ASTR-1020: Astronomy II
Course Lecture Notes
Section I

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Edition 4.0

Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1020: Astronomy II at East Tennessee State University.

I. Introduction and Needed Tools

A. The Science of Astronomy

1. Astronomy is the study of ALL things that do not reside on the Earth or in the Earth's atmosphere.

   a) It IS a **science** which means it follows the **scientific method**.

   b) This differentiates astronomy from *astrology*, which is a **pseudoscience**, that pretends to relate one's personality from the position of the planets with respect to the background stars.

   c) The language of science is **mathematics**!

   d) Science develops models that describe the physical universe, these models are written in the language of mathematics.

2. In this course, we will concentrate on the Sun's interior and all objects that lie outside the solar system.

B. Measurements

1. Measurements are often made in astronomy. Need to know both the *magnitude* of a measurement (*i.e.*, number) and *units* in which the measurement is made $\Longrightarrow$ 3 different **unit systems** are used in science:

   a) **English system** (foot-pound-second, ft-lb-s) $\Longrightarrow$ archaic! This is typically not used in science.

   b) **cgs system** (centimeter-gram-second, cm-g-s) $\Longrightarrow$ sometimes used in astronomy.

c) **SI system** [used to be called the mks system] (meter-kilogram-second, m-kg-s) $\Longrightarrow$ this is the standard for all of the physical sciences.

2. The 3 basic units in the SI system:

a) *Mass* (m or M): kilogram (kg).

b) *Length* (d, r, ℓ, ...): meter (m).

c) *Time* (t): second (s).

3. Other types of measurements can have specific units associated with them which are composites of the basic units above:

a) *Velocity* (v): m/s = m s^{-1}.

b) Acceleration (a): m/s^2 = m s^{-2}.

c) *Force* ($F = ma$): N (newton) = kg m/s^2 = kg m s^{-2}.

d) *Energy* ($E = \frac{1}{2}mv^2$): J (joule) = kg m^2/s^2 = kg m^2 s^{-2}.

e) *Power* ($P = E/t$): W (watt) = J/s = kg m^2 s^{-3}.

f) *Temperature* (T): Kelvin (K), a function of velocity.

g) *Current* (I): Ampere (A), also a function of velocity.

4. Special Astronomy Units:

a) *Ångstrom* (Å) = 10^{-8} cm = 10^{-10} m.

b) *Nanometer* (nm) = 10^{-7} cm = 10^{-9} m.

c) *Astronomical Unit* (AU) = Earth-Sun distance = 1.50×10^{11} m.

d) *Light Year* (ly) = the distance light travels in one year $= 9.46 \times 10^{15}$ m = 63,240 AU.

e) *Parsec* (pc) $= 3.09 \times 10^{16}$ m = 206,265 AU = 3.26 ly.

C. *Scientific Notation*

1. Powers of Ten.

$$\begin{aligned} 1{,}000{,}000 &= 10^6 \\ 100{,}000 &= 10^5 \\ 10{,}000 &= 10^4 \\ 1{,}000 &= 10^3 \\ 100 &= 10^2 \\ 10 &= 10^1 \\ 1 &= 10^0 \end{aligned}$$

(exponent = # of zeros after the "1")

$$\begin{aligned} 1 &= 10^0 \\ 0.1 &= 10^{-1} \\ 0.01 &= 10^{-2} \\ 0.001 &= 10^{-3} \\ 0.0001 &= 10^{-4} \\ 0.00001 &= 10^{-5} \\ 0.000001 &= 10^{-6} \end{aligned}$$

(exponent = # of decimal point moves to the right to just get past the "1")

2. Notation: $m \times 10^n$

$$\begin{aligned} 276 &= 2.67 \times 10^2 \\ -3126.25 &= -3.12625 \times 10^3 \\ .00276 &= 2.76 \times 10^{-3} \\ -0.0000000312625 &= -3.12625 \times 10^{-8} \end{aligned}$$

a) **Rule #1:** m is a positive or negative real number and $1 \leq m < 10$.

b) **Rule #2:** n must be an integer ($-\infty$, ..., -3, -2, -1, 0, 1, 2, 3, ..., ∞).

