1 Introduction to Astrophysics

1.1 *Observations and Observables*

Astronomy involves the observation of distant objects beyond Earth: from low-orbit spy satellites to our own Solar System to our Milky Way galaxy to other distant galaxies and out to the observable edge of the universe. A non-exhaustive list of some of the types of objects that are observed includes:

1. Planets and moons in our own Solar System
2. Stars (including our Sun)
3. Planets orbiting other stars
4. Remnants of 'dead' stars: white dwarfs, neutron stars, and black holes
5. Giant, cool clouds of gas and dust
6. Other galaxies beyond our Milky Way
7. Diffuse, hot gas: between stars, and between galaxies
8. The overall structure of the universe.

These observations are made using a variety of different techniques. Most frequent is the detection of electromagnetic radiation: everything from high-energy gamma- and X-rays, through ultraviolet, visible, and infrared light, and down to microwave and radio waves. When people speak of **multi-messenger astronomy**, they mean observations beyond merely electromagnetic detections. These other approaches involve the direct or indirect detection of high-energy, particles (i.e., not photons) such as the solar wind, cosmic rays, or neutrinos from . The newest set of observations includes the detection of gravitational waves from distant, massive, rapidly-rotating objects.

Because astronomy is an observationally-driven field, big advances and new discoveries often occur whenever technological capabilities improve substantially. Ancient astronomers, from well before Hipparchus down to Tycho Brahe, could only rely on what their own, unaided eyes could see. That changes with the invention of the telescope: astronomers still had to use their own eyes, but now they could see finer details (because of optical magnification) and study fainter objects (a telescope lens is larger than your eye's pupil, so it collects more light).

The next big revolution was astrophotography: a photographic setup can sit collecting light from a faint source for minutes or even hours, so much fainter and/or more distant objects could be studied than by just peering through a telescope. In the last century, the development of photoelectric detectors — first as 'single-pixel' devices and later as mega- or giga-pixel optical CCDs or infrared array detectors — has had at least as big an impact, by virtue of their dramatically enhanced sensitivity compared to photography. More recently still, other new technologies have also emerged such as interferometry to give the sharpest possible images at radio to infrared wavelengths, or adaptive optics which achieves something similar in the optical and infrared.

1.2 *Astronomy, Astrophysics, and Historical Baggage*

Astrophysics: effort to understand the nature of astronomical objects. Union of quite a few branches of physics — gravity, E&M, stat mech, quantum, fluid dynamics, relativity, nuclear, plasma — all matter, and have impact over a wide range of length and time scales.

Astronomy: providing the observational data upon which astrophysics is built. Thousands of years of history, with plenty of intriguing baggage.

Sexagesimal notation

Sexagesimal notation is one example. This means a Base-60 number system, and it qoriginated in Sumer in $\sim$3000 BC. Origin uncertain (how could it not be?), but we still use this today for time and angles: 60″ (arc-seconds) in 1′ (arc-minute), 60′ in 1^o , 360^o in one circle.

We use this angular notation to express where an object is on the Earth's surface, as well as where an astronomical object is on the sky. On Earth, this is through the latitude/longitude system – just a form of spherical coordinates, in which longitude corresponds to ϕ (the angle around the planet from the Greenwich meridian) and latitude corresponds to θ (the angle from the equator). **Celestrial coordinates** use a related approach: here, **Right Ascension** (RA or α) plays the role of ϕ or longitude (describing the angle from a point defined by the Earth's orbit) and **Declination** (Dec or δ) plays the role of θ or latitude (describing the angle north or south from a projection of the Earth's equator).

Further complicating things, all stars are in motion and so a star's coordinates slowly change over time. One subtle effect here is due to slow evolutions in the Earth's orbit. But for nearby stars, the largest effect is indeed due to their intrinsic motion; this motion of stars across the sky is called **proper motion**. The closest, fastest stars have proper motions of several arcsec per year, but proper motion is more usually measured in milliarcsec per year, or mas yr^{-1}. Sources far away (or especially, outside the Milky Way) have essentially zero proper motion.

