes.*

   This **length contraction** is given by

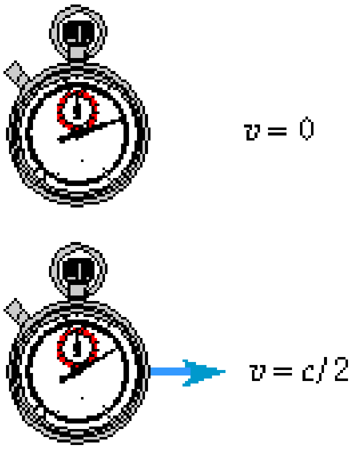
   $L = L_0 / \gamma$.

   The **Lorentz factor**

   $$\gamma = \frac{1}{\sqrt{1 - (v/c)^2}}$$

   is equal to 1 when the object isn't moving (v = 0) and approaches infinity as the object accelerates towards the speed of light (v -> c).

2. *The faster a clock moves, the slower it runs.*

   In other words, events in a moving system take longer to occur from the perspective of a system at rest.

   This **time dilation** is given by

   $T = T_0 * \gamma$.

   In the picture on the right, the stopwatch in motion measures a five-second event, while the stopwatch at rest has seen 6 seconds pass.

3. *The faster an object moves, the more massive it becomes.*

   This **mass increase** is given by

   $m = m_0 * \gamma$.

   Question: how might one measure this mass increase?

   An important consequence of mass increase is a violation of the principle of conservation of mass.

4. *Mass can be converted into energy and vice versa.*

   In addition to the violation of mass conservation above, it can be shown that conservation of energy is violated, i.e. the energy you put into accelerating an object doesn't all show up as the object's energy.

But both the missing energy and the increased mass can be explained if you allow mass to be a form of energy, according to the following relation:

$E = mc^2$

Note that, because c is so large, mass is a very, very concentrated form of energy.

This generalized principle of **conservation of mass + energy** has profound consequences, as we will see later.

5. *Nothing can travel faster than light.*

   If you are accelerating an object towards the speed of light, its mass increases without bound, making it harder and harder to increase its speed.

   As a consequence, a massive object must always travel at less than the speed of light.

   Since light itself travels at the speed of light, it must have no mass!

6. *Newton's Laws of Motion are approximations to Special Relativity that are applicable only at low speeds.*

   In other words, Special Relativity is a generalization of Newton's Laws of Motion.

   In practice, one must be traveling faster than ~0.1c (30,000 Km/s!) to observe these special relativistic effects.

   Nevertheless, with sensitive experimental equipment such as atomic clocks, the predictions of Special Relativity have been verified to high precision.

- **Extra:** C-ship provides movies to help you visualize the effects of special relativity at high speeds.

9.4 The General Theory of Relativity

(Discovering the Universe, 5th ed., §13.2)

- The equivalence of mass and energy soon led Einstein to develop the **General Theory of Relativity**, published in 1916.

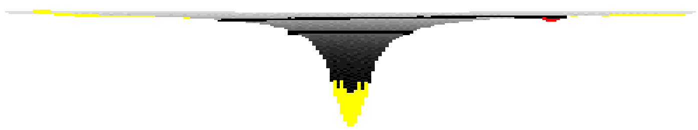
  Light has no mass, but it does have energy, so it should be affected by the presence of massive objects such as the Sun, just as the planets are.

- The General Theory of Relativity is based on a four-dimensional geometric framework of space and time called **space-time**.

  Space-time is not an emptiness, but instead has a physical presence that is affected by its contents.

  The predictions of General Relativity include:

  1. *The presence of mass or energy will curve space.*

     You can think of space as a three-dimensional "rubber sheet" that is usually flat.

     But when a mass is placed on this "rubber sheet", it stretches and curves in response.

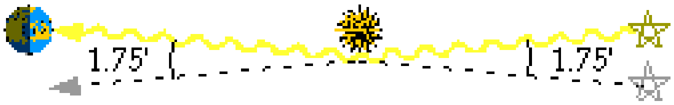
     When space is curved, a moving object must follow the curvature, i.e. change its speed and direction, just as a car must turn when the highway curves.

     Curvature of space thereby replaces Newton's concept of force as a means to accelerate objects.

     The gravity well takes on a new physical meaning, with the massive Sun sitting at its bottom, and the planets forced to curve around the walls of the well.

     Light must also curve around a massive object such as the Sun (see the yellow line in the picture above).

Question: what shape will light's path have?



The deflection of light near the Sun was verified during the solar eclipse of 1919, when a star that should have been invisible behind the eclipsed Sun could be seen.

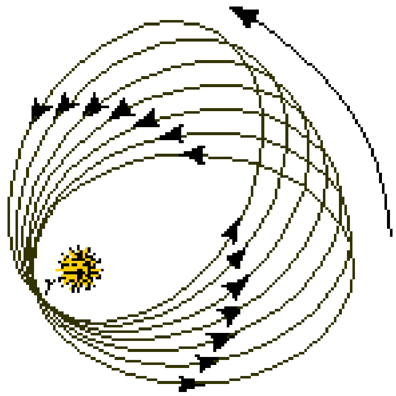
The observed amount of deflection, 1.75 arc sec, is the same as that predicted by General Relativity.

2. *The presence of mass or energy will slow down time.*

   In other words, clocks run more slowly near a massive object, another form of time dilation.

   Atomic clocks can detect a time difference between the bottom and top of a tall building!

   Time dilation near the Sun explains why Mercury's orbit precesses.

   Recall that angular momentum is given by

   $AM \sim mr^2/P$

   AM is a conserved quantity, and the perihelion distance *r* doesn't change, either.

   So *P*, the time per orbit, must also be fixed.

   But time must dilate in the vicinity of the Sun, which means the orbit must become *longer*, i.e. the perihelion shifts its position in the direction of motion.

   The observed amount of perihelion shift, 43 arc sec/century, is the same as that predicted by General Relativity.

3. *Newton's Laws of Motion and Law of Gravitation are approximations to General Relativity that are only applicable away from large masses or other concentrations of energy.*

   In other words, General Relativity is a generalization of Newton's Laws of Motion and Gravitation.

In practice, one must have an escape velocity faster than ~0.1*c* to observe these general relativistic effects.

Nevertheless, with sensitive experimental equipment such as atomic clocks, the predictions of General Relativity have been verified to high precision.

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Introduction to Astronomy

Lecture 10: The Nature of Light

Two glasses where herself herself beheld
A thousand times, and now no more reflect;
Their virtue lost, wherein they late excell'd,
And every beauty robb'd of his effect:
'Wonder of time,' quoth she, 'this is my spite,
That, you being dead, the day should yet be light.

-- William Shakespeare, *Venus and Adonis*

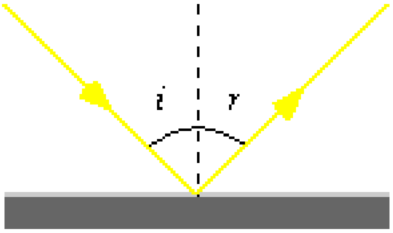
10.1 Reflection and Refraction

(Discovering the Universe, 5th ed., §4.x)

- We have already seen that, while light usually travels in a straight line, a massive object can deflect it.

  It is also possible to change its motion by means of material devices such as shiny surfaces, transparent materials, and apertures.

- A basic property of light is **reflection**, a redirection of its motion by a shiny surface such as a mirror.

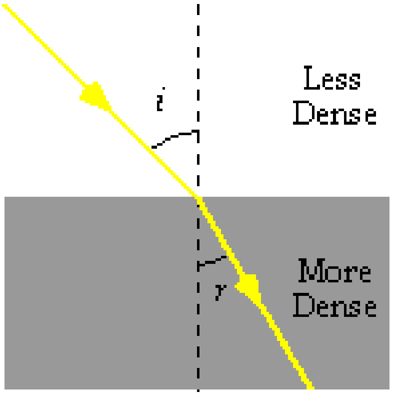
  

  Measuring from the perpendicular to the surface, the **angle of incidence** *i* is *always* equal to the **angle of reflection** *r*.

  Reflection can be explained by conservation of momentum along the surface but a reversal of momentum perpendicular to the surface.

  Question: what would be required to cause a reversal of momentum?

- Light will also change directions when passing from one transparent medium into another, a property known as **refraction**.

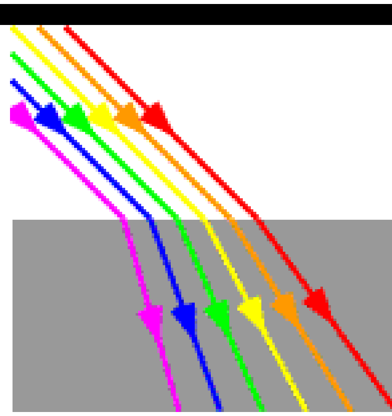
  The **angle of refraction** *r* will depend not only on the angle of incidence *i* but also on the two materials through which the light passes.

  Whichever way the light is traveling, the angles will be larger in the less dense medium, such as vacuum or air, and smaller in the more dense medium, such as water or glass.

  Refraction can be explained by assuming that, in denser media, light travels more slowly (less than the speed in vacuum, *c*), which has been verified by experiment.

  Most materials that refract light will also partially reflect it.

  Question: can you think of an example of this?

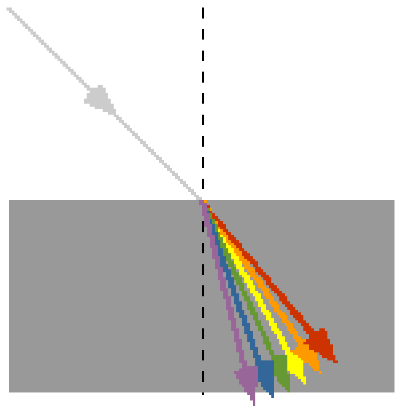


- The angle of refraction will also depend on the color of the light.

  For the same angle of incidence, red light will be refracted the least, with orange, yellow, green, and blue each being refracted increasingly more, and with violet being refracted the most.

  The mnemonic ROYGBV ("roy g. biv") can be used to remember the color order.

  This variation in angle of refraction implies that different colors travel at slightly different speeds in dense media, red being the fastest and violet the slowest.



- When **white light** is refracted, one finds that it spreads out into a rainbow of colors, or **spectrum**, in the order given above.

  The spreading out of light into a spectrum is called **dispersion**.

- In addition to his work on motion and gravity, Isaac Newton also studied light and its dispersion.

  Newton demonstrated that a spectrum dispersed from white light could be recombined back into white light.

  Newton therefore concluded that white light is a mixture of all colors, instead of the alternative theory that the colors were properties of the materials with which light interacts.

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Introduction to Astronomy

Lecture 12: The Interior of the Sun

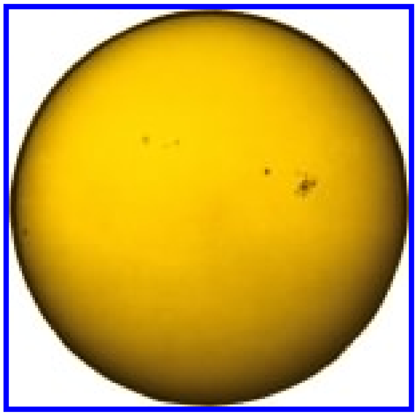
Sometime too hot the eye of heaven shines,
And often is his gold complexion dimm'd:
And every fair from fair sometime declines,
By chance, or nature's changing course, untrimm'd.

-- William Shakespeare, *Eighteenth Sonnet*

12.1 Basic Characteristics of the Sun

(Discovering the Universe, 5th ed., §9.0)

Photo Information



- The Sun is just a star like all of the others, with one very important difference: it is very close to us, and is therefore our primary source of heat and light.

  A small change in the Sun's behavior could melt our icecaps or start another Ice Age.

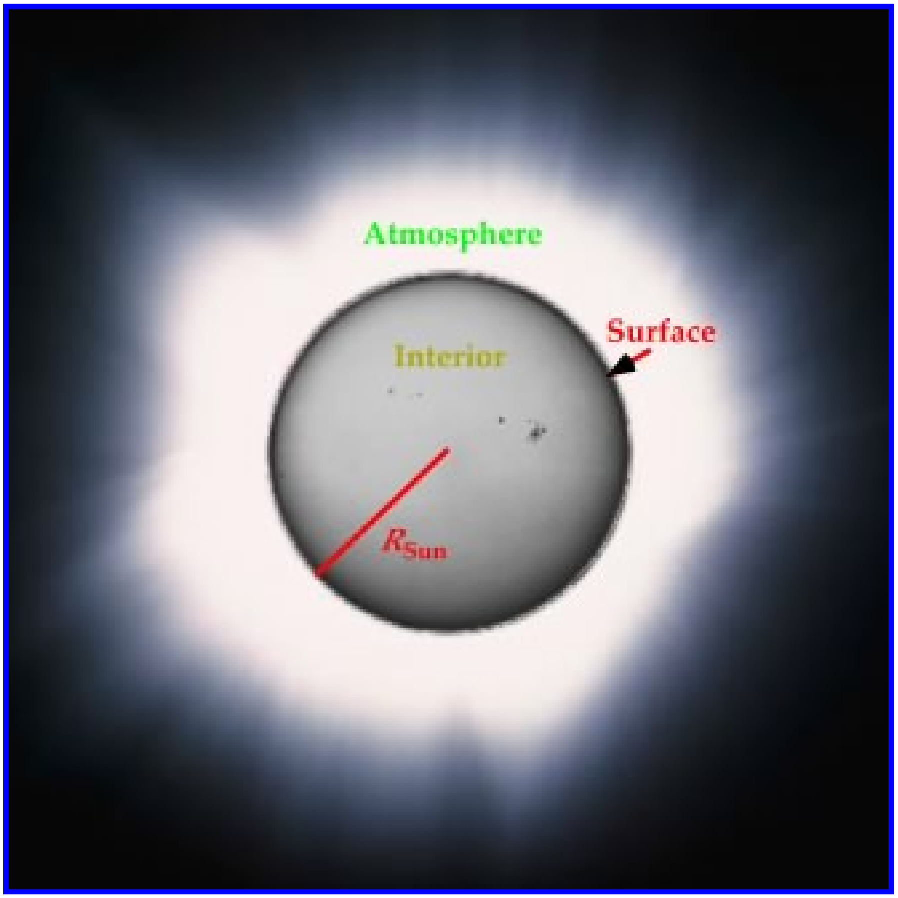
  Click here for a real-time image of the Sun from the National Solar Observatory/Sacramento Peak (available when the telescope is operating).

- The Sun is an average star, in any of the different ways we might describe it:
  - **Size**: R_{Sun} = 7.0 x 10^5 Km = 1/200 AU = 110 x R_{Earth}
  - **Mass**: M_{Sun} = 2.0 x 10^{30} Kg = 3.3 x 10^5 x M_{Earth}
  - **Density**: d_{Sun} = 1.4 g/cm^3
  - **Composition**: 74% H, 25% He, 1% other elements
  - **Temperature**: $T_{surface}$ = 5800 K
  - **Luminosity**: L_{Sun} = 3.9 x 10^{26} W
  - **Age**: 5 Gy

12.2 The Sun's Structure

(Discovering the Universe, 5th ed., §9.0, 9.8)

Picture Information



- The Sun can be divided into two basic parts.

  The **interior** of the Sun is a spherical region that is opaque to visible light and is relatively high density.

  The **atmosphere** of the Sun surrounds the interior, and is transparent to visible light and is relatively low density.

  The **surface** of the Sun is the boundary between the interior and the atmosphere, and is more or less what we "see" when we look at the Sun.

  The "size" of the Sun given above, R_{Sun}, is the radius of the interior and the surface.

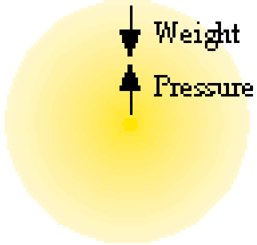
  Although the interior is relatively high density and the atmosphere is relatively low density, there is no sharp drop-off in density such as occurs at the Earth's surface.

- The Sun is so hot that molecules are torn apart into atoms, which are, in turn, mostly torn apart into a plasma of charged particles: positive ionized atoms (including "bare" nuclei) and negative electrons.

  The Sun is therefore a large ball of fluid plasma, held together by its own gravity.

- The size of the Sun does not change, so it must be in **mechanical equilibrium**.

  Because the Sun consists of a fluid, this is also called **hydrostatic equilibrium.**



For this equilibrium to exist, there must be a balance between the *inward* force of gravity, trying to compress the Sun, and the *outward* fluid pressure, which resists compression.

The deeper you go inside the Sun, the greater the weight of the mass above you.

Therefore, the opposing pressure must *also* increase with depth.

As the pressure increases, the density and temperature will also increase:

$P \sim dT$

- So, at the center of the Sun it must be very hot and very dense.

  It is calculated that:

  P_{center} = 340 Gbar
  T_{center} = 15.5 MK
  d_{center} = 160 g/cm^3.

  Question: if the average density of the Sun is only 1.4 g/cm^3, what does that say about the density of the atmosphere of the Sun?

- Because of the Sun's fluid nature, it is possible for its density to increase with little or no increase in pressure; this would require its temperature to *decrease:*

  P (no change) ~ d (up)T (down)

  So, it's possible for gravity to compress the Sun even further than it currently is.

  To maintain its mechanical equilibrium, then, the Sun must prevent its temperature from decreasing.

  The Sun maintains its temperature by producing energy in its core.

  Question: if the Sun didn't maintain its temperature, what would prevent it from completely collapsing?

12.3 The Sun's Energy Source

(Discovering the Universe, 5th ed., §9.7)

- The source of the Sun's energy was not understood until this century.

  It *was* known that familiar sources of energy could not be responsible.

  For example, if the Sun was made of oil, to produce the observed luminosity its mass would be burned up in a few thousand years, and the Earth was known to be much, much older than that.

