Astronomy 400B Lecture 2: Magnitudes, the Milky Way, and Other Galaxies

Brant Robertson

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1 Magnitudes

1.1 Vega Magnitudes

Vega magnitudes are both the scourge and pride of astronomy, and enable astronomers to engage in discussions no other scientists understand. The *apparent magnitude* difference $m_1 - m_2$ between two stars is related to the ratio of their fluxes F_1 and F_2 via the relation

$$m_1 - m_2 = -2.5 \log(F_1/F_2). \tag{1}$$

Note that I have used fluxes here rather than flux densities, but in fact we can use Equation 1 with flux densities as well (see below).

Typically, when we measure a magnitude we are band-limited by a filter with a bandpass function $T_{\mathrm{BP}}(\lambda)$. The total flux in a given filter can be written as

$$F_{\mathrm{PB}} = \int_0^\infty T_{\mathrm{BP}}(\lambda) F_\lambda(\lambda) d\lambda \approx F_\lambda(\lambda_{\mathrm{eff}}) \Delta\lambda \tag{2}$$

where $\Delta\lambda$ is the wavelength-width of the filter and λ_{eff} is the effective wavelength of the filter

$$\lambda_{\mathrm{eff}} = \int_0^\infty \lambda T_{\mathrm{BP}}(\lambda) F_\lambda(\lambda) d\lambda \bigg/ \int_0^\infty T_{\mathrm{BP}}(\lambda) F_\lambda(\lambda) d\lambda \, . \tag{3}$$

The apparent magnitude difference between two objects measured in a given filter is

$$m_{1,\mathrm{BP}} - m_{2,\mathrm{BP}} = -2.5 \log \left\{ \int_0^\infty T_{\mathrm{BP}}(\lambda) F_{1,\lambda}(\lambda) d\lambda \bigg/ \int_0^\infty T_{\mathrm{BP}}(\lambda) F_{2,\lambda}(\lambda) d\lambda \right\}. \tag{4}$$

For some bands, such as in the UV, there were no well-measured stellar spectra. In this case, astronomers would define the average flux density

$$\langle F_{\mathrm{BP}} \rangle = \frac{\int T_{\mathrm{BP}}(\lambda) F_\lambda(\lambda) d\lambda}{\int T_{\mathrm{BP}}(\lambda) d\lambda}, \tag{5}$$

from which we could define

$$m_{\mathrm{BP}} = -2.5 \log \left(\frac{\langle F_{\mathrm{BP}} \rangle}{\langle F_{V,0} \rangle} \right). \tag{6}$$

The quantity $\langle F_{V,0}\rangle \approx 3.63\times10^{-9}$erg cm^{-2} s^{-1} Å^{-1} is the average flux density of a star with apparent(!) magnitude $m_V = 0$ (e.g., Vega). A quick cheat is

$$m_{\rm BP} = -2.5\log\langle F_{\rm BP}\rangle - 21.1 \tag{7}$$

if $\langle F_{\rm BP}\rangle$ is also measured in units of erg cm^{-2} s^{-1} Å^{-1}.

Why are Vega magnitudes appalling? The issue is $F_\lambda(\lambda)$ must be known for Vega for all wavelengths. A corollary is that the differences between the apparent magnitudes of different stars in different filters depend on the spectral shape of Vega. It's a bit insane.

2 AB Magnitudes

Eventually, astronomers came to their senses and started using "AB" magnitudes that are measured relative to a source that is flat in F_ν. There are two main advantages:

1. Magnitudes depend on the spectral shape of the measured object but not a reference star.
2. Magnitudes can be defined as a flux density easily, e.g., AB magnitudes $\equiv$ Janskys.
3. Absolute magnitudes are easily understood interms of flux density (including luminosity and distance).

Let's redefine the average flux density in some filter as

$$\langle F_{\rm BP}\rangle = \frac{\int T_{\rm BP}(\nu)F_\nu(\nu)d\nu}{\int T_{\rm BP}(\nu)d\nu}. \tag{8}$$

This quantity has units erg cm^{-2} s^{-1} Hz^{-1}, which is just a multiple of the Jansky.

For distant extragalactic work, the micro- (μJy) and nanojansky (nJy) are most convenient. We can easily convert between the AB magnitude and nanojansky as

$$m_{\rm AB} = 31.4 - 2.5\log\left(\frac{\langle F_\nu\rangle}{1\ \rm nJy}\right). \tag{9}$$

Note that this sensibly has nothing to do with Vega.

