ASTR-1010: Astronomy I
Course Notes
Section I

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Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1010: Astronomy I taught by Dr. Donald G. Luttermoser at East Tennessee State University.

I. Introduction

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 <u>IS</u> a **<u>science</u>** 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.

2. In this course, we will concentrate on solar system objects, the night sky, and techniques used to study the cosmos.

3. Scientists who study astronomy are called **astronomers**. Some of these also study the physical processes that occur in astronomical objects or phenomena and are called **astrophysicists**.

- **a)** Astronomers who develop mathematical tools and/or model astronomical processes are called **theoretical astronomers**.

- **b)** Astronomers who test a theoretician's model for validity or catalogs observational characteristics of a phenomenon are called **observational astronomers**.

4. Specifically, astronomers and astrophysicists attempt to understand the Universe in terms of **models** that invariably describe correctly the behavior of the Universe.

B. The Scientific Method

1. Science does <u>not</u> try to answer the question *why* the Universe works, but instead tries to answer the question *how* it works.

2. Tentative stages of a model are called a **hypothesis**. When pieced together in a self-consistent manner which is supported by observational (or experimental) evidence, it becomes a valid **theory**. This statement is the basis of the **scientific method**.

3. **Theory** is <u>not</u> a dirty word! Theory does not mean one has any proof. Indeed, in order for a hypothesis to be accepted as a theory, one must present observational or experimental verification to support it.

4. Science is not done merely by stating ideas as fact. As technology progresses, measurements improve and models become more sophisticated so that new theories arise $\Longrightarrow$ 1930's observations that all galaxies are receding from each other lead to the development of the Big Bang Theory.

5. Charlatans abound in the real world that make claims (sometimes in scientific terminology) about beliefs they have.

   a) **Pseudoscience** is any subject that makes claims which are not subjected to scientific testing, or fail such testing, yet are still believed.

   b) Sometimes pseudoscience undergoes scientific tests (*e.g.*, ESP and astrology) and then fail these tests, yet people who are strong believers in such dogma often do not believe the validity of the tests, or they claim of conspiracies to hide the truth (*e.g.*, UFO's) $\Longrightarrow$ **it is not science unless it can be repeatedly validated through proper experimental tests by different scientists** (*e.g.*, cold fusion is a good example of a claim not being repeatable by other scientists).

6. The language of science is **mathematics**!

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

b) A scientist must describe all kinds of physical objects from atoms to stars.

c) Then they must document how these objects interact and change over time $\Longrightarrow$ which is done with <u>mathematics</u>.

C. Measurements

1. Measurements are often made in astronomy. Besides wanting to know the *magnitude* of a measurement (*i.e.*, number), you should also report the **units** in which the measurement is made. There are 3 different **unit systems** that are used in science (note: the last two are part of the metric system).

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

b) **cgs system** (centimeter-gram-second, cm-gr-s) $\Longrightarrow$ this metric system is often 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 (don't confuse units with variables — variables will be in a *script* font in these notes):

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

4. There are other units that are also based upon the fundamental units, but in a more indirect way.

a) *Temperature* (T): Kelvin (K). Temperature is nothing more than a measure of a particle's velocity as can be seen by equating the thermal energy to the kinetic energy of a particle: $\frac{3}{2}k_BT = \frac{1}{2}mv^2$.

b) *Current* (I): Ampere (A). The current multiplied by the voltage in a wire is equal to the energy supplied to the circuit per second.

5. Periodically, we will make use of special units. Some of the more common ones are:

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 (actually, it is the length of the semimajor axis of the Earth's orbit about the Sun) = 1.50×10^{11} m.

d) *Light Year* (ly) = amount of time it takes light to travel in one year = 9.46×10^{15} m = 63,240 AU. (**Note that the light year is a unit of distance and not a unit of time!**)

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

D. Math Primer

1. Cross Multiplication:

$$mx = ny \Longleftrightarrow \frac{x}{y} = \frac{n}{m}.$$

2. Factoring:

$$y = mx + mb \Longleftrightarrow y = m(x + b).$$

3. Powers and Roots:

a) $a \times a \times a \times a \times a \times a \times a \times a = a^8.$

OR

$$a \times a \times a \times \cdots (m \text{ times}) \times a = a^m$$

$\Longrightarrow$ "a" is raise to the "m" power.

b) $a^{1/m} = \sqrt[m]{a} \Longrightarrow$ the "m"-th root of "a".
Example:
$4 \cdot 4 = 4^2 = 16, \qquad 16^{1/2} = \sqrt{16} = 4.$

c) $a^0 = 1.$

d) $a^{-m} = \frac{1}{a^m}$, Example: $2^{-2} = \frac{1}{2^2} = \frac{1}{4} = 0.25.$

e) $(ab)^m = a^m b^m, \qquad (\frac{a}{b})^m = \frac{a^m}{b^m} = a^m b^{-m}.$

f) $a^m a^n = a^{m+n}, \qquad \frac{a^m}{a^n} = a^{m-n}.$

g) $(a^m)^n = a^{mn}, \qquad \sqrt[n]{a^m} = a^{m/n}.$
Examples:

$$\begin{aligned}
3^4 = 3 \cdot 3 \cdot 3 \cdot 3 &= 81 = 8.1 \times 10^1, \\
2^{-3} = \frac{1}{2^3} = \frac{1}{2 \cdot 2 \cdot 2} &= \frac{1}{8} = 0.125 = 1.25 \times 10^{-1}, \\
15^2 = (3 \cdot 5)^2 = 3^2 \cdot 5^2 &= 9 \cdot 25 = 225 = 2.25 \times 10^2, \\
6^2 \cdot 6^3 = 6^{2+3} &= 6^5 = 7776 = 7.776 \times 10^3, \\
(\sqrt{2})^3 = (2^{1/2})^3 &= 2^{3/2} = 2^{1.5} = 2.828...
\end{aligned}$$

E. Scientific Notation

1. Powers of Ten.

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

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

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

(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 <u>real</u> 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.