- Einstein's Theory of Special Relativity provided the key when it showed that energy and mass are convertible:

  $E = mc^2$

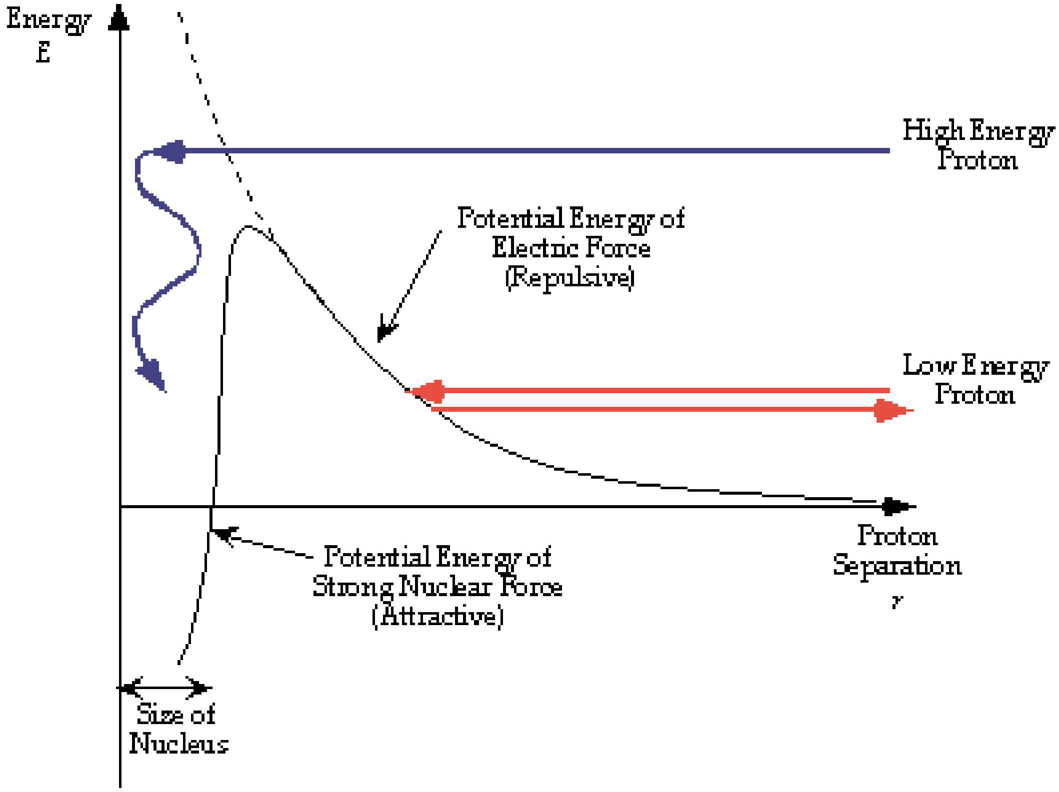
- Because c is so large, a small amount of mass can provide a huge amount of energy.

  The only question then was how this conversion from mass to energy might occur.

- The subsequent development of nuclear physics provided the necessary understanding: **thermonuclear fusion** of hydrogen into helium.

  Basically, this is nuclear fusion at a very high temperature, which is necessary to overcome the nuclei's electrostatic repulsion.

- Recall that the positive charge on hydrogen nuclei (protons) ordinarily keeps them far apart.

  The proton's electric potential energy increases as they get closer together, so they will slow down, stop, and begin to separate again.

  This is like trying to roll a ball up a hill; with too little energy, it will turn around and roll back down.

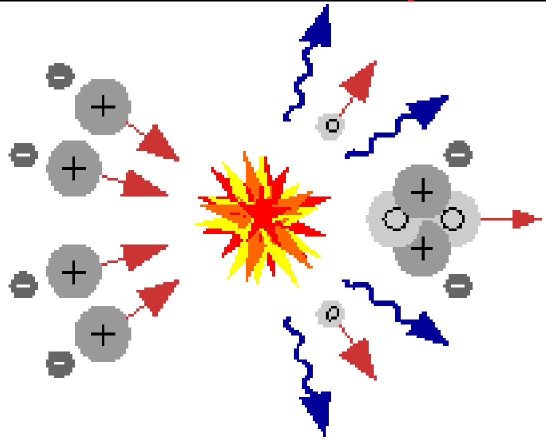
- If the protons are hot enough, however, they will have enough energy that that they can get quite close together.

- At short (nuclear) distances, the strong nuclear force will dominate the electric force, so that the protons are now attracted to each other, and they can fuse together into a new nucleus.

  This would be like a ball with enough energy to roll up and over the top of a hill, and down the other side.

- The energy required for protons to overcome their electric repulsion corresponds to a temperature of 8.5 MK.

  Since the Sun's core has a temperature of 15.5 MK, it can easily sustain hydrogen fusion, and in fact burns hydrogen faster than it would at a lower temperature.



- The actual process by which **hydrogen fusion** occurs is somewhat involved and is called the **proton-proton cycle**, summarized by the equation:

  $$4\,{}^{1}H \rightarrow {}^{4}He + 4\gamma + 2\nu + E$$

  This equation says that four hydrogen atoms (with one nucleon each) are combined to produce a helium atom (with four nucleons).

  In addition, the fusion produces four photons (represented by the Greek letter gamma, because they are gamma radiation), two neutrinos (represented by the Greek letter nu), and energy.

- According to Einstein, the proton-proton cycle must conserve mass + energy.

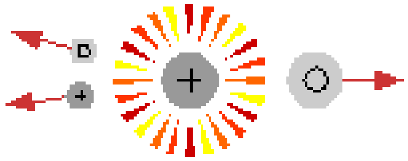
  In particular, because

  $$4\,\text{mass}({}^{1}H) > \text{mass}({}^{4}He) + 2\,\text{mass}(\nu)$$

  the overall reaction begins with more mass than it ends up with, and the difference is converted into other forms of energy.

  Question: what other forms of energy might result from this fusion?

- Note that in the above reaction, the hydrogen on the left has *four* protons, while the helium on the right has *two* protons and two *neutrons*.

  The weak nuclear force governs the reaction which turns protons into neutrons, resulting in the neutrinos:

  $$p + E \rightarrow n + e^{+} + \nu$$

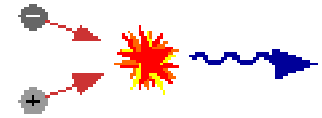
  Question: where did we previously see a similar process? how did it differ?

  Question: why does this reaction require energy to occur? (Hint: consider the masses involved.)

- In addition to a neutrino, this reaction produces a **positron**, which is a positive electron.

  The positron ensures conservation of electric charge by carrying away the proton's positive charge.

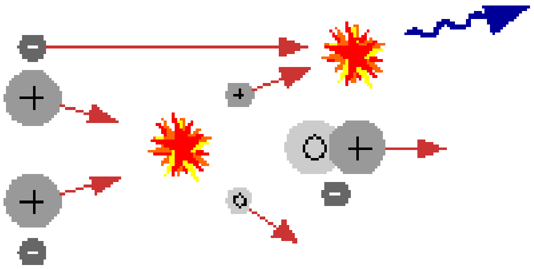
Positrons are a form of **antimatter**, particles which have the same mass as regular matter but the opposite electric charge.



Antimatter does not normally exist in nature, because it will usually quickly collide with matter and be destroyed in a process called **pair annihilation**:

$$e^+ + e^- \rightarrow \gamma$$

Note that here mass is now converted completely back into energy in the form electromagnetic radiation.

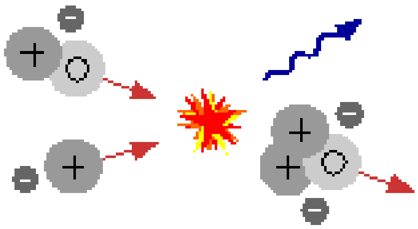


- The proton-neutron conversion occurs when two protons ("ordinary" hydrogen) fuse into a nucleus of **deuterium** ("heavy" hydrogen).

  Deuterium is an isotope of hydrogen, ^2H, with one proton and one neutron.

  $${}^1H + {}^1H \rightarrow {}^2H + \gamma + \nu + E \qquad (1)$$

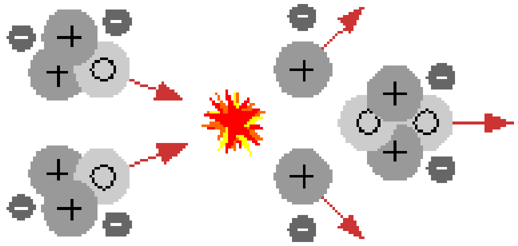
  The energy to convert the proton into a neutron comes from a net mass loss in the conversion from two protons to deuterium.



- The deuterium quickly fuses with another proton to form an isotope of helium, ^3He, which has only one neutron:

  $${}^2H + {}^1H \rightarrow {}^3He + \gamma + E \qquad (2)$$

  Another photon of gamma radiation is released in this process.



- Finally, two "light" helium nuclei fuse together, producing "ordinary" helium, and two protons:

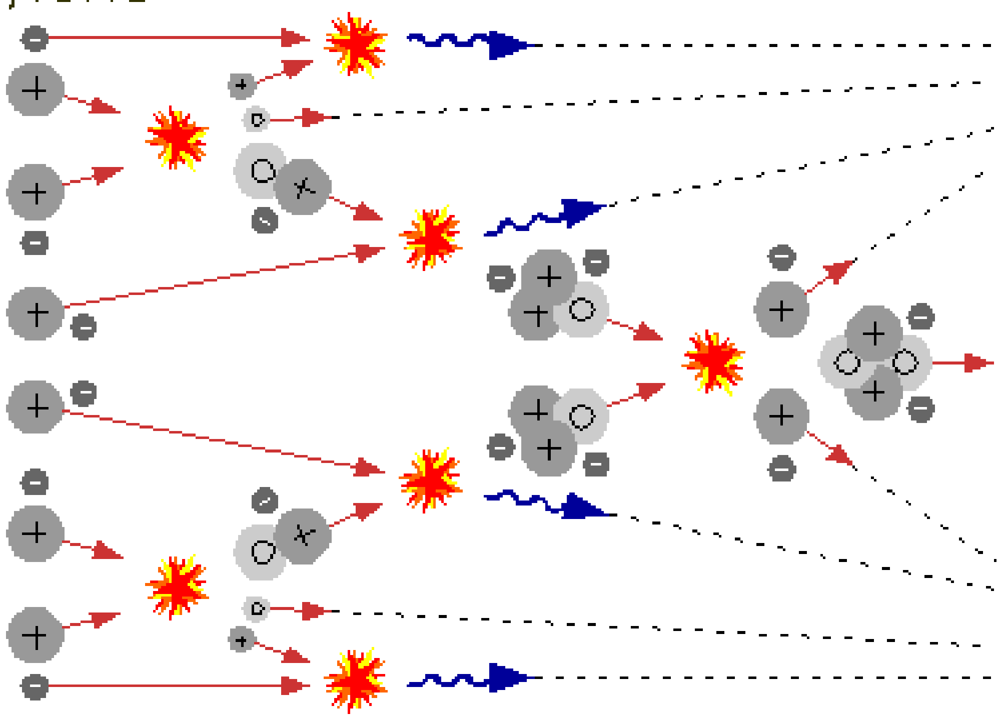
  $${}^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H + E \qquad (3)$$

- The fusions (1) and (2) occur twice, and together with fusion (3) the result is:

$$6\,{}^{1}H \rightarrow {}^{4}He + 2\,{}^{1}H + 4\gamma + 2\nu + E$$

Note that two protons are "recycled" for use in later fusions, which is how the proton-proton cycle gets its name.

The entire series of reactions is displayed at the right.



- The energy resulting from thermonuclear fusion is distributed in several ways:
  - kinetic energy of ^{4}He and the two "recycled" protons: 91%
  - electromagnetic energy of the photons: 8%
  - kinetic energy of the neutrinos: 1%

- To produce the Sun's luminosity, 600 million tons of H must be burned by this process every second.

  Because the Sun is so massive, though, it will last for another 5 billion years!

12.4 The Flow of Energy

(Discovering the Universe, 5th ed., §9.8)

- The energy produced at the center of the Sun must eventually be radiated away at its surface.

  Otherwise, the Sun would get hotter over time, which is not observed.

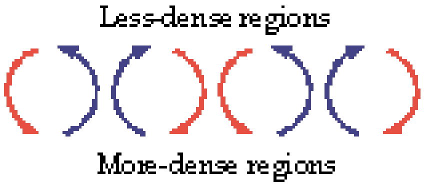
  This balance is called **thermal equilibrium**.

- There are three means by which energy might travel outward to the surface:
  - **Conduction**: this process occurs in solids or dense fluids.

    It is a "domino" effect, with one atom bumping into another atom and passing on its energy, which then bumps into another atom, etc.

    Question: where have you seen conduction take place in everyday life?

  - **Convection**: this process occurs in fluids.

    It involves the flow of matter itself, with hotter, less-dense material rising upward while cooler, more-dense material sinks downward to replace it.

    A stable structure of **convection rolls** will typically form, as shown.

    Question: where have you seen convection take place in everyday life?

  - **Radiative diffusion**: this process occurs in all materials to a varying degree.

    As we have seen before, they act like blackbodies, so their heat is converted to electromagnetic energy and radiated away as a stream of photons.

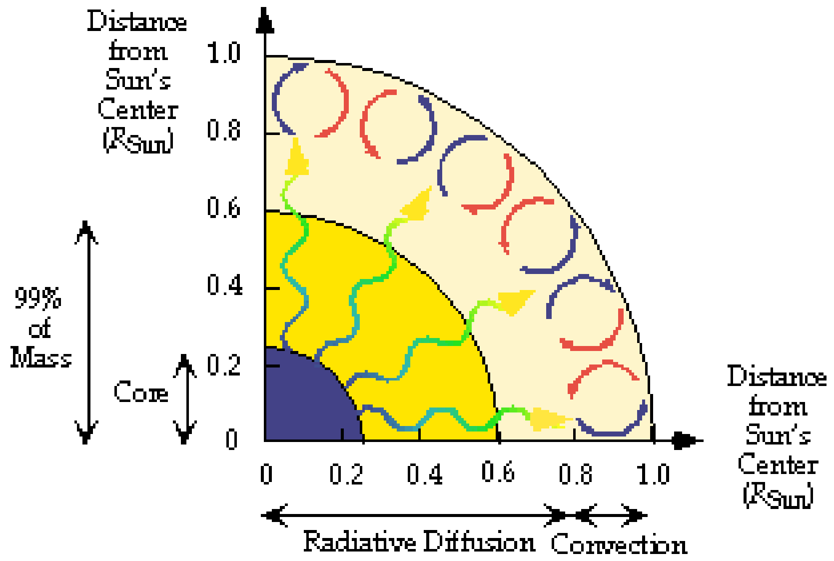
    Depending on the materials through which they pass, the photons may be absorbed and reemitted multiple times, so that they may travel at something less than the speed of light.

    Question: where have you experienced radiative diffusion in everyday life?

- Theoretical models of the Sun's interior tell us quite a bit about where its energy is produced and how it is transported to the surface.

- The Sun's **core**, the region where thermonuclear fusion occurs and energy is produced, extends out to about a quarter of the Sun's radius.

- About 99% of the Sun's mass lies within 60% of the Sun's radius.



- In the **radiative zone**, extending out to about 80% of the Sun's radius, radiative diffusion is the primary means by which the energy is transported to the surface.

- As fusion-produced photons travel outward, they interact with the nuclei and electrons which make up the Sun's plasma, and they are absorbed and reemitted time and time again.

  Travelling extremely slowly, photons can take hundreds of thousands of years to reach the surface.

- As the photons move outward from hotter to cooler regions, they will lose energy and their wavelength will decrease.

  Initially they are gamma photons; by the time they reach the surface, they have become a blackbody distribution, with about 46% visible, 43% infrared, and 11% ultraviolet.

- In the **convective zone**, the outermost 20% of the Sun's radius, the density is very low and convection becomes the most important means of energy transport.

- Although conduction certainly occurs to some degree in the denser parts of the Sun, it is not an important effect compared to radiative diffusion and convection.

12.5 The Solar Neutrino Problem

(Discovering the Universe, 5th ed., §9.9)

- Another type of radiative diffusion involves the neutrinos produced in the Sun's core, about 2×10^{38} every second.

  Becaue neutrinos don't interact easily with matter, they will mostly zip right through the Sun, carrying away their small amount of energy at close to the speed of light.

Picture Information

- A small fraction of these neutrinos reach the Earth, and scientists have set up **neutrino detectors** to observe them.

  To avoid interference from other forms of radiation in the Earth's atmosphere, these detectors are built deep underground (typically in old mines), where only neutrinos can penetrate.

  For example, the new Sudbury Neutrino Observatory in Ontario is a 12-m sphere buried 2.1 Km below the ground.

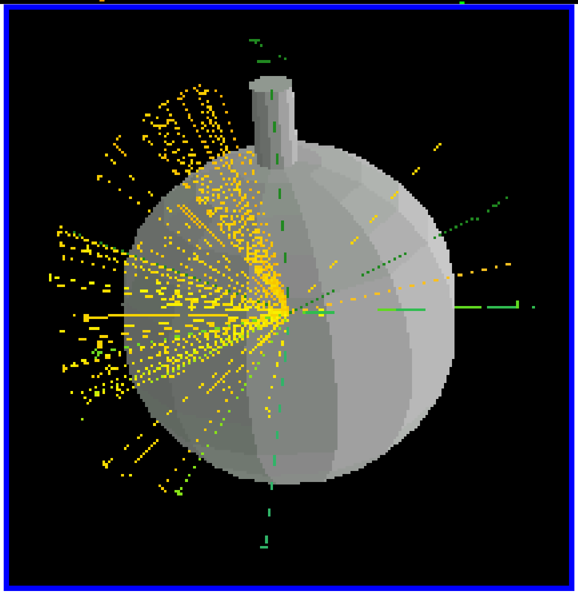
  It is filled with heavy water, which consists of oxygen and deuterium instead of "ordinary" hydrogen.

- On rare occasions, about 1 in every 10^{15} neutrinos, an interaction will occur with one of the neutrons in the deuterium to produce a proton and an electron:

  $$\nu + n \rightarrow p + e^-$$

  Neutrinos can also simply collide with existing electrons.

Picture Information



In either case, the electrons are ejected at close to *c*, the speed of light in vacuum, which is much faster than the speed of light in the surrounding water (0.75*c*).

These high-speed electrons therefore produce a shock wave of light called **Cherenkov radiation**, which can be observed by the 9600 detectors mounted around the surface of the sphere.

Information about the neutrino's energy and direction can then be determined.

Question: what other physical phenomenon have we seen which is due to the reduced speed of light in a material?

- The first neutrino detectors demonstrated that the Sun does, in fact, emit neutrinos, confirming that nuclear fusion occurs at its core.

  Extra: The developers of the first neutrino detectors recently won the 2002 Nobel Prize in Physics.

  The early neutrino experiments also resulted in one problematic observation: they only counted between 1/3 to 2/3 of the calculated number of neutrinos, depending on their energy.

  This unexpected deficit is known as the **solar neutrino problem**.

- Experimental results from the Super Kamiokande neutrino detector, reported in 1998, have provided a solution to the solar neutrino problem by demonstrating that neutrinos have mass (although we still don't know the actual values).

  There are actually three types (or "flavors") of neutrinos, distinguished by their mass; the Sun produces the lightest neutrino.