2.1 Absolute Magnitude

The absolute magnitude of an object is the apparent magnitude of an object if it were placed at a distance of 10pc

$$M = m - 5\log(d/10\rm pc). \tag{10}$$

For instance, the absolute magnitude of the Sun depends on the filter used to measure the Sun's flux density (and for Vega magnitudes the spectral shape of Vega). It should be clear that the Vega and AB absolute magnitudes for the Sun (or any other star) are not the same. For Vega magnitudes, the absolute filter magnitudes of the Sun are

$$[U,B,V,R,I,J,H,K] = [5.61, 5.48, 4.83, 4.42, 4.08, 3.64, 3.32, 3.28]. \tag{11}$$

In AB magnitudes, the absolute filter magnitudes of the Sun are

$$[U,B,V,R,I,J,H,K] = [6.36, 5.36, 4.82, 4.65, 4.55, 4.57, 4.71, 5.19]. \tag{12}$$

2.2 Bolometric Correction

The absolute magnitude of a star (nominally) measures the bandpass averaged flux of an object, referenced to a distance of 10 parsecs. This quantity involves the luminosity (density) of the object in a given filter, and differs from the total luminosity of an object. The *bolometric magnitude* of an object is related to its total luminosity, and we can define the *bolometric correction* to be the amount that needs to be subtracted from the bandpass magnitude of an object to find its bolometric magnitude. In an equation, we can write

$$M_{\mathrm{bol}} = M_V - \mathrm{BC} \tag{13}$$

For the Sun in Vega magnitudes, BC ≈ 0.07.

3 The Milky Way

The Milky Way is a fantastic galaxy, and not just because we live there. It has a terrific richness of structure and complexity, and simply put we currently do not know how such a galaxy forms.

The main structures of the Milky Way are (**See Figure 1.8 of Sparke and Gallagher**)

1. The dark matter halo, consisting of (presumably) subatomic particles that participate only in weak (Weak, gravitational force) interactions. The mass of the Milky Way halo is about $10^{12}M_{\odot}$. The radius of the dark matter halo is roughly 300kpc. The dark matter halo is thought to obey a roughly broken power-law density profile, with $\rho \propto r^{-1}$ within about 30kpc and $\rho \propto r^{-3}$ in the exterior.

2. The stellar halo, consisting of old, metal-poor stars and globular clusters (old clusters of $\sim 10^5 - 10^6$ stars). The stellar halo is only about $10^9 M_{\odot}$.

3. The central bulge of the galaxy is a pseudospheroidal distribution of stars with a luminosity of $L \approx 5 \times 10^9 L_{\odot}$ and mass $2 \times 10^{10} M_{\odot}$.

4. The supermassive black hole at the center of the Milky Way, which has a mass of about $\approx 4.1 \times 10^6 M_{\odot}$.

5. The stellar disk of the galaxy is roughly exponential, such that the surface density scales as $\Sigma(r) \propto \exp(-r/h)$, with a scale length $h \approx 3$kpc. The total luminosity of the disk is about $2 \times 10^{10} L_{\odot}$ and with a mass in stars of about $6 \times 10^{10} M_{\odot}$. The stellar disk has a *thin disk* component with a scale height of about 300pc containing 95% of the mass, and a *thick disk* containing about 5% with a scale height of about 1kpc.

6. The gaseous disk of the galaxy is a thin layer about a 100pc thick consisting mostly of neutral hydrogen (HI) and molecular hydrogen (H_2) gas. The gaseous disk also contains a warm ionized and hot ionized interstellar medium (ISM; see below). The gaseous disk is also very dusty!

4 Ionized Gas

The Milky Way (and other galaxies) contain a variety of ions of various elements, and the emission and absorption mechanisms of this gas enables us to learn a lot about the galaxies observationally. The radiation emitted by the gas can be in the form of spectral lines or continuum processes (like bound-free emission).

Atoms and ions produce line emission when electrons move between orbitals and release the corresponding energy difference between orbitals as a photon. Recombination radiation occurs when free electrons get captured into an orbital and release the corresponding free energy difference as light. *Balmer* lines from Hydrogen correspond to electrons entering the $n = 2$ state, while the *Lyman* series corresponds to transitions to the $n = 1$ state. Transitions between $n = 2$ and $n = 1$ correspond to the *Lyman* α line at $\lambda = 1216$Å (10.2eV).

4.1 Photoionization

We call the process of freeing electrons from ions via the absorption of a photon *photoionization*. The energy of a photon required to photoionize an ion depends on the electrical properties of the ion. A photon of energy 13.6eV or more and wavelength $\lambda = 912$Å or shorter can fully liberate an electron from the ground state of Hydrogen. Such photons are called *Lyman continuum* photons.

4.2 Collisional Ionization

For hot gas, when the mean kinetic energy $k_{\mathrm{B}}T$ is comparable to the energy difference between levels, then *collisional ionization* may occur via the collision of two ions. In this case, we will have the reaction

$$\mathrm{A} + \mathrm{B} \rightarrow \mathrm{A}^* + \mathrm{B}; \mathrm{A}^* \rightarrow \mathrm{A} + h\nu \tag{14}$$

where $h\nu \sim k_{\mathrm{B}}T$ is the energy of photon emitted after the ion A is collisionally excited.

4.3 Forbidden Lines

The rate of emission depends on density, and some *forbidden lines* that forge less probable paths through the orbital ladder of an ion require very low densities since their emission timescale can be of order 1s (allowed lines have emission timescales that are $\sim 10^{-8}$s). The *critical density* of a line corresponds to the density where emission is the most likely compared with further excitation or collision. Forbidden lines therefore provide information about the density and temperature of their emitting gas. We typically indicate a forbidden line with the [] notation, as the famous [OIII] line at $\lambda = 5007$Å.