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

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

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*).

F. 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°.

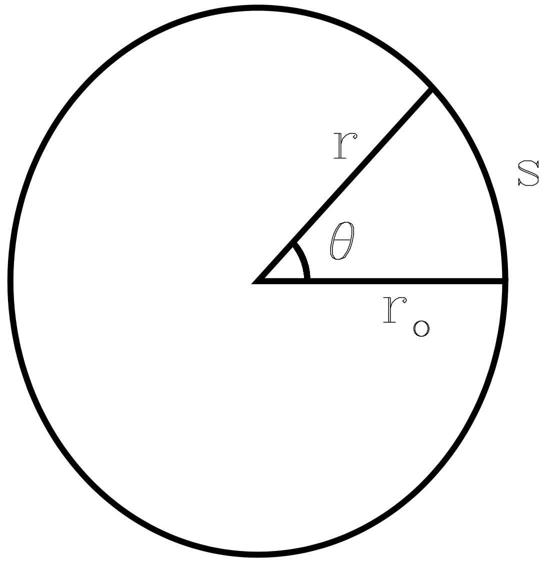
c) The angular size of the Sun and the Moon are both about 30 arcmin (= 1/2 degree).

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

3. Once we measure the angular size of an object on the sky, we can determine its actual (*i.e.*, linear) size by knowing the distance to the object $\Longrightarrow$ **small angle formula**. This formula can be derived as follows:

a) If C is the circumference of a circle and r be the radius of the circle, then the ratio of C to the diameter of a circle $(2r)$ of <u>all</u> circles is a number called (pi) $\pi = 3.1416$: $\frac{C}{2r} = \pi$.

b) Rewriting, we get $C = 2\pi\, r$, note that C and r are measured in both units of length and π is unitless. The following figure shows the definition of an arclength of a circle s. If we extent s completely around the circle, it becomes C.



c) From this analogy, we can write

$$s = \theta \, r, \tag{I-1}$$

where θ is the angle subtended by r as it rotates around the center of the circle from some reference radius $r_\circ$. Note that in this equation, θ is measured in **radians**. (*Note that "radian" is not a unit, anything written with radian after it can be considered a pure number.*) From our analogy above, there are 2π radians in 360° or 1 rad = 57.3°.

d) Since there are 60 arcmin (') in 1° and 60 arcsec (") in 1 arcmin,

$$1 \text{ rad } = 57.3^\circ \times \frac{60'}{1^\circ} \times \frac{60''}{1'} = 206,265'',$$

and from this, Eq. (I-1) becomes

$$s = \frac{\alpha \, r}{206,265}, \tag{I-2}$$

where α has now replaced θ and is the angle subtended along the arclength s measured in *arcseconds*.

e) Assume now that the above circle represents the sky with the Earth at the center. Let the distance to some object on the sky from the Earth be represented by d (*i.e.*, r is replaced by d in Eq. I-2) and the linear size of object in the sky by D (*i.e.*, its diameter which replaces s in Eq. I-2). Then the actual diameter D of an object in space just depends on its distance d and its angular diameter α via

$$D = \frac{\alpha\, d}{206,265}, \qquad \text{(I-3)}$$

where D is in the same length units as d and α is measured in arcseconds.

Example I-1. The star Betelguese (α Ori) has an angular size of 0.040 arcsec (40 milliarcseconds = 40 mas) and it is at a distance of 200 pc. What is the linear size of Betelgeuse? How does this size compare to the planet's distances from the Sun in our solar system?

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

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

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

where $D_\odot$ is the Sun's diameter.

We now will calculate the diameter of Betelgeuse in AU:

$$D = \frac{1.20 \times 10^{12} \text{ m}}{1.50 \times 10^{11} \text{ m/AU}} = 8.0 \text{ AU}\,.$$

Since the radius of a circle or sphere is half the diameter, we can compare the radius of Betelgeuse to the orbital distances of planets in the solar system from the Sun. The radius of Betelgeuse is hence $R = 0.5$ (8.00 AU) = 4.00 AU. If it was put in the place of the Sun, then Mercury (0.39 AU), Venus (0.72 AU), Earth (1.0 AU), and Mars (1.5 AU) would be inside Betelgeuse

— all of these planets would be vaporized! The planet Jupiter (5.2 AU) would be close (1.2 AU) to the photosphere ("surface") of Betelgeuse.

Actually, some 5 billion years from now, the Sun will expand and cool becoming a red giant star whose "surface" will extend out to Earth's orbit. (Note that the Sun's birth, evolution, and death are covered in ASTR-1020: *Astronomy II.*)