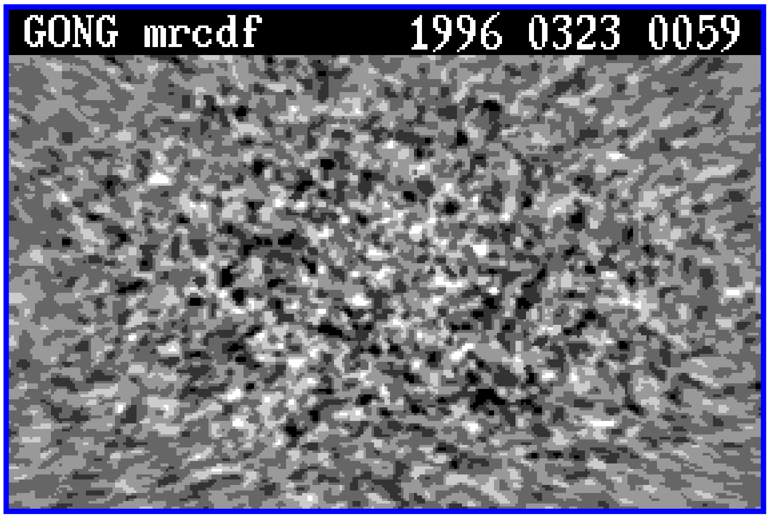
  Because they have mass, neutrinos can easily "oscillate" from one flavor of neutrino to another.

  Since older neutrino detectors couldn't detect the heavier neutrinos after an oscillation occurred, there appeared to be a deficit of the Sun's lighter neutrinos.

12.6 Helioseismology

(Discovering the Universe, 5th ed., §9.8)

Picture Information



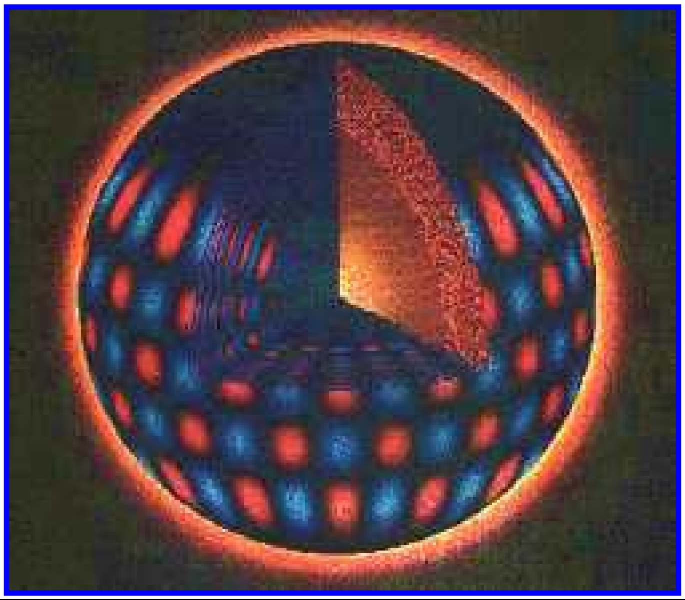
- In the 1960s astronomers discovered that the Sun's surface vibrates slightly, with a period of five minutes.

  Other vibrations were subsequently discovered, with periods of 30 minutes and longer.

  The study of these vibrations is known as **helioseismology**, from the Greek for "Sun" and "to shake".

  The image to the right of the Sun's surface reveals a mixture of these vibrations over a one-hour period.

Picture Information



- The Sun's vibrations are resonant sound waves, like those that occur inside the chambers of musical instruments.

  At any given time different portions of the Sun's surface are moving outward while other portions are moving inward.

  Question: which color (red or blue) corresponds to which motion?

  These vibrations can extend all the way

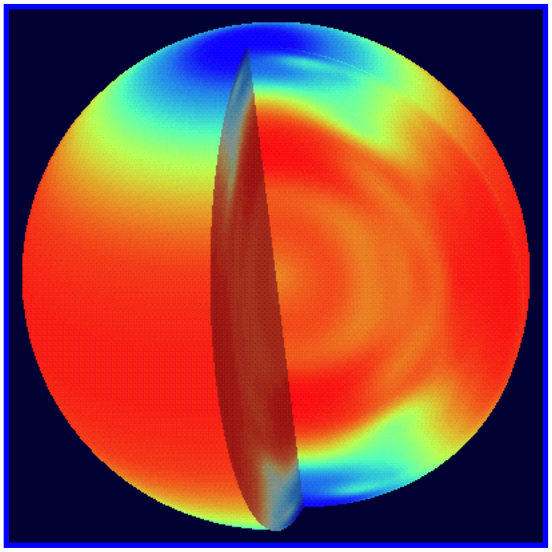
into the interior of the Sun.

If these vibrations were in air, they would sound like this. (AU format; Sound Information.)

- Analysis of these vibrations provides information about the interior of the Sun, in particular how its movements, density, temperature, and chemical composition vary with depth.

  As a result, observations of these vibrations provide important tests for theories of stellar structure and evolution.

Picture Information



- One important result of these observations are descriptions of the motion of the Sun's interior.

  The Sun experiences a **differential rotation**, i.e. different parts rotate at different rates, as shown in the picture at the right.

  This is not surprising, given that the Sun is fluid.

  There are two different regions: an outer shell, which correspond to the convective zone, and an inner sphere, which correspond to the radiative zone.

  In the outer shell, rotation varies with latitude.

  Outer equatorial regions rotate relatively rapidly, with a period of about 25 days (red).

  Outer polar regions rotate relatively slowly, with a period of about 35 days (blue).

  Intermediate latitudes (orange/yellow/green) rotate with a period in between these extremes.

  In the inner sphere, there is little variation in rotation, with a relatively short period of 25 days (red).

  Question: why might the inner regions of the Sun have much less variation in rotation speed?

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Introduction to Astronomy

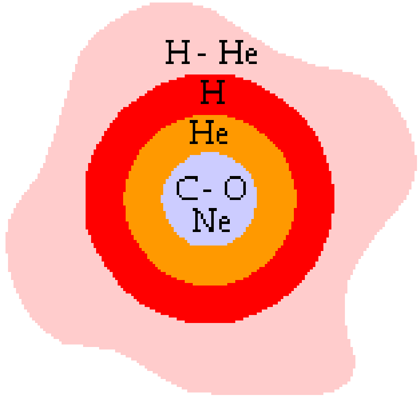
Lecture 19: The Death of High-Mass Stars

The bigger they come, the harder they fall.

-- "Gentleman Jim" Corbett

19.1 The Acceleration of Fusion

(Discovering the Universe, 5th ed., §12.4)



- As we saw in Lecture 17, all stars will eventually expand to become supergiants.

  If the star has a high mass, larger than about eight solar masses, it will have a carbon-oxygen-neon inner core that is not burning, surrounded by a shell of burning helium, and finally an outer shell of burning hydrogen.

  As with other stars, the core is buried deep inside the outer layers of the star, which consist of nonburning H and He.

- With no energy source in the inner core to balance the gravity, the star is out of mechanical equilibrium.

  A high-mass star can squeeze its core more than a low-mass star due to its larger gravity.

  So, the core is again compressed, and its pressure and temperature will rise.

  The higher temperatures provide the energy for other nuclei to fuse into new elements, provide a new source of energy in the core, and restore equilibrium.

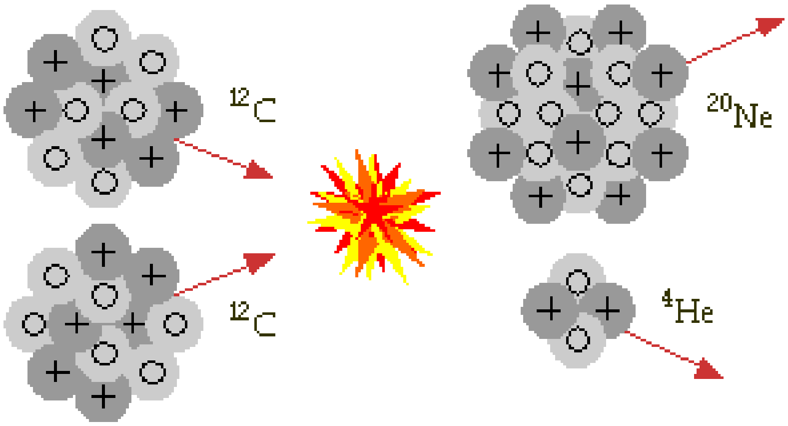
  The most important of these reactions are detailed below, though there are others that also provide energy and produce other elements.

  In addition, many other reactions that *require* energy to occur are possible at these high temperatures.

  In this way every heavy element in nature is created, in proportions that are predictable from our understanding of nuclear fusion.

- When the temperature of the inner core reaches 600 MK, **carbon fusion** will begin to produce neon and helium:

  $$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He + E$$

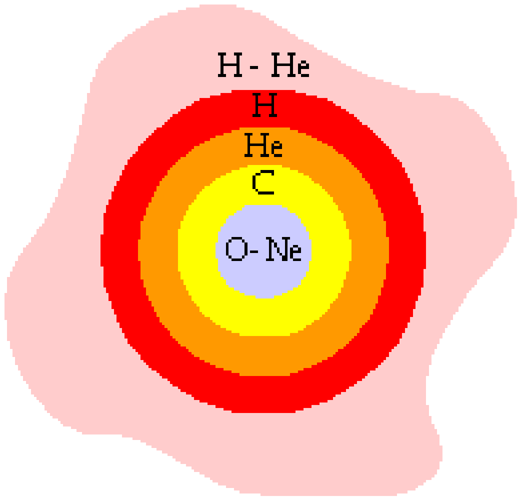
  With this new source of energy in the inner core, the star's mechanical equilibrium is again restored.

  However, this balance is short-lived; in a 25-solar mass star, this process (and others) will use up most of the carbon in the core in only 600 years!

- So carbon fusion soon dies off, and the inner core becomes primarily oxygen and neon.

  Without an energy source in the inner core, the compression-shell burning process occurs once again.

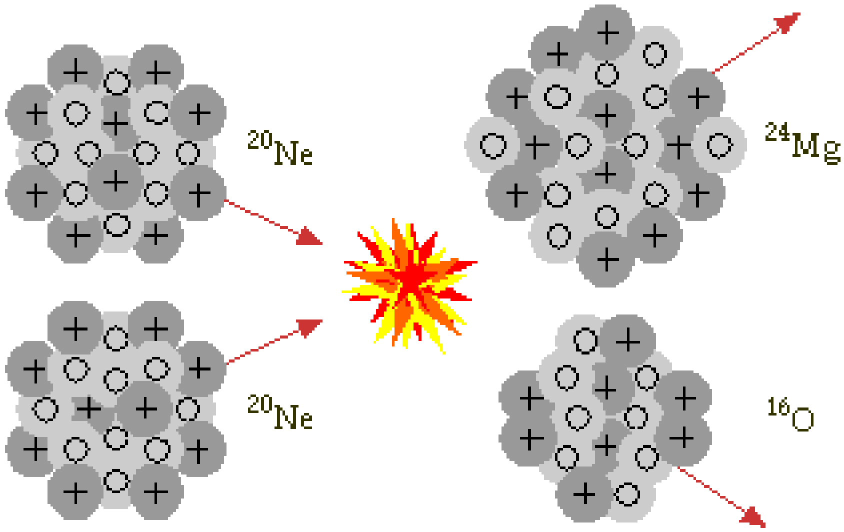
  Fresh carbon produced in the upper layers of the core is pushed deeper, and the nonburning inner core becomes surrounded by a shell of burning carbon.



- Then the compression- heating- fusion- balance process repeats itself in the inner core.

  When the temperature of the inner core reaches 1200 MK = 1.2 GK, **neon fusion** will begin to produce magnesium and oxygen:

  $$^{20}Ne + {}^{20}Ne \rightarrow {}^{24}Mg + {}^{16}O + E$$



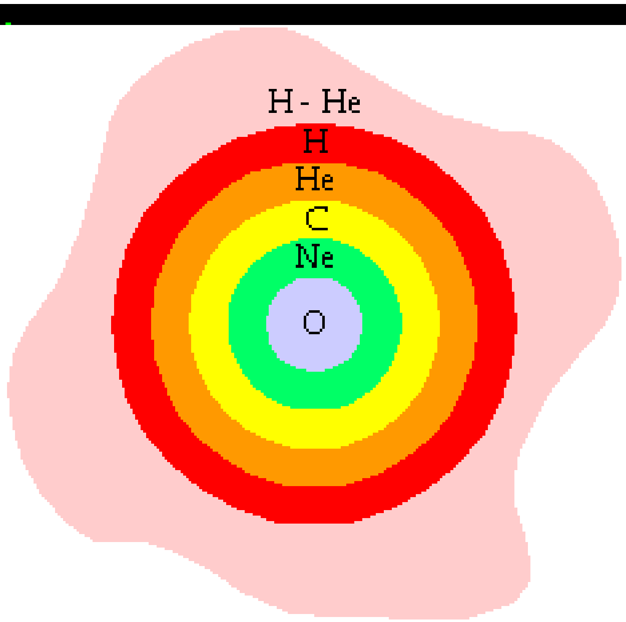
  With this new source of energy in the inner core, the star's mechanical equilibrium is again restored.

  However, this balance is even shorter-lived; in a 25-solar mass star, this process (and others) will use up most of the neon in the core in only one year!

- So neon fusion quickly dies off, and the inner core now becomes primarily oxygen.

  Without an energy source in the inner core, the compression-shell burning process occurs yet again.

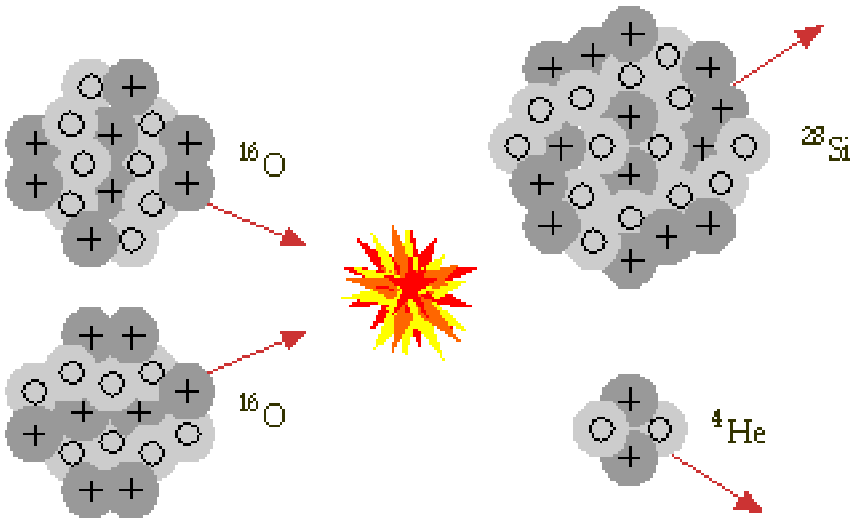
  Fresh neon produced in the upper layers of the core is pushed deeper, and the nonburning inner core becomes surrounded by a shell of burning neon.



- Then the compression- heating- fusion- balance process repeats itself in the inner core.

  When the temperature of the inner core reaches 1500 MK = 1.5 GK, **oxygen fusion** will begin to produce silicon and helium:

  $^{16}O + {}^{16}O \rightarrow {}^{28}Si + {}^{4}He + E$



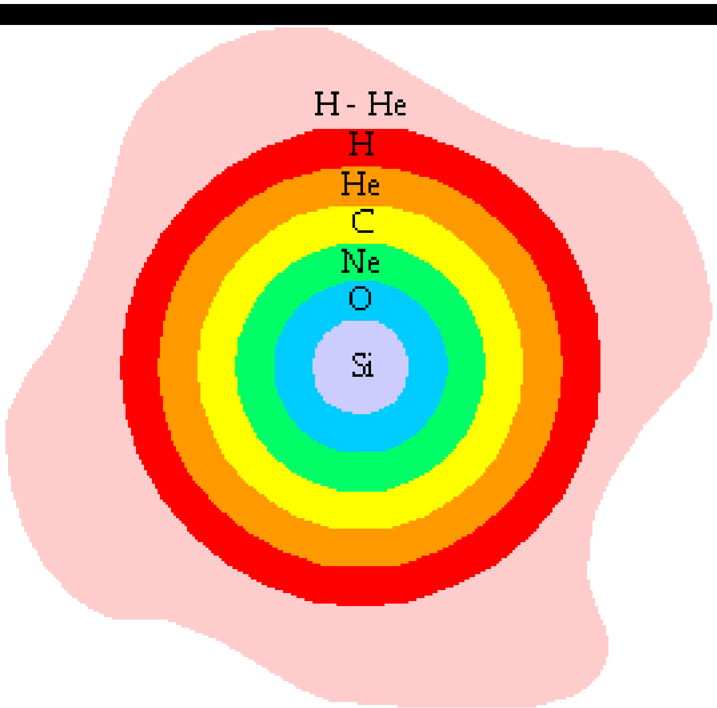
  With this new source of energy in the inner core, the star's mechanical equilibrium is again restored.

  However, this balance is again very short-lived; in a 25-solar mass star, this process (and others) will use up most of the oxygen in the core in only half a year!

- So oxygen fusion quickly dies off, and the inner core now becomes primarily silicon.

  Without an energy source in the inner core, the compression-shell burning process occurs once again.

  Fresh oxygen produced in the upper layers of the core is pushed deeper, and the nonburning inner core becomes surrounded by a shell of burning oxygen.

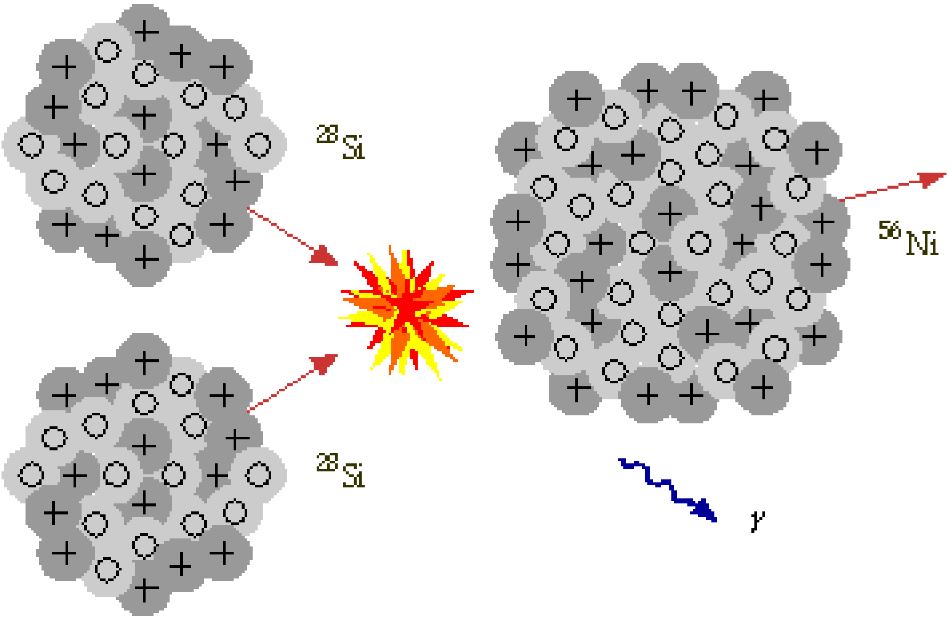


- Then the compression-heating- fusion- balance process repeats itself one last time in the inner core.