3. Arithmetic with Scientific Notation.

a) Multiplication:

$$\begin{aligned}(-4.6 \times 10^{16})(2.0 \times 10^{2}) &= (-4.6 \times 2.0)(10^{16+2}) \\ &= -9.2 \times 10^{18}\end{aligned}$$

$$\begin{aligned}(5.0 \times 10^{8})(6.0 \times 10^{-10}) &= (5.0 \times 6.0)(10^{8-10}) \\ &= 30. \times 10^{-2} \\ &= 3.0 \times 10^{-1} = 0.3\end{aligned}$$

b) Division:

$$\begin{aligned}\frac{6.3 \times 10^{8}}{3.0 \times 10^{4}} &= \frac{6.3}{3.0} \times 10^{8-4} \\ &= 2.1 \times 10^{4}\end{aligned}$$

$$\begin{aligned}\frac{-6.3 \times 10^{8}}{3.0 \times 10^{-4}} &= \frac{-6.3}{3.0} \times 10^{8-(-4)} \\ = -2.1 \times 10^{8+4} &= -2.1 \times 10^{12}\end{aligned}$$

c) Roots and Powers:

$$(200)^2 = (2 \times 10^2)^2 = 2^2 \times (10^2)^2 = 4 \times 10^4$$

$$\begin{aligned}(1600)^{1/2} = (16 \times 10^2)^{1/2} &= (16)^{1/2} \times 10^{2/2} \\ &= (4^2)^{1/2} \times 10 \\ &= 4^{2/2} \times 10 = 4 \times 10 = 40\end{aligned}$$

d) Significant Figures: Never write down a *ton* of digits after a decimal point. Your answer can have no more significant digits than the input number with the least amount of significant digits.

$$\begin{aligned}(3.0379624 \times 10^{-24}) \cdot (\underline{2.6} \times 10^{-2}) &= (3.0379624 \times 2.6) \cdot (10^{-24+(-2)}) \\ &= 7.898702 \times 10^{-26} \quad \text{(incorrect)} \\ &= \underline{7.9} \times 10^{-26} \quad \text{(correct)}\end{aligned}$$

$$\underline{29}\,\underbrace{\underline{0000}}_{\text{n.s.}}. \qquad\qquad 0.\underbrace{\underline{000}}_{\text{n.s.}}\underline{139}$$

The underlined digits are significant in the above numbers. Leading zeros are never significant and trailing zeros *sometimes* are not significant (in this example they are labeled with a *n.s.* for *not significant*).

D. *Angular Measure*

1. Astronomers measure positions on the sky in terms of angles.

a) A full circle is divided into 360° (° = degree).

b) A right angle is 90°.

c) 1° = 60 arcmin = 60'.

d) 1' = 60 arcsec = 60".

2. You can use common everyday objects to measure angles on the sky.

a) Width of your finger at arm's length = 1°.

b) Width of your fist at arm's length = 10°.

c) The angular size of the Sun and the Moon are both about 30 arcmin.

d) The separation of the 2 *pointer stars* of the Big Dipper is about 5°.

3. From angular size, the actual (*i.e.*, linear) size can be determined by knowing the distance to the object $\Longrightarrow$ **small angle formula**.

$$D = \frac{\alpha d}{206,265} \tag{I-1}$$

a) D = linear size of the object in the same units a d.

b) d = distance to the object.

c) α = angular size of the object measured in arcseconds.

Example I–1. The star Betelguese (α Ori) has an angular size of 0.040 arcsec and it is at a distance of 200 pc. What is the linear size of Betelgeuse?

$$d = 200 \text{ pc x } 3.09 \times 10^{16} \text{ m/pc} = 6.18 \times 10^{18} \text{ m}$$
$$D = 0.040 \text{ x } 6.18 \times 10^{18} \text{ m / 206,265} = 1.20 \times 10^{12} \text{ m.}$$

The Sun is 1.39×10^9 m in diameter which means that Betelgeuse is

$$D = \frac{1.20 \times 10^{12} \text{ m}}{1.39 \times 10^{9} \text{ m/D}_\odot} = 860 \text{ D}_\odot = 8.0 \text{ AU.}$$

Betelgeuse is 860 times bigger than the Sun! Since the radius of a circle or sphere is half of the diameter, we can compare the radius of Betelgeuse to the orbital radii of the planets in the solar system. The radius of Betegeuse is $R = 0.5 \;(8.0 \text{ AU}) = 4.0$ AU. If Betelgeuse was put in the place of the Sun, then Mercury ($r = 0.4$ AU), Venus ($r = 0.7$ AU), Earth ($r = 1.0$ AU), and Mars ($r = 1.5$ AU) would be inside Betelgeuse!

