Today in Astronomy 142: observations of stars

What do we **know** about individual stars?

- Determination of stellar luminosity from measured flux and distance
  - Magnitudes
- Determination of stellar surface temperature from measurement of spectrum or color
  - Blackbody radiation
  - Bolometric correction

At right: the old open cluster M7 (NOAO).

What do we want to know about stars?

As a function of mass and age, find...

- Structure of their interiors
- Structure of their atmospheres
- Chemical composition
- Power output and spectrum
- Spectrum of oscillations
- All the ways they can form
- All the ways they can die
- The details of their lives in between
- The nature of their end states
- Their role in the dynamics and evolution in their host galaxy

For the visible stars, measure…

- Flux at all wavelengths, at high resolution (probes the atmosphere)
- Magnetic fields, rotation rate
- Oscillations in their power output (probes the interior)
- Distance from us, and position in galaxy
- Orbital parameters (for binary stars)

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(We can do what's in green, this semester)

Flux and luminosity

Primary observable quantity: **flux** (power per unit area) within some range of wavelengths. The flux at the surface of an emitting object is often called the **surface brightness.**

Stars, like most astronomical objects, emit light **isotropically** (same in all directions)

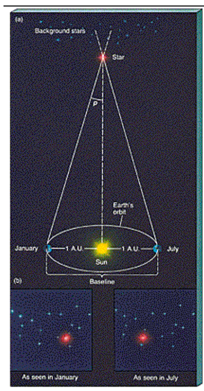
- Since the same total power L must pass through all spheres centered on a star, and is uniformly distributed on those spheres, the flux a distance r away is

$$f = L / 4\pi r^2$$

To obtain **luminosity** (total power output), one must

- add up flux measurements over all wavelengths
- measure the distance

Best distance measurement: trigonometric parallax



Trigonometric parallax

Relatively nearby stars appear to move back and forth with respect to much more distant stars as the Earth travels in its orbit.

Since the Earth's orbit is (nearly) circular, this works no matter what the direction to the star.

Since the size of the Earth's orbit is known very accurately from radar measurements, measurement of the **parallax** p determines the distance to the star.

Figure: Chaisson and McMillan, *Astronomy Today*

Trigonometric parallax (continued)

Mean distance between centers of Earth and Sun:

$$1\text{AU} = 1.496 \times 10^{13} \text{ cm}$$

Thus

$$r = 1\text{AU}/\tan p \cong 1\text{AU}/p$$

where p is measured in radians.

- Parallax is usually expressed in fractions of an arcsecond (π radians = 180 degrees = 10800 arcminutes = 648000 arcseconds); the distance to an object with a parallax of 1 arcsecond, called a **parsec**, is 3.0857×10^{18} cm= 3.2616 ly.
- Good parallax measurements: about 0.02 arcsec from the ground, about 0.002 arcsec from the *Hipparcos* satellite.

Parallax examples

What is the largest distance that can be measured by parallax with ground-based telescopes? With the Hipparcos *satellite?*

First note that we can write the distance-parallax relation as

$$r = \frac{1\ \text{AU}}{p[\text{radians}]} = \frac{1\ \text{parsec}}{p[\text{arcsec}]} \quad .$$

- So if the smallest parallax we can measure is 0.02 arcsec, the largest distance is 1/0.02 = 50 parsecs.
- Similarly, *Hipparcos* gets out to 1/0.002 = 500 parsecs.
- The ESA satellite *Gaia*, due to be launched in 2011, will measure parallax with an accuracy of 0.00002 arcsec, thus perhaps stretching out to 50 000 parsecs = 50 kpc.
  - Compare: we live 8 kpc from the center of our Galaxy.

Parallax examples

APP problem 2.27: if we lived on Mars, what would be the value of the parsec?

Mars's orbital radius is 1.524 AU, so the parsec is a factor of 1.524 larger:

$$\begin{aligned} r = 1\ \text{"parsec"} &= \frac{1.524\ \text{AU}}{1\ \text{arcsec}} \\ &= \frac{1.524\times 1.496\times 10^{13}\ \text{cm}}{1\ \text{arcsec}}\left(\frac{3600\ \text{arcsec}}{1^\circ}\right)\left(\frac{180^\circ}{\pi}\right) \\ &= 4.703\times 10^{18}\ \text{cm} = 4.971\ \text{light years.} \end{aligned}$$