  When the temperature of the inner core reaches 2700 MK = 2.7 GK, **silicon fusion** will begin to produce nickel:

  $$^{28}Si + {}^{28}Si \rightarrow {}^{56}Ni + \gamma + E$$

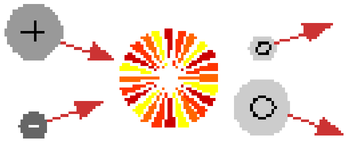
  (Silicon fusion actually occurs through a series of reactions, but the result is the same.)



  With this new source of energy in the inner core, the star's mechanical equilibrium is again restored.

  But this balance is also ephemeral; in a 25-solar mass star, this process will use up the silicon in the core in only one day!

- Finally, the nickel rapidly decays into iron by **neutronization**, in which protons "capture" electrons to produce a neutron and a neutrino:

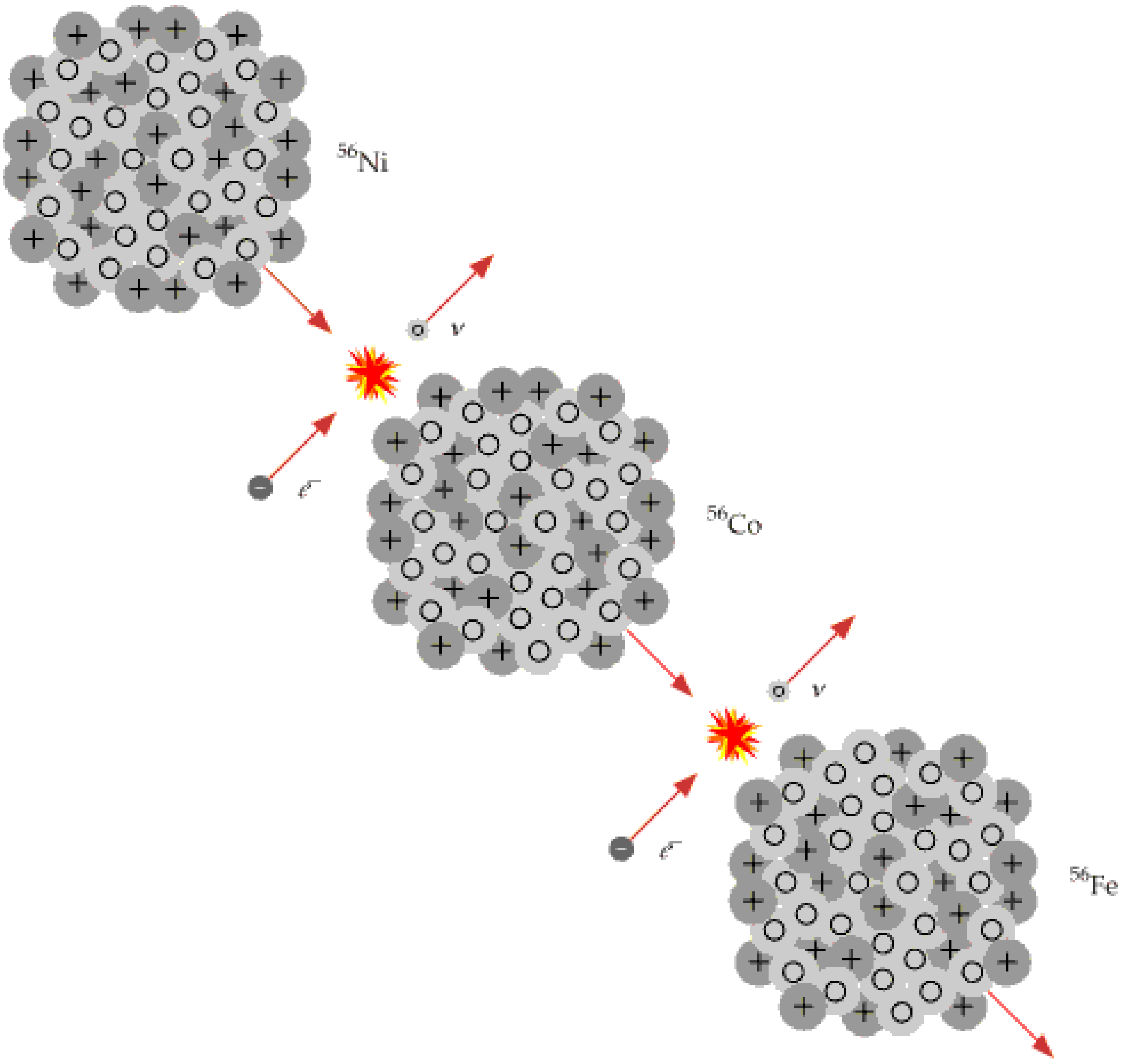


$p + e^{-} + E \rightarrow n + \nu$

Question: where have you seen a similar process? How did it differ?

Neutronization requires energy to occur, but such a large nucleus can provide it from the resulting reduction in the number of its protons.

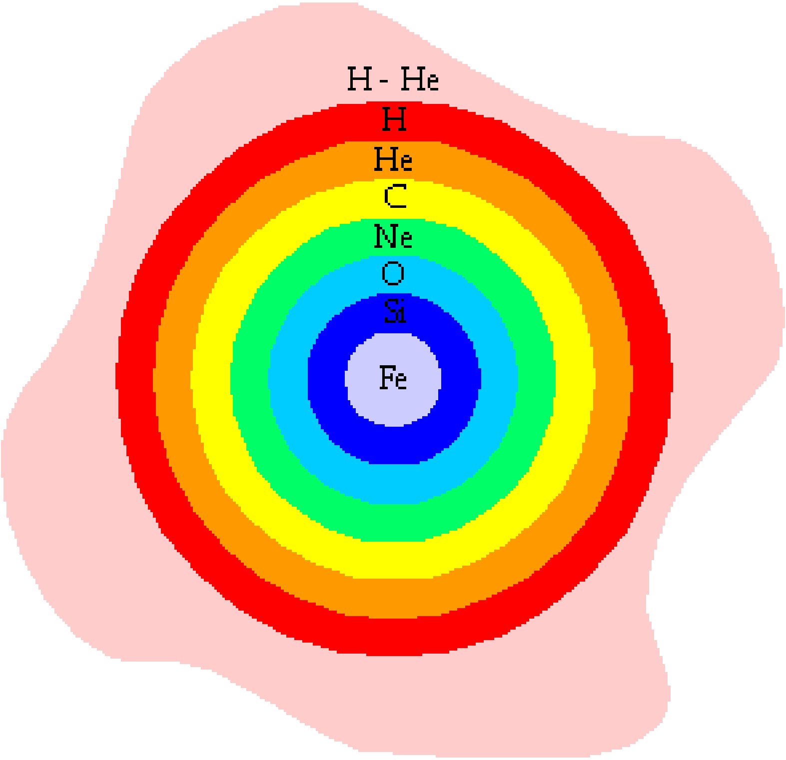
Question: how does reducing the number of protons provide energy?



- So silicon fusion ends almost as soon as it began, and the inner core now becomes primarily iron.

  Without an energy source in the inner core, the compression-shell burning process occurs once again.

  Fresh silicon produced in the upper layers of the core is pushed deeper, and the nonburning inner core becomes surrounded by a shell of burning silicon.



19.2 Supergiants

(Discovering the Universe, 5th ed., §12.4)

- The star's core now resembles an onion, with layer on top of layer of burning gas.

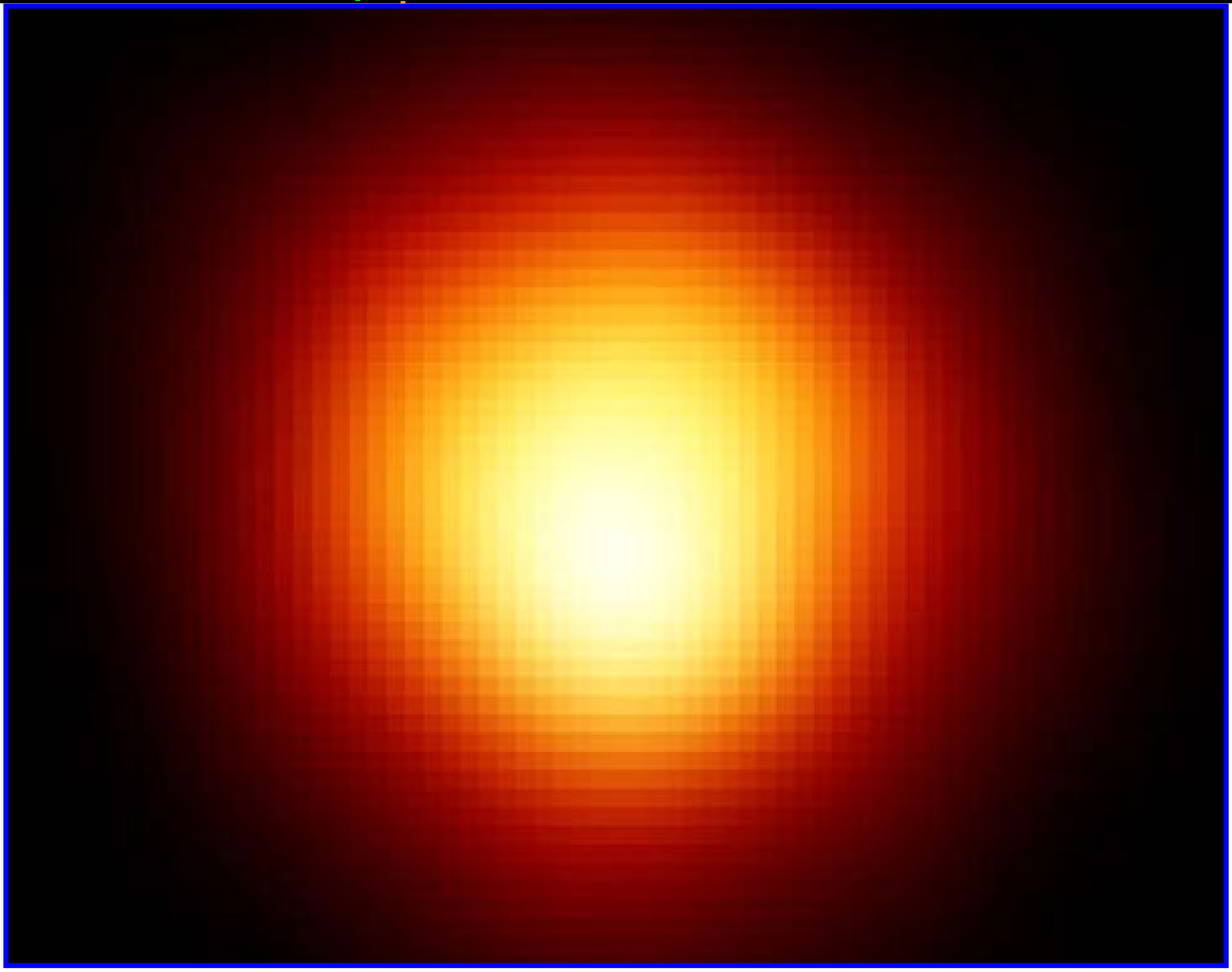
  As each new layer is added, the luminosity increases and the star expands, becoming a luminous supergiant (class Ia), with a brightness of ~$10^5\ L_{Sun}$.

  While the star becomes almost as big as the orbit of Jupiter, the core is highly compressed, only 10^{-5} of that size, about the diameter of the Earth.

- A familiar supergiant is the M1Ia star **Betelgeuse**, the left shoulder of Orion.

  Betelgeuse is ~500 ly away, and is estimated to be 18-20 solar masses.

  Betelgeuse has recently been imaged by the Hubble Space Telescope, the first star besides the Sun whose surface has been observed:



Picture Information

In this false-color picture taken in the ultraviolet, Betelgeuse's surface can be seen (red), as well as a large hot spot (white).

- As a star becomes a bigger and brighter supergiant, its mass loss also increases.

  As with red giants, mass loss occurs continuously, carried away by the stellar wind.

  If this material collides with surrounding interstellar material, it can be pushed into a **circumstellar shell**, with a typical diameter of a light year.

  The interior star may then ionize it, producing a bright nebula.

  The Bubble Nebula (NGC 7635) is a beautiful example of such a shell, surrounding the massive blue supergiant BD+602522:

- A supergiant may also eject matter in brief explosive intervals, probably the result of the many changes in nuclear fusion occuring in its interior.

Ejections of matter may be the result of overall pulsations of the star's surface, or convection cells that carry material rapidly outward (like bubbles in boiling water).

Extra: learn more about recent observations of Betelgeuse's atmosphere that support the latter idea.

These ejections may also surround the supergiant with a slowly expanding circumstellar shell.

- Betelgeuse is estimated to be losing ~10^{-6} solar masses per year, and may already have lost half of its main sequence mass.

  Betelgeuse's circumstellar shell is expanding at a rate of about 10 Km/s, and is currently 1/3 ly across.

- An outstanding example of mass loss in a luminous supergiant can be found deep inside the Great Nebula of Carina (NGC 3372), 9000 light years away in the southern sky:

Picture Information

The dark nebula covering the brightest portion is known as the Keyhole Nebula (NGC 3324).

To the lower left of the the Keyhole lies a bright yellowish billowing cloud, which hides the luminous red supergiant **Eta Carinae**.

In the near (2 μm) infrared, Eta Carinae becomes quite visible (at the lower left):

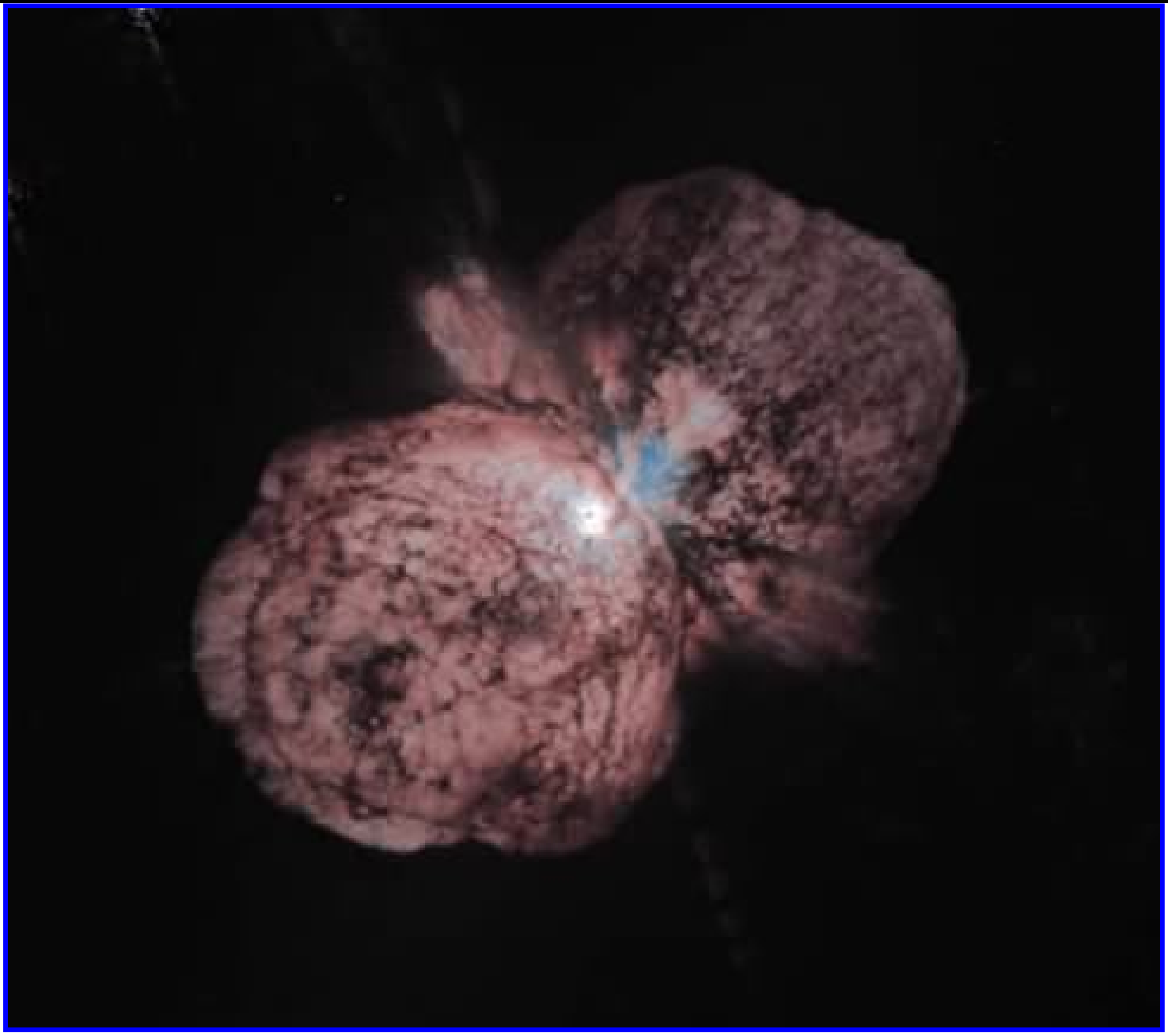
Picture Information

Eta Carinae may at one time have been as much as 100 times as massive as the Sun, and appears to be very near the end of its relatively short life.

Designated a fourth magnitude star in 1677 by Halley, Eta Carinae brightened to a magnitude of -1 by 1843, making it the second brightest star in the sky.

Then, between 1857 and 1870, Eta Carinae dimmed and finally disappeared from naked-eye visibility.

The Hubble Space Telescope revealed that Eta Carinae's dimming was because it had ejected a large cloud of material that had shrouded the star:



Picture Information

Because of its outbursts, Eta Carinae may now only be about fifty or sixty times as massive as the Sun.

Presumably some of the material in the Great Nebula of Carina is due to this star's earlier mass loss.

An image from the Chandra X-Ray Observatory reveals a circumstellar ring around Eta Carinae with a diameter of about two light years:

[Picture Information](#)

The x-ray light results from the collision of supersonic ejecta with the surrounding interstellar gas and dust in the Carina Nebula.