Jupiter ($r = 5.2$ AU) would be 1.2 AU above the surface of Betegeuse.

E. Celestial Mechanics

1. Kepler's Laws of Planetary Motion.

a) **Law 1:** The orbit of a planet about the Sun is an ellipse with the Sun at one focus.

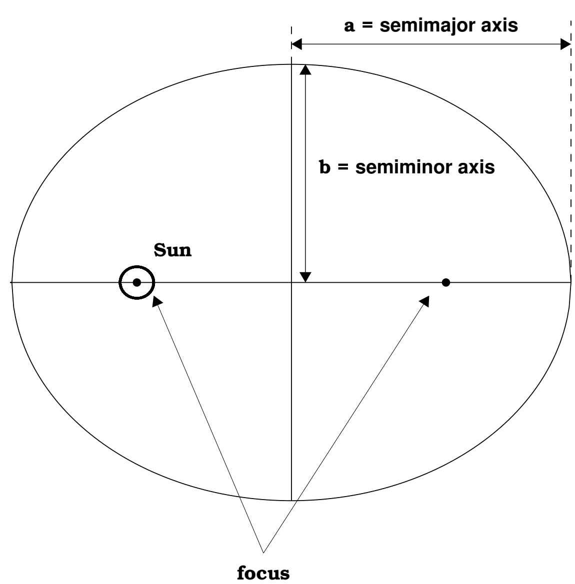
i) **Semimajor axis:** ("a") Half of the longest axis of an ellipse.

ii) **Semiminor axis:** ("b") Half of the shortest axis of an ellipse.

iii) 1 Astronomical Unit is the length of the Earth's semimajor axis.

iv) **Eccentricity:** A measure of the "flatness" of an ellipse,

$$e = \frac{\sqrt{a^2 - b^2}}{a}. \qquad \text{(I-2)}$$



b) Law 2: A line joining a planet and the Sun sweeps out equal areas in equal amounts of time (*law of equal areas*) $\Longrightarrow$ this means that a planet moves faster when it is near perihelion than at aphelion.

i) Perihelion: (r_p) Point on an orbit when a planet is closest to the Sun.

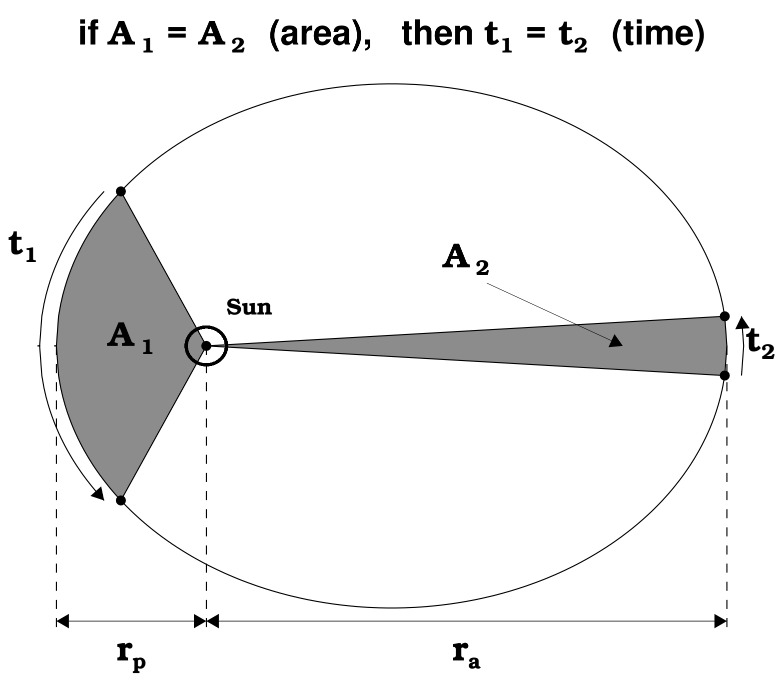
$$r_p = a\,(1 - e). \tag{I-3}$$

ii) Aphelion: (r_a) Point on an orbit when a planet is farthest from the Sun.