The classic astronomer's website for learning the coordinates, proper motion, and many other useful details of a given star is **SIMBAD**[1]. For the more well-known stars, Wikipedia isn't a terrible source either.

The Magnitude System

Magnitudes are an even more notorious example of the weight of historical tradition. These aren't especially logical, but all astronomers use them through tradition (and force of habit) as a standard way of indicating the intrinsic and apparent brightness of stars and galaxies.

The magnitude system is originally based on the human eye by Hipparchus of Greece ($\sim$135 BC), who divided visible stars into six primary brightness bins. This arbitrary system continued for $\sim$2000 years, and it makes it fun to read old astronomy papers ("I observed a star of the first magnitude,"

[1] `http://simbad.u-strasbg.fr/simbad/sim-fid`

etc.). This was revised and made somewhat more quantitative by Pogson in 1856, who semi-arbitrarily decreed that a one-magnitude difference between two objects means that one is $\sim$2.512$\times$ brighter than the other. This is only an approximation to how the eye works! To further confuse things, thanks to Hipparchus smaller magnitudes mean brighter stars: so the system 'feels backwards.'

So given two stars with apparent brightnesses b_1 and b_2, their **apparent** (i.e., relative) **magnitudes** are related by:

$$m_1 – m_2 = 2.5 \log_{10} \frac{b_1}{b_2}. \tag{1}$$

So a 2.5 mag difference means one object is 10$\times$ brighter than the other. Not very intuitive! However, it turns out that a 2.5$\times$ brightness difference also roughly corresponds to a *sim*1 mag difference – a nice coincidence. For smaller variations milli-magnitudes (mmag) are sometimes uesd, and a 1 mmag = 10^{-3} mag difference corresponds roughly to one object being 1.001$\times$ brighter — so 1 mmag is about a part-in-a-thousand brightness difference.

An alternative way of presenting the apparent magnitude system is by defining some reference brightness and defining observed magnitudes relative to that brightness level. In the typical (Vega magnitude) system we will use in this class, the reference level is the brightness of the star Vega. If we call this reference brightness b_0, then the apparent magnitudes are defined by

$$m = -2.5 \log_{10} \frac{b/b_0}{.} \tag{2}$$

Absolute magnitudes refer not to how bright objects *look* to an observer, but to their intrinsic brightness (i.e., luminosities). We need a reference point, so we say that an object's absolute and apparent magnitudes are the same if the object is 10 pc away from us (again, this is arbitrary – and doesn't make so much sense for galaxies that are much larger than 10 pc!). Also, if a star is (e.g.) 5$\times$ further away its light will be spread over 5^2 more surface area throughout the universe. The absolute magnitude M of a a star or galaxy is

$$m – M = 2.5 \log_{10} \left(\frac{d}{10 \text{ pc}} \right)^2 = 5 \log 10 \frac{d}{10 \text{ pc}}. \tag{3}$$

We will see later than absolute magnitudes are directly related to the **luminosity** (L, the true intrinsic brightness) of a star in the same way that apparent magnitudes are related to apparent brightness:

$$M_1 – M_2 = 2.5 \log_{10} \frac{L_1}{L_2}. \tag{4}$$

Magnitudes can be either

- **bolometric** — relating the total electromagnetic power (i.e. luminosity) of the object (of course, we can never actually measure this unless we have detectors operating across an infinite wavelength/frequency range

– we need models!)

- **wavelength-dependent**, in which case the magnitude only relates the power in a specific wavelength range

Finally, to confuse things just a bit more there are two different kinds of magnitude systems. These make qualitatively different assumptions about how they set their zero-points, defining the magnitude of a given brightness. The older system (which you should assume in this class, unless told otherwise) is the Vega system, in which magnitudes at different wavelengths are always relative to a 10,000 K star (similar to the star Vega). The other, more modern scheme is that of **AB magnitudes**, in which a given magnitude at any wavelength always means the same flux density (a term we will define later).

1.3 *Fundamental Forces*

All of the fundamental physical forces are important for astronomy, but some are more important than others:

1. **Gravity**. By far the most important for astronomy! In this course we will consider the force of gravity more than any other force.

2. **Electromagnetism**. Also quite important, especially for energy transport via radiation but also for interactions involving charged particles and magnetic fields.