19.3 Supernovae, Take II

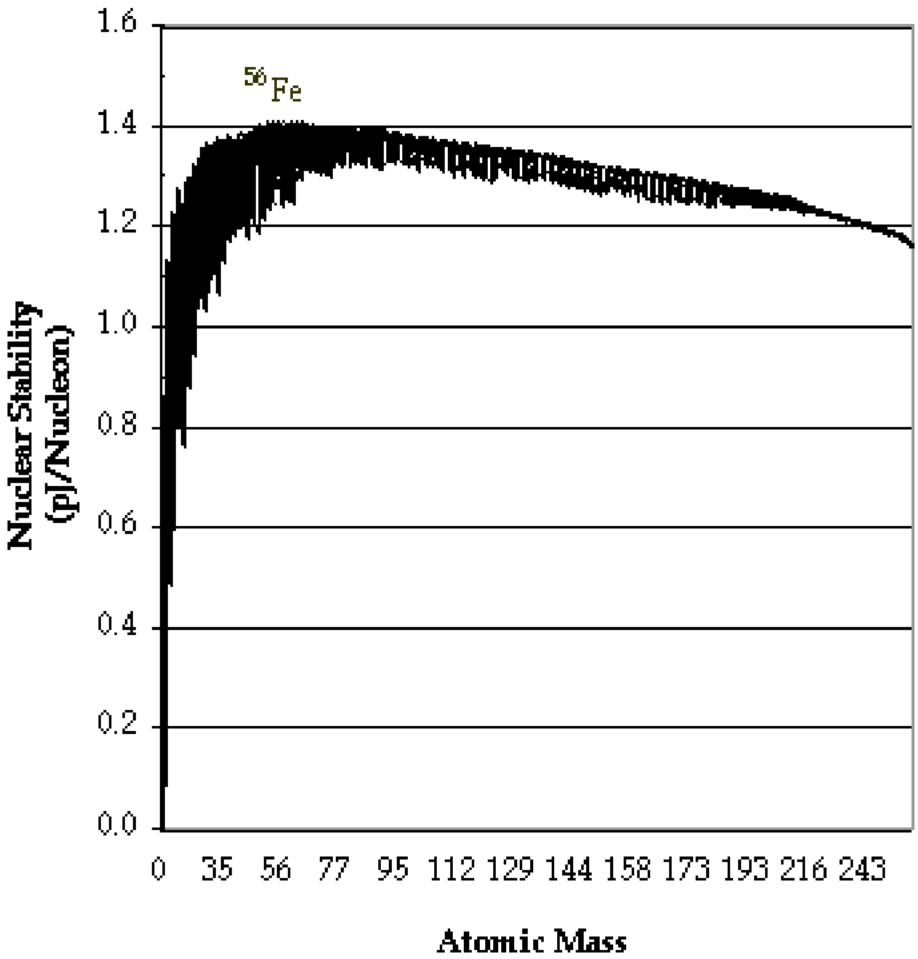
(Discovering the Universe, 5th ed., §12.5)

[Data Source](#)

- A supergiant that is concentrating iron at its core has a problem, because iron cannot be burned to produce energy!

  In the figure at the right, the dependence of nuclear stability on atomic mass is shown (the vertical variation is due to different elements with the same atomic mass).

  Iron is the most stable of all nuclei, so its fusion to create even larger nuclei requires an *input* of energy.



- With no way to counter the tremendous force of gravity, the supergiant continues to compress its core.

  Eventually the iron in the inner core is so tightly packed, a density of about 3 x 10^9 g/cm^3, that it becomes electron-degenerate.

  For a brief period of time compression is halted, and electron degeneracy pressure supports the outer layers of the star.

- As the inner core is compressed, the silicon fusion in the shell above adds more iron to the inner core, and it grows to more than one solar mass of material.

  Once the inner core reaches a diameter of about 3000 Km, the gravitational forces acting on it are so intense that it is forced to collapse.

  In about a tenth of a second, the electrons are pushed towards the iron nuclei, and the temperature increases dramatically, surpassing 5 GK.

  The core is suddenly hot enough to produce significant amounts of gamma radiation.

  The gamma photons have enough energy to break the iron nuclei apart into their constituent protons and neutrons, a process called **photodisintegration**.

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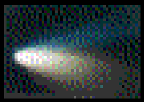
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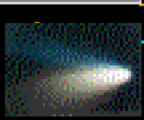


Introduction to Astronomy

Lecture 21: Planetary Systems

The optimist proclaims that we live in the best of all possible worlds; the pessimist fears this is true.

-- James Branch Cabell

21.1 Planetary Systems

(Discovering the Universe, 5th ed., §II.0)

- In Lecture 16 we saw that the formation of stars begins with the gravitational compression of gas and dust into cocoon nebulae.

  Cocoon nebulae develop one or more hot protostars in their centers, which may eventually become main sequence stars.

  Many such cocoon nebulae have been observed in recent years, such as the one at the right being pushed back by a new-born star.

- There is increasing evidence that cocoon nebulae commonly give rise to many smaller condensations of matter that orbit the protostar(s) and subsequent new-born stars.

  These objects eventually become planets, and together with the star they orbit they form a **planetary system**.

  Besides the obvious example of our own **Solar System**, numerous planetary systems around other stars have also been detected in recent years.

- Within our Solar System we find that, in addition to the planets, many smaller objects orbit the Sun and planets, from small grains of dust on up to "minor planets" hundreds of kilometers in diameter.

  The presence of minor planets beyond the orbit of Neptune is also a recent discovery that has expanded the boundaries of our Solar System.

21.2 An Overview of the Solar System

(Discovering the Universe, 5th ed., §II.4, §II.5)

- To understand how our Solar System came into existence, it is first helpful to study the basic characteristics of the objects that inhabit it: average distance from the Sun (semimajor axis), diameter, density, eccentricity, and orbital inclination.

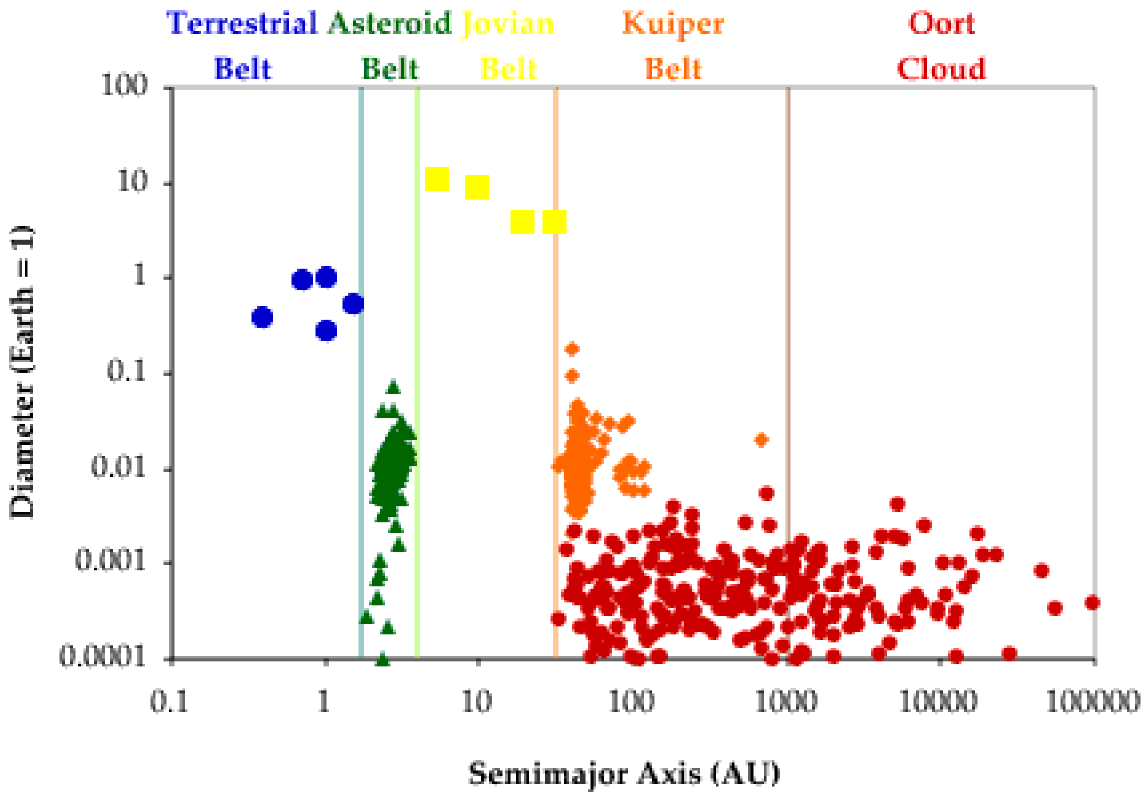
  These characteristics help us categorize these Solar System objects into a few small groups.

- Astronomers early on determined the semimajor axis of solar system objects.

  With telescopes, the diameters of the larger objects are visible and can also be measured.

  For smaller objects, diameter is often estimated based on their measured brightness and assumptions about the fraction of sunlight they reflect, known as their **albedo**.

  By comparing these two characteristics, semimajor axis and diameter, we can identify five basic groups of objects in the solar system:



- The **Jovian planets** are the largest objects, on the order of 10 times the size of the Earth, and are so-called because they all have basic similarities to Jupiter (also known as Jove).

The Jovian planets are, inclusively, Jupiter, Saturn, Uranus, and Neptune.

The region where the Jovian planets orbit, between 5 A.U. and 30 A.U., is called the **Jovian Belt**.

- The **terrestrial planets** are so-called because they all have basic similarities to the Earth.

  The terrestrial planets are, inclusively, Mercury, Venus, the Earth, the Moon, and Mars.

  The region where the terrestrial planets orbit, between 0 A.U. and 1.5 A.U., is called the **Terrestrial Belt**.

- The **asteroids** are significantly smaller than the terrestrial planets, on the order of 1/10 to 1/100 of the size of the Earth, and are therefore called **minor planets**.

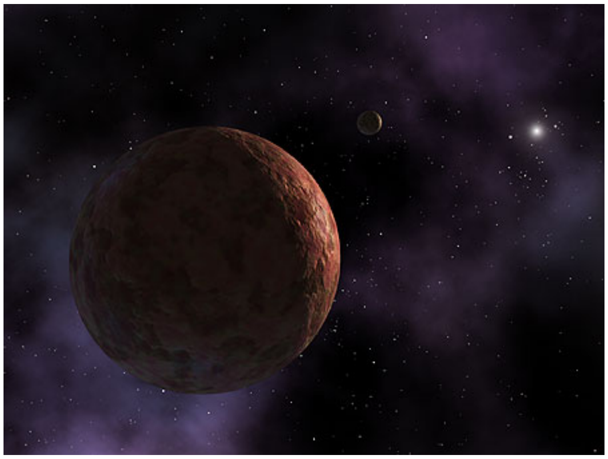
  The name asteroid comes from the fact that they are so small that they didn't show a disk in early telescopes, and were therefore "star-like".

  The three largest asteroids are Ceres, Pallas, and Vesta.

  More than 10,000 other asteroids have been identified.

  The region where most of the asteroids orbit, between 1.7 A.U. and 3.5 A.U., is called the **Asteroid Belt**.

Picture Information



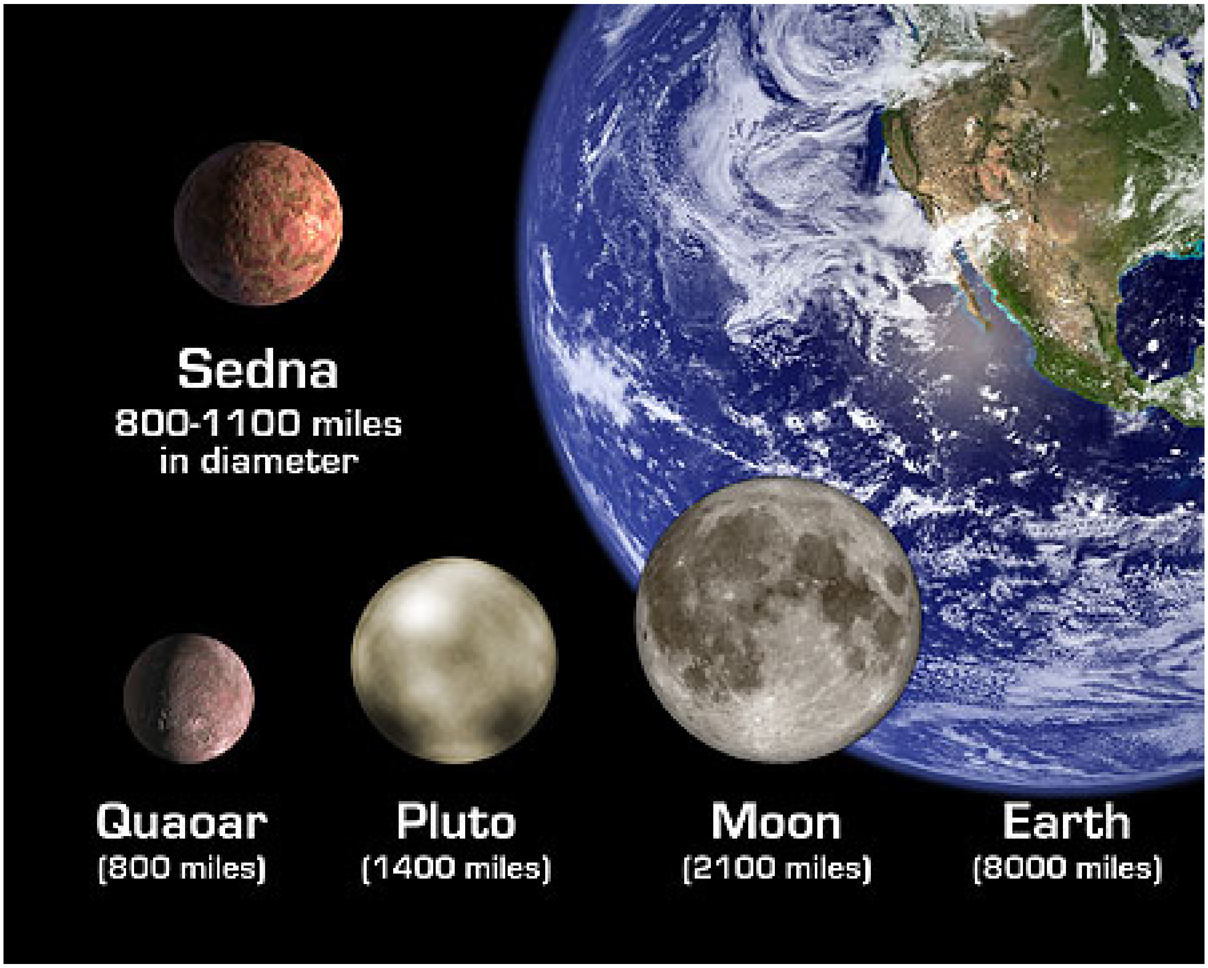
- The distant **icy asteroids** are similar in size to the asteroids, and are also called minor planets.

  Note that the smallest "planet", Pluto, is categorized here as an icy asteroid, though so far as we know it's the largest of them.

  Extra: this classification of Pluto is not "official"; read the International Astronomical Union's press release on the subject.

  Discovered in 2004, Sedna is the second largest icy asteroid known, at roughly two thirds the diameter of Pluto.

  Sedna is followed closely in size by Quaoar and then by Pluto's own moon Charon.



Picture Information

Except for Pluto (1930) and Charon (1978), all of the more than 500 icy asteroids known have been discovered since 1992.

The region where most of the icy asteroids orbit, between 30 A.U.and 1000 A.U., is called the **Kuiper Belt**, after Gerard Kuiper, the astronomer who proposed its existence in 1951.

The icy asteroids are commonly known amongst astronomers as **Kuiper Belt objects** (**KBOs**) or **trans-Neptunian objects** (**TNOs**).

- **Comets** are the smallest objects, on the order of 1/1000 to a 1/10,000 of the size of the Earth, though they sometimes approach the Earth and become very bright.

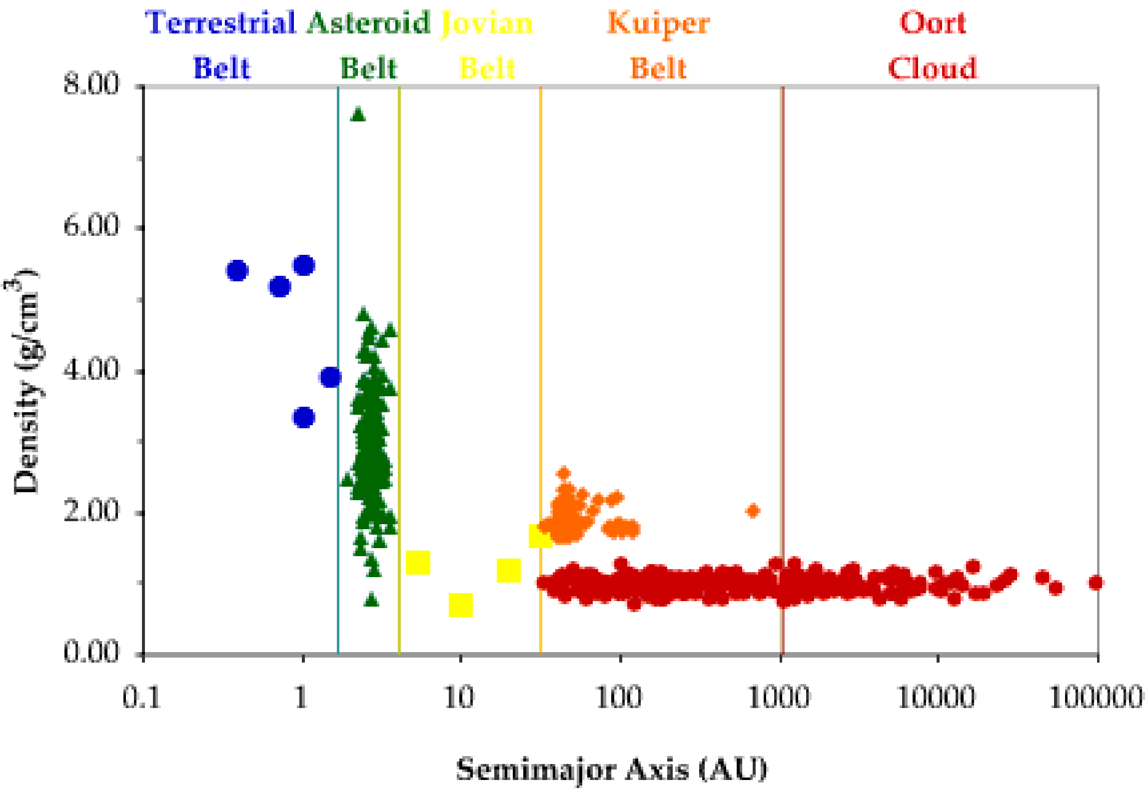
  Famous examples of comets include Halley, Hale-Bopp, and Shoemaker-Levy 9.