$$r_a = a\,(1 + e). \tag{I-4}$$

iii) Note:

$$r_p + r_a = 2a. \tag{I-5}$$



c) **Law 3:** The square of the sidereal period of a planet is proportional to the cube of the semimajor axis of a planet's orbit about the Sun (*harmonic law*).

$$\left(\frac{P}{P_\oplus}\right)^2 = \left(\frac{a}{a_\oplus}\right)^3 \qquad \text{(I-6)}$$

$$\left(\frac{P}{1\ \mathrm{yr}}\right)^2 = \left(\frac{a}{1\ \mathrm{AU}}\right)^3 \qquad \text{(I-7)}$$

OR

$$P_{\mathrm{yr}}^2 = a_{\mathrm{AU}}^3 \qquad \text{(I-8)}$$

Example I–2. A comet has a semimajor axis of 100 AU and a perihelion distance of 5 AU. What is the period, aphelion distance, and eccentricity of its orbit?

$$\begin{aligned}
\left(\frac{P}{1\ \mathrm{yr}}\right)^2 &= \left(\frac{100\ \mathrm{AU}}{1\ \mathrm{AU}}\right)^3 \\
&= (10^2)^3 = 10^6 \\
\frac{P}{1\ \mathrm{yr}} &= (10^6)^{1/2} = 10^{6/2} = 10^3 \\
P &= 1000 \times 1\,\mathrm{yr} \ = 1000\ \mathrm{yrs} \\
r_p + r_a &= 2a \\
r_a &= 2a - r_p = 2(100\ \mathrm{AU}) - 5\ \mathrm{AU} = 195\ \mathrm{AU} \\
r_p &= a(1-e) \\
\frac{r_p}{a} &= 1 - e \\
e &= 1 - \frac{r_p}{a} = 1 - \frac{5\ \mathrm{AU}}{100\ \mathrm{AU}} = 1 - 0.05 = 0.95
\end{aligned}$$

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2. Newton's laws of motion:

a) **The First Law:** A body remains at rest, or moves in a straight line at a constant speed, unless acted upon by an external force (**law of inertia**).

i) **Force (F):** Something that produces a change in the state of motion of an object.

ii) **Inertia:** The tendency of an object to remain in uniform motion.

b) **The Second Law:**

$$F = ma, \tag{I-9}$$

where m = mass of object, a = object's acceleration. Force is measured in **newtons** (N = kg m/s^2). $F = ma$ is the most important equation in all of science!

c) **The Third Law:** Whenever one body exerts a force on second body, the second body exerts an equal and opposite force on the first body. This law is the reason why rockets work.

3. Newton's Universal Law of Gravity.

a) **Gravity** is a force that every object with mass possesses.

b) The universal law of gravity states: Two bodies attract each other with a force that is directly proportional to the product of their masses, m_1 & m_2, and inversely proportional to the square of the distance, r, between them:

$$F = G\left(\frac{m_1\, m_2}{r^2}\right). \tag{I-10}$$

i) **Mass** measures how much material a body possesses, while **weight** measures the amount of gravitational force on an object.

ii) Weight changes depending on the gravitational field the object is in.

iii) Mass however never changes (unless you are traveling close to the speed of light ⇒ special relativity).