3. **Weak and Strong Nuclear Forces.** Not as critical for many situations considered in astronomy, but essential for understanding the nuclear fusion and fission that power stars and supernovae.

1.4 *Types of Particles*

- **Photons**. Electromagnetic particles that are also waves. Move at speed c, have **wavelength** λ and **frequency** ν such that $c = \lambda\nu$. Have energy $E = h\nu$ and momentum $p = E/c = h/\lambda$.

- **Protons**. Positively charged particles with mass approximately 1 amu. Found in the nuclei of all atoms, where it may be attracted to neutrons (or even other protons) via the strong nuclear force.

- **Neutrons**. Chargeless particles with mass approximately 1 amu. Found in the nuclei of all atoms except ^{1}H, where they are attracted to protons (as well as other neutrons) via the strong nuclear force. On their own, will decay relatively quickly via the weak nuclear force.

- **Electrons**. Negatively charged leptons, with $m_p/m_e \sim 1800$. Found in atoms and also found free at high temperatures when atoms become ionized.

- **Neutrinos**. Tiny, tiny, nearly-but-not-quite massless, chargeless particles. Come in three flavors (as do leptons) but in astrophysics we're mainly concerned with the **electron neutrino** ν_e and its antiparticle $\bar{\nu}_e$.

- **Antiparticles**. Every particle has a corresponding antiparticle with the same mass and opposite charge. When a particle and its antiparticle meet, they annihilate each other and release their full mass energy, $E = mc^2$. With enough energy available the reaction can be reversed and a particle and its antiparticle can be created!
- **Atoms and Ions.** The building blocks of the universe, and most of it hydrogen (with most of the rest helium).
- Molecules. Only stable at relatively cool temperatures ($\lesssim$ 4000 K), but found in planets, cool gas clouds, and the outer parts of the coolest stars.

1.5 *Concepts*

You will need to be familiar with the following (non-exhaustive) list of concepts in this course:

- **Pressure**. $P = F/A$, remember?
- **Density**. $\rho = M/V$. 'Nuff said.
- **Number density**. The number of particles per volume element, $n = N/V$. It is also related to mass density via $n = \rho/m = (M/m)1/V$.
- **Ideal gas**. We will assume most arrays of particles are ideal gases. You may be used to seeing the ideal gas law in the form of $PV = NRT$, where R is the ideal gas constant. In astronomy we often cast this instead in terms of the number density. Dividing by V, we then have $P = nk_BT$, where k_B is the Boltzmann constant.
- **Luminosity** just refers to the power output by some celestial body. Most commonly we'll refer to the luminosity of our own Sun, $L_\odot \approx 4 \times 10^{26}$ W.
- **Doppler Shift**: Waves of a given frequency and wavelength appear differently when emitted by a moving object. This applies to light waves too; at non-relativistic speeds, the observed wavelength

  $$\lambda_{obs} = \lambda_{emitted}\,(1 + v/c)\,, \tag{5}$$

  where v is the radial velocity. An object moving away from Earth has $v > 0$ and so $\lambda_{obs} > \lambda_{emitted}$: its light is redshifted. Light from objects moving toward the observer is said to be blueshifted.
- **Relativity** rears its head in several aspects. One is **mass-energy equivalence**: you've heard that $E = mc^2$. If you were to convert 10 kg of mass into energy in one second, you'd have a power (i.e., luminosity) of (10 kg)(3×10^8 m s^{-1})^2/1 sec $\approx 10^{18}$ W. Only antimatter converts to energy so entirely, but even nuclear fusion and fission convert enough to be important for stars and supernovae.

- **Quantum mechanics**: We will address a few aspects of quantum mechanics; these will be introduced as we come across them. One key aspect already mentioned is the energy of a single photon, $E = h\nu$.

- **Thermal equilibrium**: whether things are at the same temperature. E.g., in a star there are both atoms (and ions, and free electrons) and also photons. If all of these particles have about the same temperature (i.e. thermal kinetic energy), then the mixture is in thermal equilibrium. Often this applies only in a small region (after all, a star is hotter inside than on its surface) and so in these cases we often speak of **local thermal equilibrium.**

- **Order-of-magnitude estimation**: The ability to quickly and approximately calculate quantities of interest.