  The region where most of the comets orbit, between 1000 A.U. and 100,000 A.U., is called the **Oort Cloud**, after Jan Oort, the astronomer who proposed its existence in 1950.

A signficant number of comets can also be found in the Kuiper Belt, though as we will see they are physically distinct from the icy asteroids.

- We can gain more understanding and distinction of these classes by considering their mass, or more usefully, density.

  Applying Kepler's and Newton's Laws allow the determination of planetary mass, and by combining with diameter, their density:



Distinct grouping are again visible on this chart.

It's useful to compare these numbers with the density of various materials:

Iron and other dense metals such as nickel, lead, etc.:	>~ 8 g/cm^3
Rock and light metals such as aluminum:	~ 3 glcm^3
Water and other liquids/ices such as methane and ammonia:	~ 1 glcm^3
Compressed gas such as hydrogen, helium, etc. (highly variable):	<~ 0.1 g/cm^3

The terrestrial planets are the densest objects, with densities suggesting they are mixtures of iron or other metals and rock.

The asteroids have similar or smaller densities; the densest appear to be pure metal, the least dense appear to be loose piles of rock (they are not large enough for their gravity to hold onto any gas).

The icy asteroids have lower densities than the other asteroids, suggesting they may be rock covered with ice (hence their designation).

The comets have the lowest densities, indicating they are mostly ice.

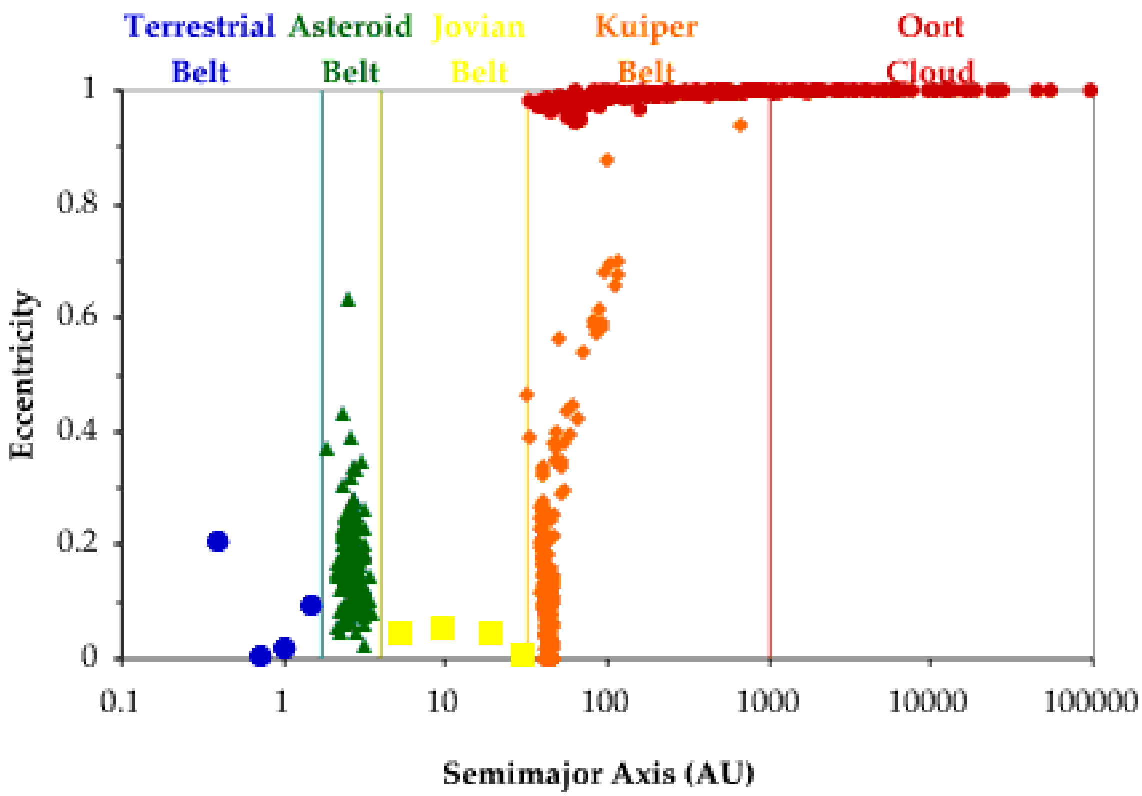
The Jovian planets also have very low densities, suggesting a large liquid and gaseous composition.

- Spectroscopic measurements of sunlight reflected by these objects have helped to confirm these compositions.

  If a dark line appears in the reflected light that isn't in the Sun's spectrum (usually because it is molecular), it must be due to absorption by the planet's atmosphere or surface.

  Question: how else might we determine the composition of these objects? To which does that apply?

- Eccentricity again helps to distinguish these objects from each other:

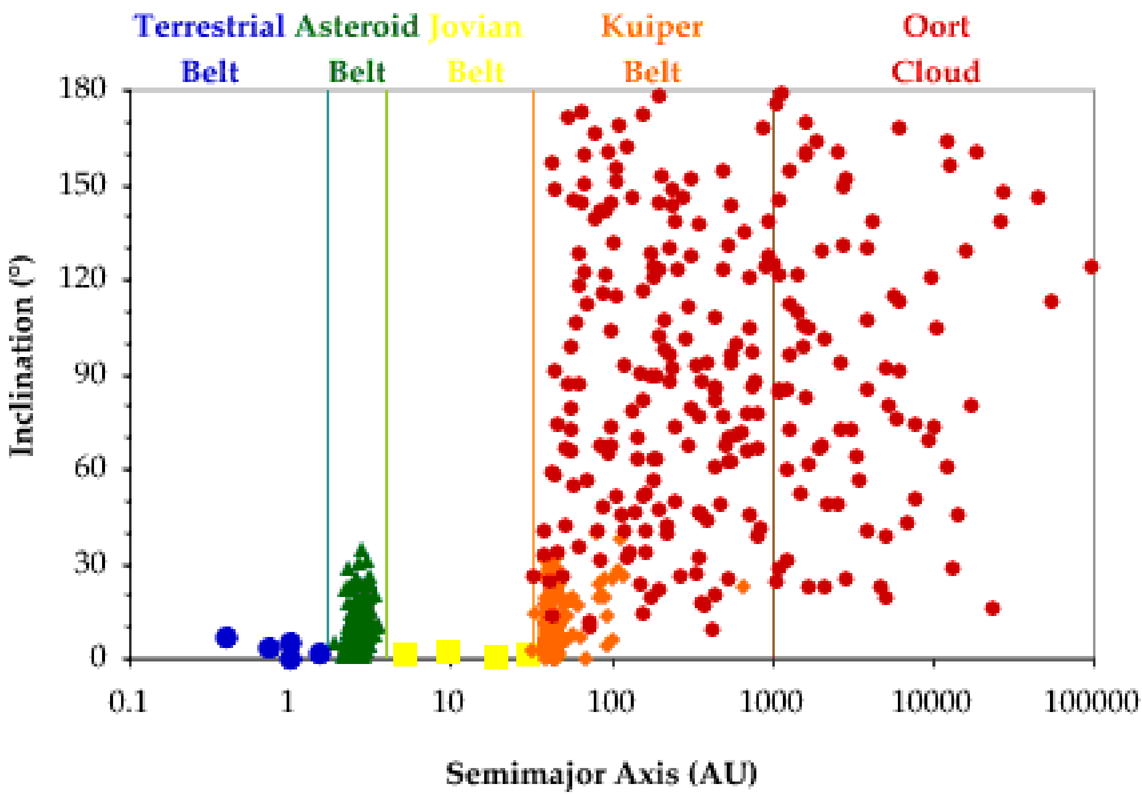


Eccentricity is relatively small for the terrestrial and Jovian worlds.

It is typically much larger for the asteroids and icy asteroids.

It is generally the maximum for the comets (possibly because these are only the ones we can observe).

- Orbital inclination is another distinguishing characterisitic:



An angle less than 90° indicates motion around the Sun in the same direction as the Earth.

An angle greater than 90° indicates motion in the opposite direction to the Earth, which is called a **retrograde orbit.**

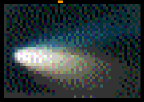
Orbital inclination is relatively small for the terrestrial and Jovian worlds, all being relatively close to the ecliptic and in the same direction as the Earth.

It is typically larger for the asteroids and icy asteroids, but still less than about 30°, and again in the same direction as the Earth.

It is every possible angle for the comets, often opposite to the direction of the Earth, a random distribution of orbits.

- We can summarize these characteristics as follows:

Object	Semimajor Axis	Diameters	Densities	Eccentricities	Inclinations
Terrestrial Planets	0 A.U. to 1.5 A.U.	Medium	High	Small	Small
Asteroids	Mostly between 1.7 A.U. to about 3.5 A.U.	Small	Mostly Medium	Small to Medium	Small to Medium
Jovian Planets	About 5 A.U. to about 32 A.U.	Large	Very Small	Small	Small
Icy Asteroids	Mostly between 32 A.U. to about 1000 A.U.	Small	Mostly Small	Small to Medium	Small to Medium
Comets	Mostly between 32 A.U. to about 100,000 A.U.	Very Small	Very Small	Large	Small to Large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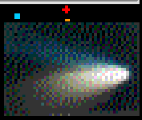

other education resources on the Internet! GEM is a project of the U.S. Department of Education. The Introduction to Astronomy Webbook is catalogued in the Gateway, and Scott R. Anderson is a member of the GEM Consortium.

Open Course Info

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Introduction to Astronomy

Lecture 35: The Structure of the Universe

Only two things are infinite, the universe and human stupidity, and I'm not sure about the former.

-- Albert Einstein (attributed, source unknown)

35.1 The Universe

(Discovering the Universe, 5th ed., §II.0)

- The **Universe** is defined to be the sum total of everything that we know about: stars, galaxies, clusters, superclusters, voids, etc.

- **Cosmology** is the study of the structure and evolution of the Universe.

  It is a subject of great current interest, as the Hubble Space Telescope and other new instruments have recently helped astronomers shed light on many important questions.

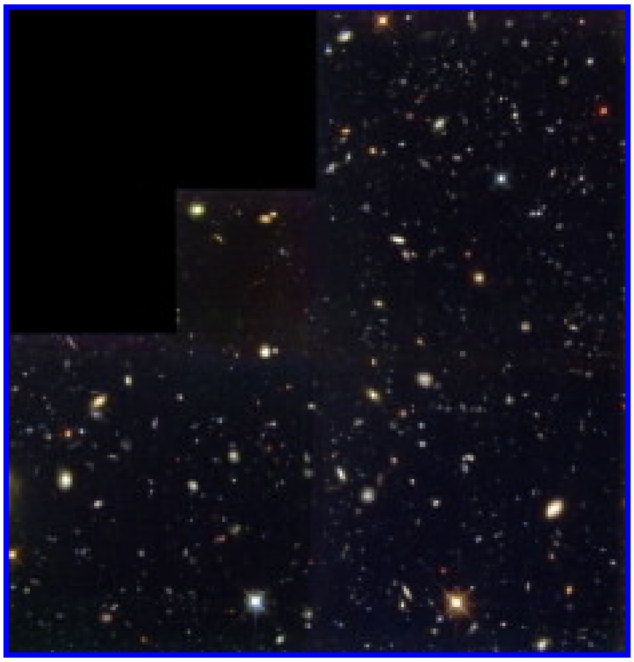
- There have been many theories about the Universe, but they generally all share one fundamental postulate, the **cosmological principle**, which has two parts.

- First, the Universe must be **isotropic** (the same in every direction).

  For example, the Hubble deep field images, extending 12 Gly away, for two completely different directions, are remarkably similar:

  Picture Information　　Picture Information

  Hubble Deep Field North　　Hubble Deep Field South

  The first image is in the northern hemisphere (Ursa Major), and the second is in the southern hemisphere (Tucana).

  Observations of the Universe such as this verify isotropy to a high degree.
- Second, the Universe must be **homogeneous** (uniform as far as one can travel in a given direction).

  In other words, no matter where you are located in the Universe, it will pretty much look the same as it does here.

  We have a little more trouble verifying homogeneity, since we can't see large distances very well.

  The size of the largest superclusters and voids is about 700 Mly, so homogeneity obviously doesn't apply below this distance.

Over larger distances, however, the Universe does appear to be relatively uniform.

- Two implications of the cosmological principle is that the Universe can have no center (which would violate isotropy) and no edge (which would violate homogeneity).

35.2 Galactic Recession

- An early indication that many "nebula" were in fact galaxies is that their spectra show a substantial redshift, i.e. they are receding from us at great speed (~10,000 km/s!).

- As Hubble studied numerous galaxies in the 1920s, he measured both their distance and their Doppler shifts, and calculated their speed.

  Interestingly, Hubble found that *all* distant galaxies are *receding* from us.

  Also, Hubble found that the more distant the galaxy, the greater its speed of recession.

  More specifically, when Hubble plotted their recessional speed v vs. their distance r, he found a *linear* relationship, called the **Hubble Law**:

  $$v = H_0\, r$$

- The slope of this line, H_0, is known as the **Hubble Constant**, and it has a value

  $$H_0 = 21 \text{ km/s/Mly } (\pm\, 2 \text{ km/s/Mly})\,.$$

- For example, the Virgo cluster is 50 Mly away, which means that it is receding at a speed of

  v = 21 km/s/Mly x 50 Mly = 1050 km/sec

35.3 The Expansion of the Universe

- How can we explain the fact that every distant galaxy is receding away from us?

  Certainly we are not at the center of the Universe; there must be some other explanation!

  Einstein's Theory of General Relativity provides the answer.

- The Newtonian idea of space is that it is static and endless.

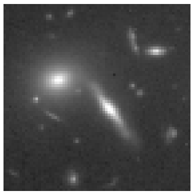
  It is "nothing"; objects exist in it but are not connected to it.

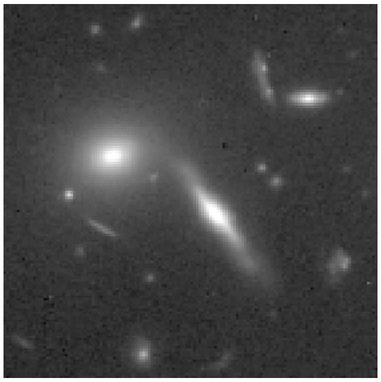
- On the other hand, General Relativity requires that space be "elastic".

  It is capable of being compressed, stretched, and even twisted by the presence of the mass and energy it contains.

  Question: what examples of this have we already seen?

- Hubble's observation of galactic redshifts demonstrated that the Universe itself must be *expanding*.

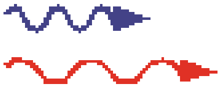
  

  The space between *any* pair of galaxies increases with time; the galaxies *separate* without actual *motion*.

  The further apart they are, the faster they separate.

  An important consequence of this is that no galaxy (including our own) is at the "center" of the Universe.

- As a photon from one galaxy travels to another, it will have its wavelength "stretched", producing a **cosmological redshift**.

  The farther the photon travels, the longer it takes, so the more stretching occurs.

- *Galaxies* do not expand: because of their large mass and compact size, their gravitational force counteracts the expansion.

  So, only *intergalactic* (and primarily intercluster) space expands.

  Nevertheless, because of their large mass, superclusters of galaxies will still have a significant contracting effect on the Universe.

- Before Hubble announced his observations, Einstein had realized that this contracting effect must exist.

  However, Einstein had philosophical difficulty with the notion of a contracting Universe.

  Einstein therefore introduced an expansive force into his theory, called the **cosmological constant**, which would just balance the effect of gravity and create a *static* Universe.

- As we have seen, however, the Universe is *neither* contracting *nor* static, but instead expanding.

  The simplest explanation of the observed expansion is that the Universe received an initial large "push", easily overcoming gravity, which became known as the **Big Bang**.

  This prompted Einstein to remark that the cosmological constant was the "biggest blunder" of his life (even he is subject to the prick of Occam's Razor!).

35.4 The Geometry of the Universe

- General Relativity also predicts that the Universe must have a distinct "shape", which depends directly on how much mass is in it and on how fast it is expanding (i.e. the Hubble Constant).

- The relevant parameter here is the **critical density** of mass and energy, which, for H_0 = 23 km/s/Mly, is calculated to be

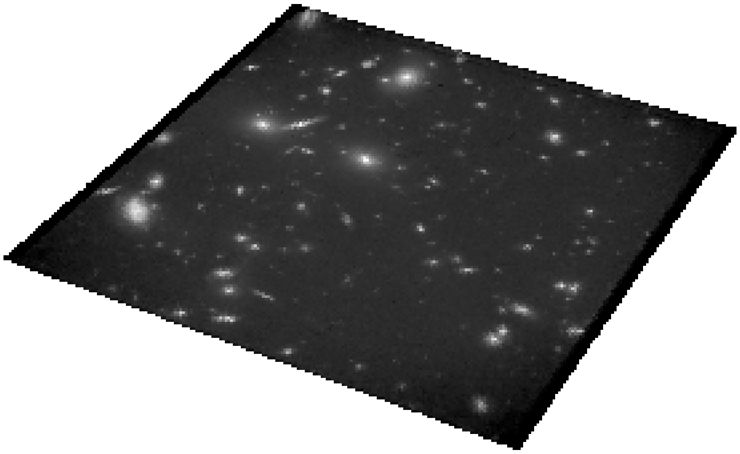
$$d_c = 2.4 \times 10^{-26} \text{ kg/m}^3 .$$

This is roughly fourteen hydrogen atoms per cubic meter, or about one Milky Way-sized galaxy for every 4 Mly in each direction.

- Because of the cosmological principle, the actual density of the Universe must be the same everywhere (at least over scales larger than about 700 Mly).

  There are therefore only three possibilities for the geometry of the universe: flat, hyperbolic, and spherical.

- If the Universe has *exactly* the critical density, it is said to be a **critical** or **flat Universe**.



  Imagine that instead of being three dimensional, the Universe was two-dimensional.

  Imagine also that you could stand "outside" of it and look at it (although in actuality this is not possible -- *everything* is inside the Universe!).

  A flat Universe would then appear to be a plane (it would have **zero curvature**).

Picture Information

  From within a flat Universe, we could determine its geometry by the fact that two parallel beams of light will always remain parallel to each other.

  A flat Universe must have no edges and therefore must extend indefinitely in every direction (or else it would violate the cosmological principle).

- One way for a flat Universe to extend indefinitely is if the Universe is **infinite** in size.

  Such a Universe is also said to be **open**.