4.4 Fine Structure Lines

The *fine structure* lines of an atom correspond to level splittings that arise from the coupling between an electron orbital's angular momentum and the electron spin. The energy difference between typical orbital transitions and fine structure lines is a factor of $\sim \alpha^{-2}$, where α is the fine structure constant

$$\alpha = \frac{1}{2\epsilon_0}\frac{e^2}{hc} \tag{15}$$

where ϵ_0 is the permitivity of free space, e is the charge of the electron, h is Planck's constant, and c is the speed of light. The value of $\alpha^{-1} \approx 137.036$ is famous throughout physics.

This large factor means that the fine structure lines of metals typically lie at wavelengths $> 100\mu$m. Fine structure lines of Carbon at 158μm and Oxygen at 63μm and 145μm provide some of the strongest coolants of ≈ 100K gas in the Milky Way ISM.

The energy of a 158μm [CII] fine structure photon corresponds to $T = 91.2$K. The volumetric emissivity rate of [CII] can be approximated as

$$\Lambda(\mathrm{C}^+) = n_\mathrm{e} n(\mathrm{C}^+) T^{-1/2} \exp(-91.2\mathrm{K}/T) \times 8 \times 10^{-20}\ \mathrm{erg\ cm^{-3}\ s^{-1}} \tag{16}$$

The exponential term arises from the *Maxwellian* velocity distribution that we will encounter later in the course.

4.5 Hyperfine Lines

The hyperfine transitions in atoms owe to coupling between the nuclear spin and the magnetic field generated by an orbiting electron. The most important hyperfine line is the 21cm line of Hydrogen. The emission timescale of the 21cm hyperfine line is about 10^7yr.

4.6 Molecular Lines

In addition to energy levels of the electron orbitals of their constituent atoms, molecules have vibrational and rotational degrees of freedom that are quantized and produce line radiation. The vibrational modes of molecules like CO have wavelengths of a few microns, while rotational modes have millimeter wavelengths.

Molecular Hydrogen (H_2) is symmetrical, and its rotational modes are α^{-2} times slower. The shortest wavelength H_2 transition is at $\sim 20\mu$m, and cold (< 1000K) H_2 does not radiate efficiently.

UV photons in the *Lyman-Werner bands* at $\lambda < 2000$Å can excite H_2 into an electron level with a larger energy than two unbound H atoms. About 10% of H_2 molecules excited by these UV photons will *dissociate* into separate H atoms.

See Table 1.8 of Sparke and Gallagher

Most molecules are collisionally excited, and are seen only when the kT of the gas is larger than the energy of the upper level of the transition. Many of these rotational lines will be optically thick. CO is the most abundant molecule after H_2, and has strong lines at 1.3mm and 2.6mm from gas with densities $n(H_2) \sim 100 - 1000\mathrm{cm}^{-3}$ and temperatures $T \sim 10 - 20$K.

4.7 Continuum Emission

Continuum free-free emission, aka *bremsstrahlung*, involves the deflection of electrons off of other charged particles. The typical temperature of free-free emitting gas is $\sim 10^7 - 10^8$.

Synchrotron emission occurs when an electron is accelerated by a magnetic field, which typically produces radio emission from supernova remnants and galactic nuclei.

5 Doppler Shifts

Relative motions between an emitting source and an observer induce a *Doppler shift* in the observed radiation owing to relativistic constraints. The observed wavelength $\lambda_{\rm obs}$ of the emitted radiation is related to the emitted wavelength $\lambda_{\rm e}$ by the Doppler equation

$$1 + z \equiv \frac{\lambda_{\rm obs}}{\lambda_{\rm e}} = 1 + \frac{v}{c} \tag{17}$$

where z is called the *redshift* (and is negative in the case of a blueshift) and v is the line-of-sight velocity. Objects with a receeding (positive) velocity have their emitted radiation observed at a longer wavelength, while approaching objects (with negative velocity) will have their radiation observed with a shorter wavelength.

6 Extinction

Dust absorbs and scatters optical light, and we can describe the rate at which light is absorbed as it travels along the x direction through the differential relation

$$\frac{dF_\lambda}{dx} = -\kappa_\lambda F_\lambda \tag{18}$$

where κ_λ is the *opacity*. This relation has a simple solution

$$F_\lambda(x) = F_\lambda(x=0) \exp\left(-\int_0^x \kappa_\lambda dx'\right) \tag{19}$$

where we can define the optical depth

$$\tau = \int_0^x \kappa_\lambda dx' \tag{20}$$

In the limit of pure absorption, a system is *optically thick* when $\tau = 1$ and $F_\lambda = F_\lambda(x=0)/e$. For optical light, interstellar dust has approximately $\kappa_\lambda \propto 1/\lambda$.

6.1 Dust and Gas

In the Milky Way, dust traces cold gas reliably. Dust along the line of sight can lead to visual extinction (measured in magnitudes) as a function of the Hydrogen column density as

$$A_V \approx \frac{N_H}{1.8 \times 10^{21} \mathrm{cm}^2} \tag{21}$$