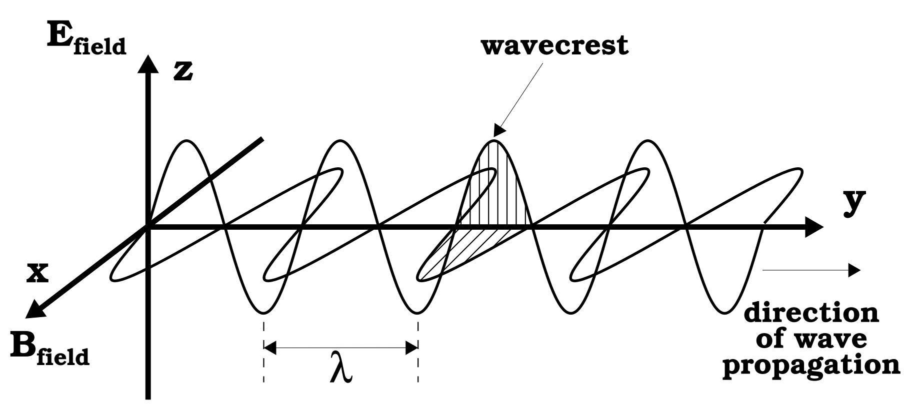
c) Newton was able to prove Kepler's 3rd law mathematically through his laws of physics. For two masses orbiting each other (m_1 and m_2), they obey the equation:

$$P^2 = \left[\frac{4\pi^2}{G(m_1 + m_2)}\right] a^3. \qquad \text{(I-11)}$$

F. The Nature of Light

1. Light travels in empty space at 3.00×10^8 m/s $= 3.00 \times 10^5$ km/s. More precisely, c (**speed of light**) $= 2.99792458 \times 10^8$ m/s.

2. Light is **electromagnetic** (E/M) **radiation** which consists of oscillating electric (E) and magnetic (B) fields which self-propagate at c.



a) The separation of 2 successive wavecrests is called a **wavelength**, λ.

b) E/M radiation is characterized by its wavelength.

c) ν = frequency $\Longrightarrow$ number of wavecrests/sec that pass a given point. Note that:

$$\nu = \frac{c}{\lambda}. \tag{I-12}$$

3. Visible light is just one form of E/M radiation $\Longrightarrow$ **the electromagnetic spectrum**:

a) **Gamma rays:** Highest energy, shortest wavelengths: $0 < \lambda < 0.1$ Å (1 Å $= 10^{-10}$ m $= 10$ nm).

b) **X-rays:** 0.1 Å $< \lambda <$ 100 Å.

c) **Ultraviolet (UV):** 100 Å $< \lambda <$ 4000 Å.

d) **Visible (visual):** 4000 Å $< \lambda <$ 7000 Å.

e) **Infrared (IR):** 7000 Å $< \lambda <$ 1 mm.

f) **Microwaves:** 1 mm $< \lambda <$ 10 cm.

g) **Radio waves:** 10 cm $< \lambda < \infty$.

4. A **spectrum** is defined to be the *brightness* (intensity or flux) as a function of *wavelength* (or frequency or energy).

G. Thermal Radiation

1. Objects in **thermal equilibrium** are at *uniform temperature* throughout its volume.

2. **Temperature** is a quantity that reflects how vigorously atoms are moving and colliding in matter. In this class, we will use the *absolute temp scale:* **Kelvin**.

a) 0 K $\equiv$ coldest obtainable temperature $\rightarrow$ no atomic motion.

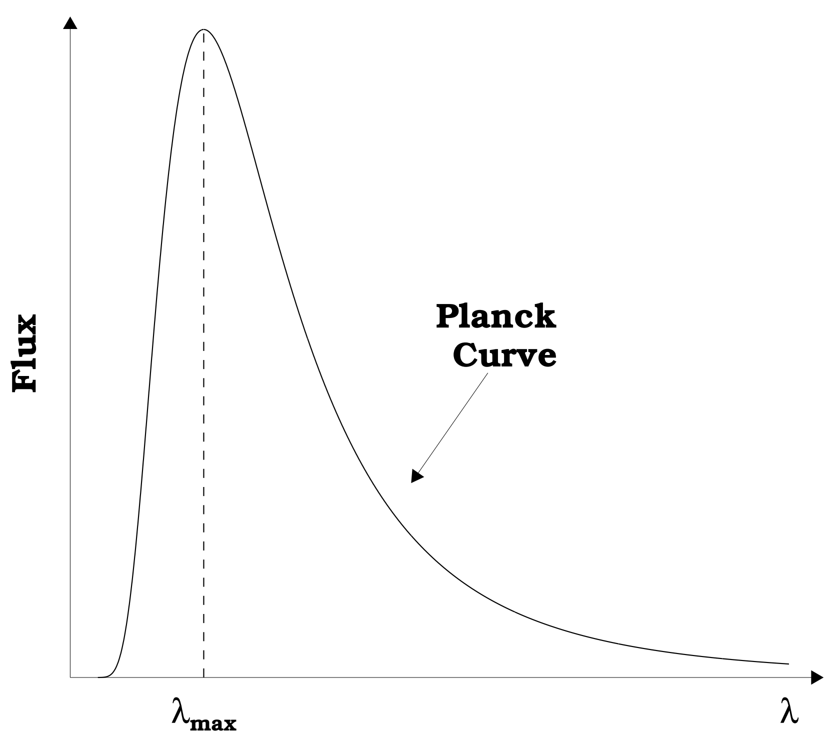
b) Room temperature $\approx$ 300 K.