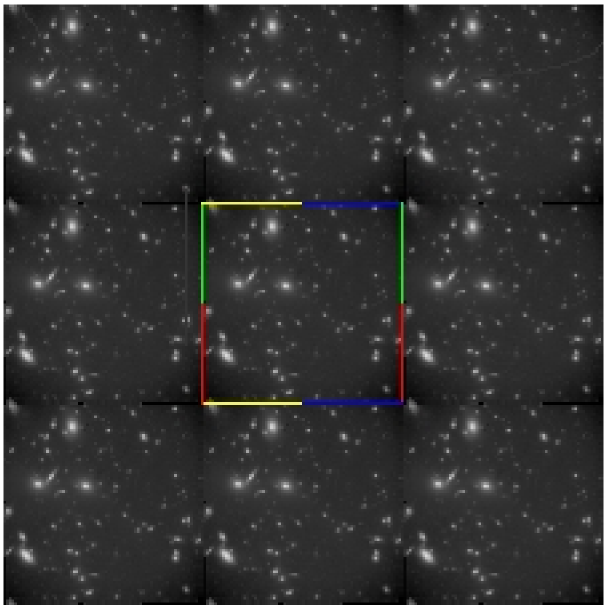
  In an open Universe, a light beam will never return to its starting point.

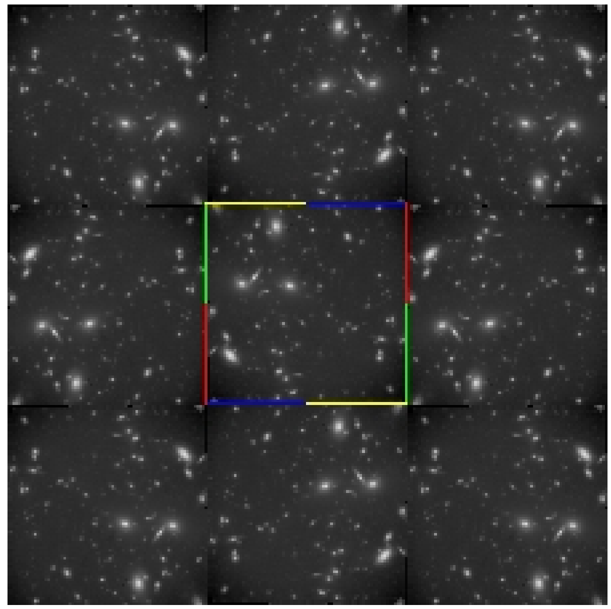
- Another way for a flat Universe to extend indefinitely is if the Universe connects back on itself after a certain distance, in which case it is **finite** in size.

  Such a Universe is also said to be **closed**.

  In the picture below, you can see how a finite Universe appears to repeat itself over and over again (but it is actually only the size of the colored square).

Picture Information





In each picture, the red edge connects to the red edge and the yellow edge connect to the yellow edge, etc.

In the left-hand picture the connection is direct, while in the right-hand picture the connection is to the opposite end, making the space "twisted" (like a Möbius strip).

With a three-dimensional space, there are even more ways for a closed Universe to be connected together.

In a closed Universe, a light beam will eventually return to its starting point, and then retraverse the same distance, over and over again.

Question: For these two Universes, how do they differ with respect to the distance travelled by a light beam before it returns to its starting point?

- If the Universe is closed, we should be able to "see ourselves" by looking far enough away in the distance.

The only problem is that we are also looking back in time, since light takes a finite time to traverse the Universe and return to us.

This distorts our view since we would be seeing our galaxy when it was much younger, and we might not recognize it!

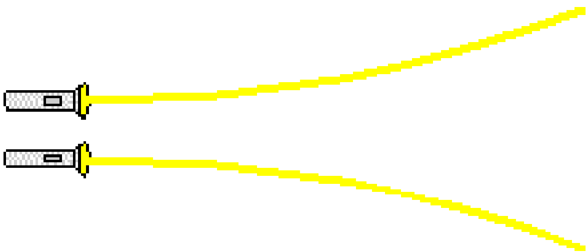
- If the Universe has *less* than the critical density, gravity is relatively weak, and the expansion causes space to curve away from itself.

The Universe is then said to be **hyperbolic**.

To an imaginary outside observer, a hyperbolic Universe would appear to have a saddle shape (it would have **negative curvature**).

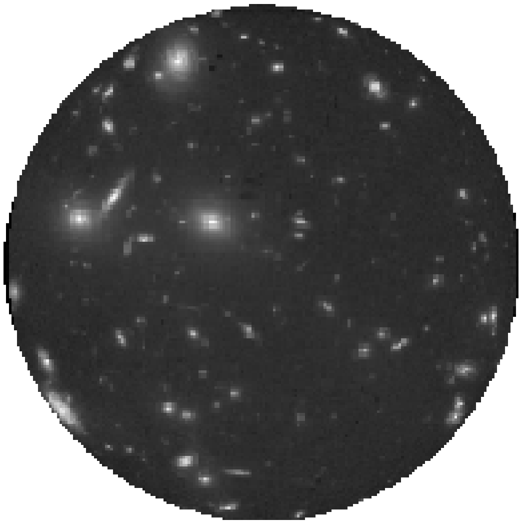
Picture Information

Within a hyperbolic Universe, two parallel beams of light will diverge from each other.



A hyperbolic Universe, like a flat universe, must extend indefinitely far in every direction, and again could be either open or closed.

- If the Universe has *more* than the critical density, gravity is relatively strong, and causes space to fold over towards itself.



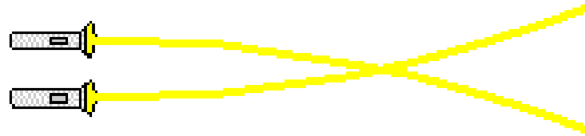
The Universe is then said to be **spherical**.

To an imaginary outside observer, a spherical Universe would appear like the surface of a sphere (it would have **positive curvature**).

Note that the spherical Universe does not include the *interior* of the sphere (and therefore has no center, in compliance with the cosmological principle).

Picture Information

Within a spherical Universe, two parallel beams of light will converge together and cross each other.



Unlike a flat or hyperbolic Universe, the spherical Universe is necessarily finite in size and closed.

The spherical Universe still extends indefinitely, just like here on the surface of the Earth, where you can circle the globe forever if you chose to do so.

35.5 The Cosmic Dilemma

- As we have seen, it is very difficult to determine the amount of mass and energy in the Universe, because so much of it is in the form of dark matter.

  However, by observing the motions of galaxies, clusters, and superclusters, we can still estimate the total amount.

  Recent results suggest that there is about ten times as much dark matter as luminous matter, and that the total density of matter is

  $d \sim 5 \times 10^{-27}$ kg/m$^3 \sim d_c/10$.

  In other words, it would seem that we live in a hyperbolic Universe.

- On the other hand, observations of the most distant galaxies fail to reveal any evidence of curvature, suggesting instead that we live in a flat Universe!

- Resolving the contradiction between these two sets of observations will require a better understanding of how the Universe is evolving.

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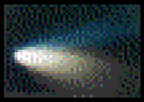
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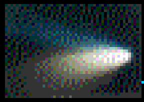


Introduction to Astronomy

Lecture 36: The Evolution of the Universe

There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory which states that this has already happened.

-- Douglas Adams, *Hitchhiker's Guide to the Galaxy*

36.1 The Big Bang

- If the Universe is expanding, at some time it must have been concentrated in a single point, with infinite density.

  This point is called the **cosmic singularity**.

- This singularity is like that of a black hole, in that all matter and energy were crushed together at a single point.

- Some sort of "explosion" must have occurred to start the expansion of the Universe outward from the cosmic singularity; it is called the **Big Bang**.

- This is *not* like an explosion in which debris goes flying off into space.

  Instead, it is the expansion of space *itself*, and therefore occurred *everywhere* simultaneously.

- The Hubble Constant

  $$H_0 \sim 21 \text{ Km/s/Mly} = 68 \text{ Km/s/Mpc}$$

  gives a rough estimate of the time since the Big Bang (i.e. the age of the Universe):

  $$\text{time} = \text{distance/velocity} = r/v = 1/H_0 = 13 \text{ Gy}.$$

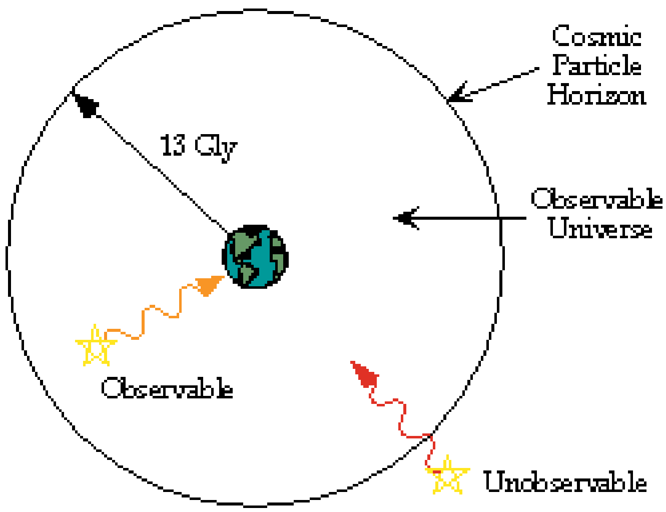
- Other estimates put it at as little as 8 Gy, or as much 16 Gy.

- In any case this must certainly be an *overestimate*, because the gravitational pull of the Universe's mass has slowed down the expansion (i.e. H_0 has decreased with time).

- This is a problem, because stellar theory indicates that the oldest stars are at least 14 Gy old.

There has therefore been a great deal of controversy about the exact value of the Hubble Constant.

- Any galaxies which are farther than 13 Gly away we cannot see, because there hasn't been enough time for the light to arrive here.



- The spherical surface at distance of 13 Gly from us is called the **cosmic particle horizon**; the **observable universe** lies inside this surface.

36.2 The Cosmic Microwave Background

- There is additional evidence for the Big Bang besides the observed expansion of the Universe.

- Because all of the observed mass and energy in the Universe must have been initially concentrated in a very small space, the mass/energy density must have been very high, which means a very high temperature, hotter than the interior of any star.

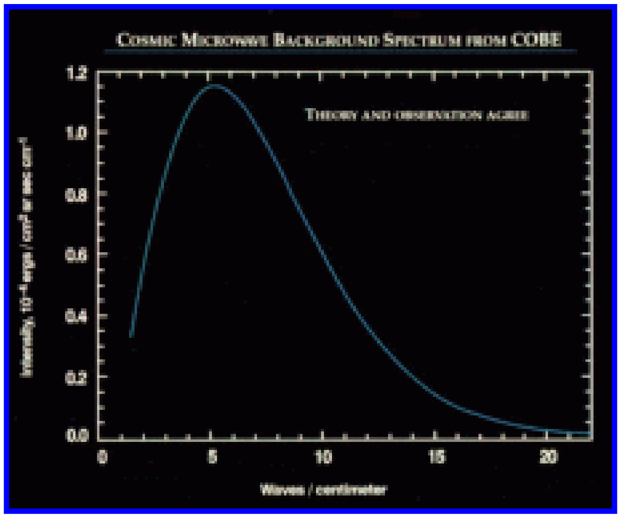
- At these temperatures, most of the mass/energy existed in the form of high-energy gamma radiation. These photons interacted with each other and with other particles, gaining and losing energy as they collided, resulting in a variety of wavelengths with a blackbody distribution.

- As the Universe expanded in size, the mass/energy density decreased and the temperature dropped. The blackbody spectrum must have therefore shifted its peak to longer wavelengths as well, as described by Wien's law:

$$\lambda_{peak} \propto 1/T$$

- Now, 13 Gy later, the photons have shifted to low-energy microwaves.

- This radiation is known as the **cosmic microwave background**. Its existence is not predicted by any other theory of the Universe.

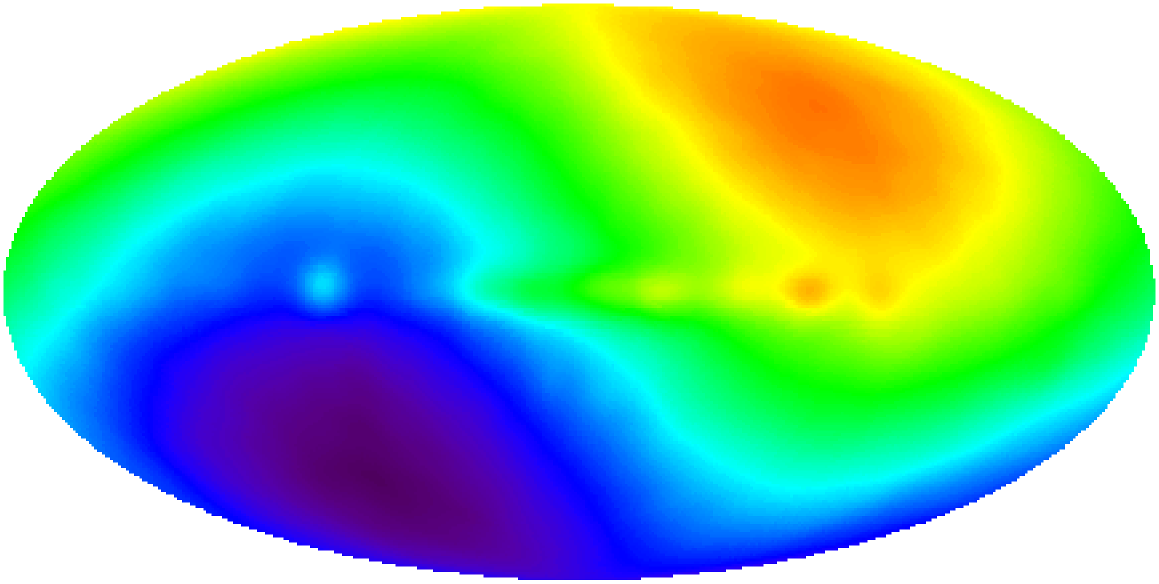


- It was discovered by Penzias and Wilson at Bell Labs in the early 1960s; they were working on a microwave antenna to relay telephone calls to communications satellites, and found a background noise with a peak wavelength around 1 mm, corresponding to $T = 3$ K.

- The Cosmic Background Explorer (COBE) satellite was sent into orbit in 1989 to measure the background radiation; it was found to be a perfect blackbody spectrum for $T = 2.735$ K.

- COBE also found that the background is almost perfectly isotropic.

- There do exists slight anisotropies, however . For one thing, the radiation is slightly "warmer" (blueshifted) in the direction of the constellation Leo, and "cooler" (redshifted) towards Aquarius. The following image is a projection of the entire sky, with the Milky Way horizontal across the middle and Sagittarius in the center. (Note: the colors are actually the reverse of what might be expected; Leo is in the red region at the upper right and Aquarius is in the blue region at the lower left.)



- This smooth variation in the background radiation is due to the motion of the *Earth* with respect to the background.

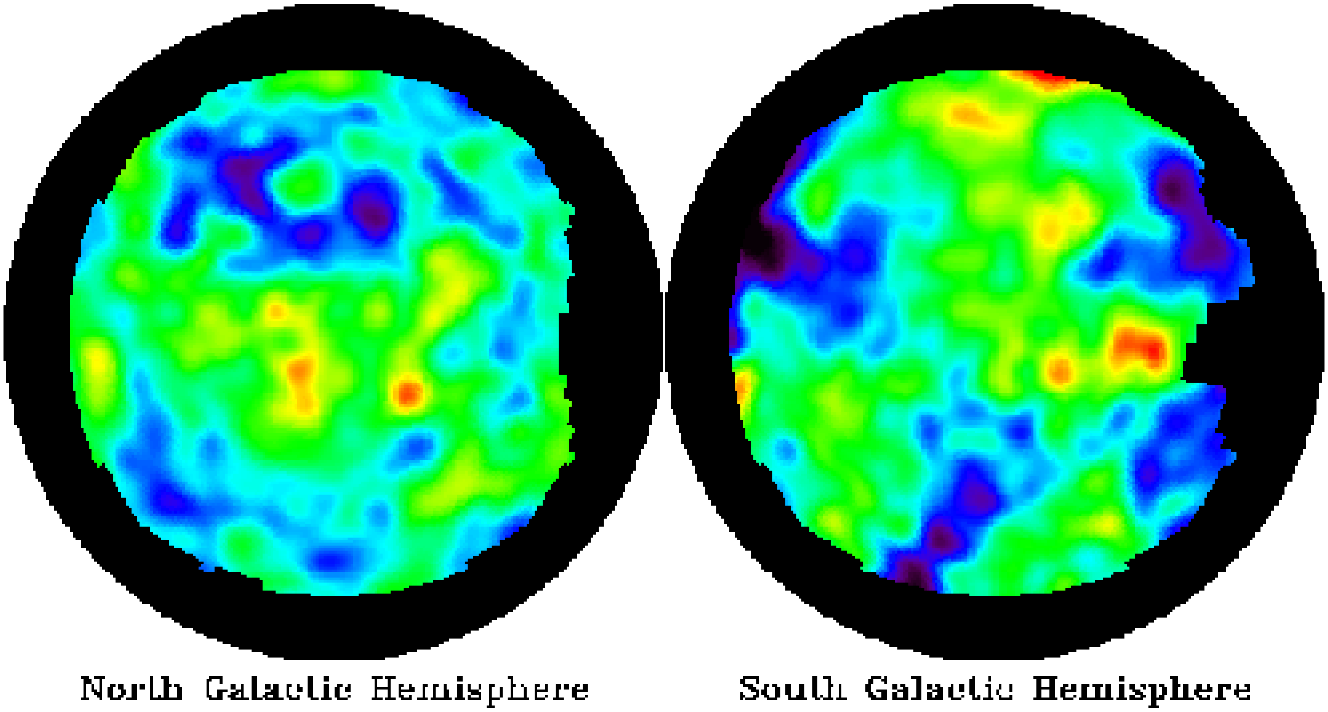
  In the direction we are travelling a *blueshift* occurs (the same as if we were standing still and it moved towards us).

- Analysis of the data indicates that we are moving at a speed of 390 km/s towards Leo.

- Taking into account our motion around the galaxy (horizontally to the right), this means that the entire galaxy must be moving at a speed of 600 km/s in the direction of Centaurus, somewhat closer to the center of this figure (in the green).

- We are pulled in that direction by the gravitational force of several nearby galaxy clusters (including the Virgo Cluster), and a gigantic supercluster called the **Great Attractor**.

- When the motion of the Earth is accounted for, remaining fluctuations in the background radiation are still found, although they are at most 100 μK warmer or cooler than the average:



- These variations are believed to be due to concentrations of mass in the early universe, which prevented complete isotropy of the background radiation by gravitationally redshifting it (regions of greater density appear blue here).