1.6 *OOMA: Order-of-Magnitude Astrophysics*

One of the key tools one should have in their toolkit is the ability to quickly and approximately estimate various quantities. Astronomy is a fun field because in many cases it's fine to calculate a quantity to within a factor of a few of the correct value. When we speak of an **order of magnitude**, we mean estimating an answer to within a factor of ten or so. See your "OOMA" handout for a rundown of handy approximations to many important astronomical and physical quantities.

We'll spend a lot of time on stars, so it's important to understand some key scales to get ourselves correctly oriented. For example, consider the electron and neutron, which have $m_e \sim 10^{-30}$ kg and $m_n \sim 2 \times 10^{-27}$ kg. The ratio of these two is

$$\frac{m_n}{m_e} \approx 1800 \approx \frac{R_{\rm WD}}{R_{\rm NS}} \tag{6}$$

where $R_{\rm WD}$ and $R_{\rm NS}$ are the radii of a white dwarf and a neutron star: dead stellar remnants mainly supported by electrons and neutrons, respectively (we'll get to these more, later).

Meanwhile the mass of our Sun is $M_\odot \approx 2 \times 10^{30}$ kg. So while considering the masses involved might make it seem that objects in this course are astronomically far from the considerations of fundamental physics, this couldn't be further from the truth. In fact, many astrophysically large quantities can be almost purely derived from fundamental physical constants. E.g., the maximum possible mass of a white dwarf before it collapses under its own weight:

$$M_{\rm WD,max} \approx \left(\frac{\hbar c}{G}\right)^{3/2} m_H^{-2} \tag{7}$$

(where m_H is the mass of a hydrogen atom), or the Schwarzschild radius (size of the event horizon) of a nonrotating black hole:

$$R_S = 2\frac{G}{c^2}M_{\rm BH}. \tag{8}$$

As another example, consider the gravitational acceleration at Earth's surface. If one can't remember that this is 9.8 m s^{-2}, we would hopefully still remember that $g \equiv GM/R^2$. If we can't recall $M_\oplus$ or $R_\oplus$, we might still remember that the Earth's circumference is $2\pi R_\oplus \approx 40,000$ km and the Earth has a mean density of about 5 g cm^{-3} = 5000 kg m^{-3} (rocks are $\sim$5$\times$ denser than water). So

$$R_\oplus \approx \frac{40,000 \text{ km}}{2\pi} \sim \frac{40,000 \text{ km}}{6} \sim 6,500 \text{ km} \tag{9}$$

and

$$\begin{aligned} M_\oplus = & \quad \rho_\oplus \left(\tfrac{4}{3}\pi R_\oplus^3\right) \\ \sim & \quad \left(5\times 10^3 \text{kg m}^{-3}\right)\left(4\left[6.5\times 10^6 \text{ m}\right]^3\right) \\ \sim & \quad 20 \times 10^{21} \times 250 \text{ kg} \\ \sim & \quad 5 \times 10^{24} \text{ kg}. \end{aligned}$$

This is remarkably close (by astronomical standards) to the true value of 5.97×10^{24} kg. We could then finally estimate the surface gravity as

$$\begin{aligned} g_\oplus = & \quad G\tfrac{M_\oplus}{R_\oplus^2} \\ \approx & \quad \left(\tfrac{2}{3}\times 10^{-10} \text{ N m}^2 \text{ kg}^{-2}\right)\left(\tfrac{5\times 10^{24} \text{ kg}}{[6.5\times 10^6 \text{ m}]^2}\right) \end{aligned}$$

$$\sim \frac{2\times 5}{3\times 40} \times \frac{10^{-10}\times 10^{24}}{10^{12}}\ m\ s^{-2}$$

$$\sim 0.1 \times 10^2\ m\ s^{-2} = 10\ m\ s^{-2}.$$

Again, surprisingly close to the true value of 9.8 m s^{-2}! So some basic order-of-magnitude assumptions lead to a pretty good answer – this is often the case in astrophysics.