3. An object at thermal equilibrium emits a thermal spectrum and is called a **blackbody radiator**.

a) A blackbody does not reflect any light, it absorbs all radiation falling on it.

b) All radiation it does emit results from its temperature.

c) A blackbody spectrum is represented by a **Planck curve:**



d) The **energy flux** (F) is the amount of energy emitted from each square meter of an objects surface per second. The flux of a blackbody is a function only of its temperature and is given by the **Stefan-Boltzmann law**:

$$F = \sigma\, T^4, \tag{I-13}$$

where T is the temperature and $\sigma = 5.67{\times}10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant.

e) The total brightness, or **luminosity** (L), of a blackbody is just the flux integrated over all of the surface of the object. For a spherical object, the surface area is $4\pi\, R^2$, so

$$L = 4\pi\, R^2\, F = 4\pi\, \sigma\, R^2\, T^4. \tag{I-14}$$

Note that we can rewrite this equation by making a ratio equation with respect to the Sun (as shown in the example below):

$$\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4. \tag{I-15}$$

f) The hotter a blackbody, the bluer its peak emission of light $\Longrightarrow$ the cooler, the redder its light. The wavelength of peak brightness for a blackbody is given by **Wien's law**:

$$\lambda_{\rm max} = \frac{0.0029 \text{ m K}}{T}. \tag{I-16}$$

Example I–3. A star has a temperature of 10,000 K and a radius of 20 $R_\odot$, what is its flux and wavelength of maximum flux? What is its luminosity with respect to the Sun? (Note that $R_\odot = 6.96 \times 10^8$ m and $T_\odot = 5800$ K.)

$$\begin{aligned} F &= (5.67 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4})\,(10,000 \text{ K})^4 \\ &= (5.67 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4})\,(10^4 \text{ K})^4 \\ &= (5.67 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4})\,(10^{16} \text{ K}^4) \\ &= 5.67 \times 10^8 \text{ W m}^{-2} \end{aligned}$$

$$\lambda_{\rm max} = \frac{0.0029 \text{ m K}}{10,000 \text{ K}} = 2.9 \times 10^{-7} \text{ m} = 2900 \text{ Å} \Longrightarrow \text{ UV light!}$$

$$L = 4\pi\, \sigma\, R^2\, T^4$$

$$
\begin{aligned}
\frac{L}{L_\odot} &= \frac{4\pi\,\sigma\,R^2\,T^4}{4\pi\,\sigma\,R_\odot^2\,T_\odot^4} \\
&= \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4 \\
&= \left(\frac{20\,R_\odot}{R_\odot}\right)^2 \left(\frac{10,000\ \mathrm{K}}{5800\ \mathrm{K}}\right)^4 = (400)\,(1.72)^4 \\
&= (400)\,(8.84) = 3500 \\
L &= 3500\ L_\odot
\end{aligned}
$$

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4. The energy of a single photon is given by:

$$E = h\,\nu = \frac{h\,c}{\lambda}, \qquad \text{(I-17)}$$

where $h = 6.625 \times 10^{-34}$ J s is **Planck's constant** and c is the speed of light.