  This mass eventually condensed into the superclusters, clusters, and galaxies we now observe.

36.3 The First Few Instants

- No one knows what caused the Big Bang initially, but once it occurred, we know that the Universe underwent many changes as it expanded and its temperature decreased. The first few instants, in particular, resulted in a rapid set of developments.

- During an initial short period of time called the **Planck time** = 10^{-43} s, mass and energy were so concentrated that space and time were not describable by our current knowledge of physics (much like in the immediate vicinity of a black hole's singularity).

- All of the forces of nature were **unified**, with no distinction between how they affected particles. This is quite different from the present case, where, for example, the electric repulsion between a pair of electrons is 10^{42} times larger than their gravitational attraction.

- After the Planck time, the temperature had decreased to 10^{32} K, which allowed gravity to separate out from the other forces of nature to become its own distinct, weaker interaction.

- Although the remaining forces continued in their unified condition, this high-energy state is familiar to physicists from their studies of the sub-atomic world using particle accelerators.

36.4 The Creation of Matter

- Most of the mass of the Universe was created throughout the first second of its existence, via a process called **pair production**. At these high energies, pairs of photons can collide and produce particle/antiparticle pairs such as electrons and positrons:

  $$2\gamma \rightarrow e^+ + e^-$$

- Pair production can result in many different types of particles, but only so long as the photons have at least as much energy as the total mass of the particles. So, as the temperature of the Universe decreased and photons had less energy, less and less massive particles could be produced.

- Pair production of all types ended by a time of about 1 s, when the temperature had dropped to 6 x 10^9 K.

- Pair production is the reverse of the [pair annihilation] that occurs in the core of the Sun, where electrons and positrons collide to produce photons. As more and more particles were created, pair annihilation also increased.

- Once a particular type of particle could no longer be produced, it rapidly disappeared because pair annihilation can always occur, independent of temperature.

- Due to a **symmetry breaking** in the pair production process, slightly more matter than antimatter was produced, maybe one particle in a billion. Therefore, once all of the antimatter was destroyed, only a small amount of matter remained, which is the mass we see today.

36.5 The Formation of Nuclei

- Recall that the elemental abundance of stars is about 74% H, 25% He, 1% others.

- The 1% other is known to be produced inside of stars themselves, but only 10% of the helium can be understood as being produced inside of stars.

- Where did the rest of the He come from?

- The Big Bang could explain this, however; immediately afterward, it would have been so hot that a large amount of H fusion would occur *everywhere* in space.

  $$4\,{}^{1}H \rightarrow {}^{4}He + 4\gamma + 2\nu + E$$

- After about 300,000 y the temperature in the Universe decreased to about 3000 K, corresponding to a peak wavelength in the near infrared. Before this time, the Universe was very much like the interior of a star: all matter existed as a plasma of charged particles, because it was too hot for neutral atoms to exist, and the Universe was opaque, because photons couldn't travel very far before being scattered.

- After this time, however, matter was largely converted into neutral atoms. This **decoupling** happened in a matter of seconds, letting photons travel relatively freely through the Universe.

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Index of Terms

When *I* use a word, it means just what I choose it to mean — neither more nor less.

-- Humpty Dumpty, in Lewis Carroll's *Through the Looking Glass*

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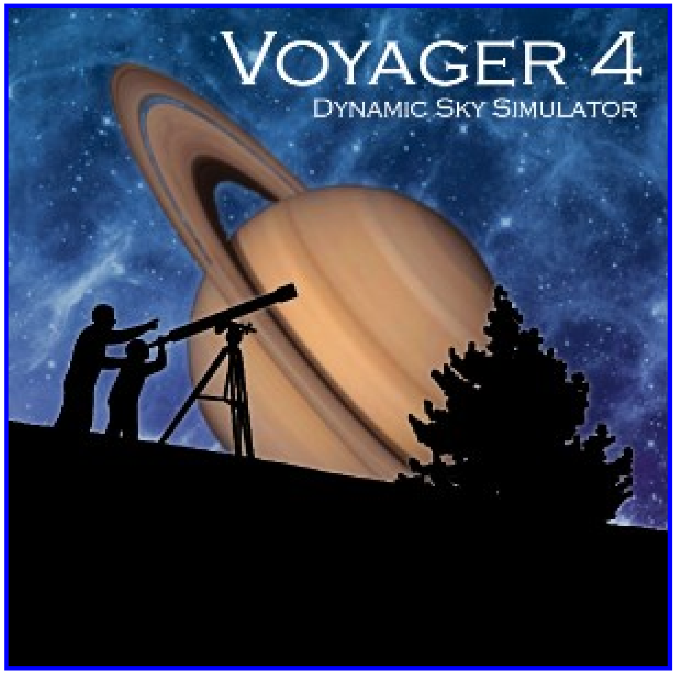

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We are now shipping *Voyager 4*, release 4.0.8, for Mac OS X and Windows. *Voyager 4* represents the biggest leap foward in our astronomy software line since it was first introduced more than 15 years ago.

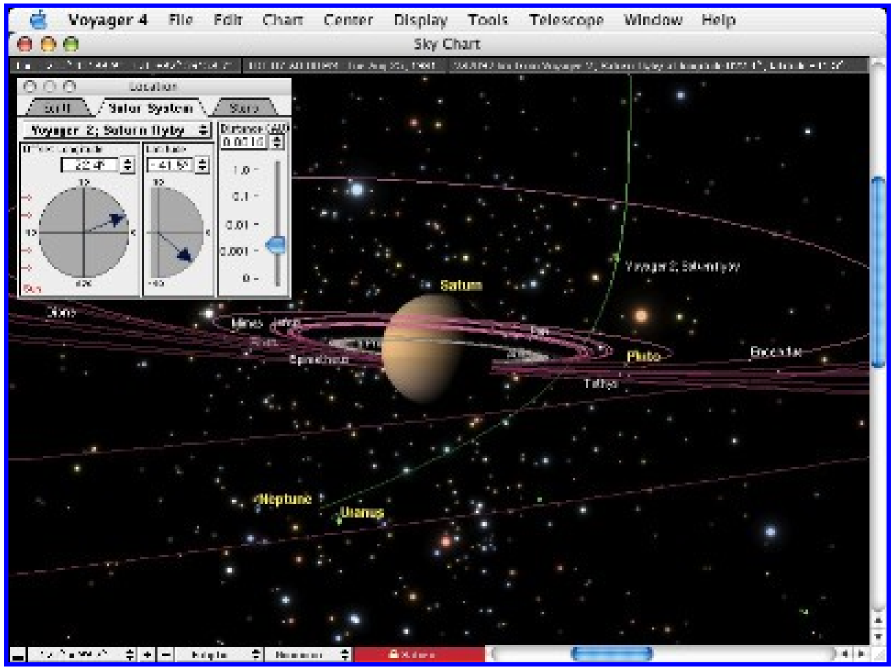
A free demo version of *Voyager 4* is available for download.

After months in development, we have updated and released our popular educational program *SkyGazer 4*, for Mac OS X and Windows. *SkyGazer 4* designed for classroom instruction and for those new to astronomy.

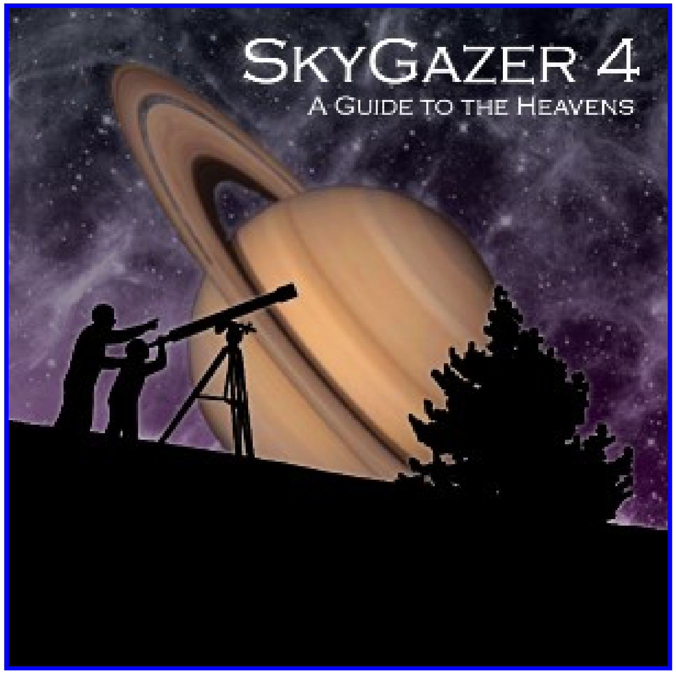
And after years of design and development, we are introducing new larger models of our original line of telescope mounts.

Voyager 4, release 4.0.8, is now available for Mac OS X and Windows. The Mac OS X version of *Voyager 4* is a Universal Binary application, and will run natively on both Intel and PowerPC Macintosh computers. The Windows version supports Windows 2000, XP, and Vista. Both versions feature a completely rewritten graphics and computational engine able to reproduce astronomical phenomena over a million-year timespan.

Voyager 4's object database includes every known planet, moon, asteroid, comet in the solar system; and gigabytes of stars, star clusters, nebulae, and galaxies from the latest professional astronomical catalogs. It can display the sky with unprecedented realism and accuracy.



Voyager 4 includes our SkyPilot telescope control interface, and can drive most commercially-available computer controllable telescopes, such as the Celestron NexStar GPS and Meade LX-200 GPS.



SkyGazer 4, the educational version of *Voyager 4*, is an exciting introduction to the fascinating world of astronomy. Designed for the novice, *SkyGazer 4* is the ideal companion for the backyard astronomer who is exploring the wonders of the night sky for the first time.

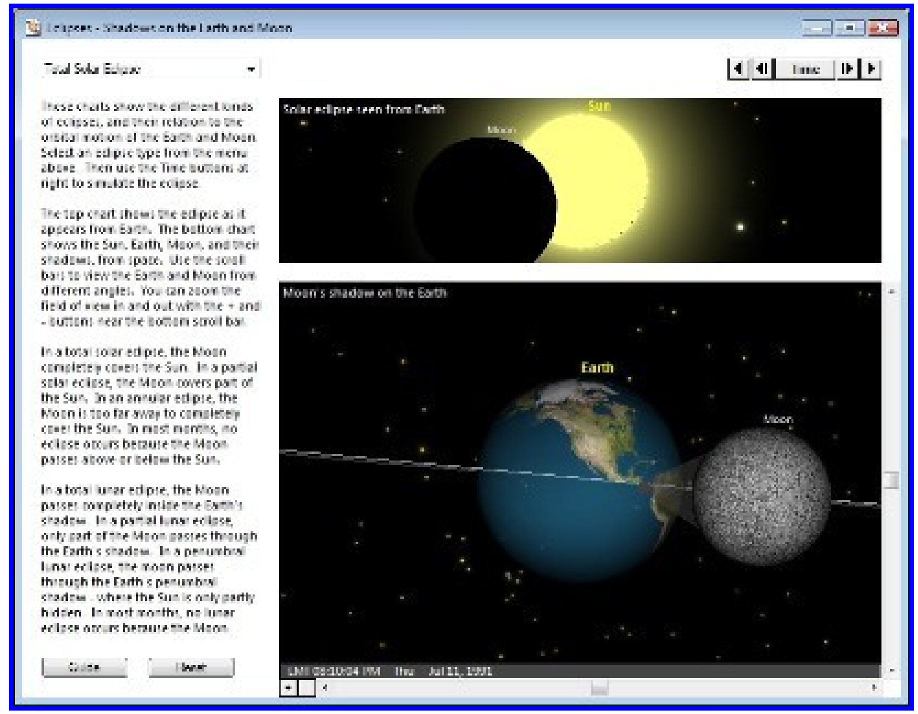
You can download an unregistered - but otherwise fully functional - version of *SkyGazer 4* from our website, or order a copy from us, shipped to you on CD-ROM.

We are pleased to announce that publisher Pearson Addison-Wesley has selected *SkyGazer 4* to be included with its college astronomy textbooks.

SkyGazer 4 is a celestial adventure for all ages.

SkyGazer 4, release 4.0.7, is now available for Mac OS X and Windows. As with *Voyager 4*, the Mac OS X version of *SkyGazer 4* is a Universal Binary application, while the Windows version supports Windows 2000, XP, and Vista. *SkyGazer 4* features *Voyager 4's* advanced graphics and computational engine, but contain a smaller selection of data. That selection includes only the objects which are visible to the naked eye, through binoculars, or with a small telescope.

SkyGazer 4 presents a streamlined and simplified user interface which uses less technical terminology than *Voyager 4*. It includes interactive 3D demonstrations of phenomena like eclipses, precession, the seasons, and the motions of the planets. It also includes an illustrated guide to basic astronomical concepts, the solar system, and the constellations.



For users of Mac OS 8-9 and Windows 95/98/ME, the older versions of our products, Voyager III and Voyager III SkyGazer, are still available for purchase. Click the links in the table of contents at left for more information.

And last but not least - our original line of telescope mounts has been expanded to include the MI-500, the MI-750, and MI-1000. Originally manufactured between 1982 and 1992, this mount family is now available in German equatorial and equatorial fork configurations.

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This site was last updated on 14 February 2008.

Open Course Info

Scott R. Anderson

Ph.D., Physics, University of Chicago, 1987

B.S. with Honors, Physics and Mathematics, University of Wisconsin-Madison, 1980

srca@mindspring.com

Educational Interests: Education Technology

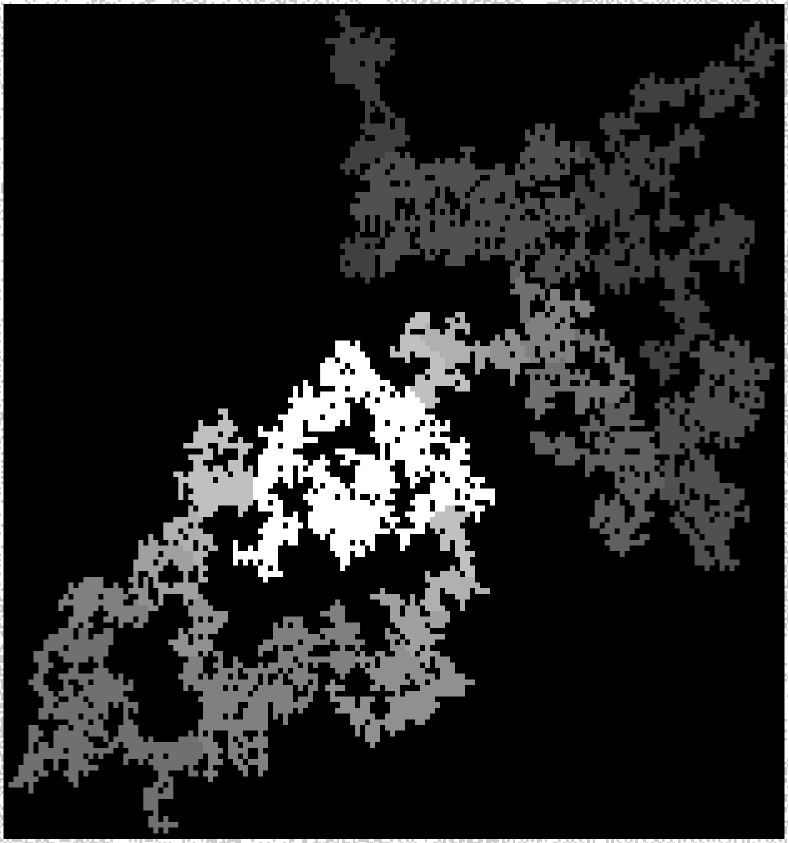
I have for many years developed a web-based Introduction to Astronomy course.

I'm also currently promoting the concept of Open Courses in my work with educational institutions.

Research Interests: Theoretical and Computational Condensed Matter Physics

My research is oriented towards those systems which exhibit some type of growth phenomena, such as domains in temperature-quenched magnetic systems, clustering and thin films on surfaces, dielectric breakdown, and viscous flow in porous media. In each of these systems, there exist two media separated by an interface, and one of the media grows at the expense of the other. Physical quantities such as the range of correlation or the roughness of the interface will increase with time, and a structure will develop which is often fractal in character. This is an area of physics which has seen great activity in the past few years, as numerous models of equilibrium and nonequilibrium growth have been introduced and studied. The techniques that can be employed range from renormalization group calculations to Monte Carlo simulations to numerical solution of differential equations.

The formation of many disordered systems can be described by a growth process in which individual particles join together to form an interconnected, percolating network. A simple model for such systems is the percolation model, in which sites on a lattice are randomly chosen and occupied. Nearest-neighbor particles are then considered to be connected, resulting in clusters of varying sizes and geometries (as shown with different colors in the picture on the left). When the concentration is larger than some critical value, it is found that one cluster will percolate through the entire lattice (the white one shown on the left). Its formation signifies a geometric phase transition, and is accompanied by the divergence of the mean cluster size and the range of connectivity. The percolating cluster is not solid, but rather has holes of many different sizes, making it a fractal object. If the cluster is made up of N particles and has a linear size L, then the fractal dimension D of the cluster is given by the relation $N \sim L^D$. In two dimensions, a solid cluster has $D = 2$, but a percolating cluster is found to have $D = 1.9$.



In the interactive percolation model we introduced, the occupation of a lattice site is dependent on the presence or absence of neighboring particles, which is a more realistic description of physical systems such as adsorption of gas atoms on metallic surfaces. This can dramatically effect the structure of the percolating cluster (note the background of this page). If the particles prefer to adsorb in the presence of other particles, solid islands with rough edges can grow for some time before joining together with other islands to form the percolating cluster. This is the situation shown in the picture at the right.

Interestingly, the fractal dimension of this cluster is the same as in ordinary percolation; this is because, on the large length scales which characterize a percolating cluster, there is no distinction between the individual particles and the larger, solid islands. In recent years, however, there have been several studies which indicate that the short-range details of a percolating cluster may have some effect on the ability of a particle to diffuse through the percolating cluster. In the picture above, the diffusion probability (starting from near the center) is indicated by the shade of gray, with white being the most-visited locations. The time necessary to travel a distance R through a cluster can be expressed as $t \sim R^a$, where $a = 2$ for a solid cluster. For an ordinary percolation cluster, however, $a \sim 2.9$. I am currently investigating how this diffusion exponent might depend on the strength of the interactions introduced into the percolation model.

The fractal dimension and the diffusion exponent are not the only exponents which characterize a percolation cluster. Diffusion is simply related to the ability of a current to pass through the cluster. It has recently been shown that the distribution of currents in the different branches of the cluster can be used to define an infinite number of independent dimensions which provide detailed information about its structure. In this sense, the percolation cluster is a "multifractal". In future research, therefore, I am interested in examining the multifractal characteristics of interactive percolation clusters.

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