The thirty nearest stars

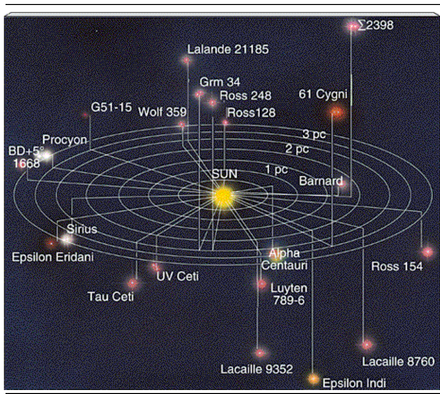


Figure: Chaisson and McMillan, *Astronomy Today*

Secret astronomer units: magnitudes

Ancient Greek system: first magnitude (and less) are the brightest stars, sixth magnitude are the faintest the eye can see. (**Magnitude ⇑, brightness ⇓.**)

The eye is approximately **logarithmic** in its response: perceived brightness is proportional to the logarithm of flux.

To match up with the Greek scale,

$$5 \text{ mag} \Leftrightarrow \text{ a factor of 100 in flux}$$

$$1 \text{ mag} \Leftrightarrow \text{ a factor of } (100)^{1/5} \cong 2.5 \text{ in flux}$$

or, for two stars with apparent magnitudes m_1 and m_2,

$$m_2 - m_1 = 2.5 \log\left(f_1/f_2\right)$$

Magnitudes (continued)

Most people find magnitudes confusing or even stupid at first, but they turn out to be very useful once one gets used to them.

- Magnitudes are dimensionless quantities: they are related to *ratios* of fluxes or distances.
- Our legacy from the Greeks: magnitudes run backwards from the intuitive sense of brightness.
  - Brighter objects have **smaller** magnitudes. Fainter objects have **larger** magnitudes.
- Fluxes from a combination of objects measured all at once add up algebraically as usual. The magnitudes of combinations of objects do not. (See example below.)

Magnitudes (continued)

The reference point of the apparent magnitude scale is a matter of definition. The practical definition of **zero apparent magnitude** is Vega (α Lyrae), which has m = 0.0 at nearly all wavelengths < 20 μm. Other definitions:

Absolute magnitude is the apparent magnitude a star would have if were placed 10 parsecs away.

Bolometric magnitude is magnitude calculated from the flux from all wavelengths, rather than from a small range of wavelengths.

In Homework #1 you'll show that the absolute and apparent bolometric magnitudes, M and m, of a star are related by:

$$M = m - 5\log\left(r/10 \text{ pc}\right) = 4.75 - 2.5\log\left(L/L_{\odot}\right)$$

Magnitude-calculation examples

The absolute bolometric magnitude of the Sun is 4.75. What is its apparent bolometric magnitude?

That is, the Sun's apparent magnitude is 4.75 when seen from 10 parsecs (subscript 2) and we see it from 1 AU (1):

$$m_1 = m_2 + 2.5\log\left(\frac{f_2}{f_1}\right) = m_2 + 2.5\log\left(\frac{L_\odot}{4\pi r_2^2}\frac{4\pi r_1^2}{L_\odot}\right)$$

$$= 4.75 + 2.5\log\left(\frac{[1\ \mathrm{AU}]^2}{[10\ \mathrm{parsecs}]^2}\right) = 4.75 + 5\log\left(\frac{1\ \mathrm{AU}}{10\ \mathrm{parsecs}}\right)$$

$$= -26.82 \quad .$$

Recall: $\log x^2 = 2\log x$.

Magnitude-calculation examples

APP problem 2.5: Two objects are observed to have fluxes f and $f + \Delta f$ ($\Delta f \ll f$). What is the difference Δm between their magnitudes?

$$\Delta m = m_1 - m_2 = 2.5\log\left(\frac{f+\Delta f}{f}\right) = 2.5\log\left(1 + \frac{\Delta f}{f}\right)$$

$$= \frac{2.5}{\ln 10}\ln\left(1+\frac{\Delta f}{f}\right) \cong 1.09\frac{\Delta f}{f} \qquad \text{to first order in } \Delta f.$$

Thus, if two objects differ in flux by 1%, they differ in magnitude by 0.011.

- It is very hard to measure fluxes from astronomical objects more accurately than 1%, so typically magnitudes are not known more accurately than ±0.01 or so.

Magnitude-calculation examples

Two stars, with apparent magnitudes 3 and 4, are so close together that they appear through our telescope as a single star. What is the apparent magnitude of the combination?

Call the stars A and B, and the combination C:

$$m_B - m_A = 1 = 2.5\log(f_A/f_B) \quad \Rightarrow \quad \frac{f_A}{f_B} = 10^{\frac{1}{2.5}} = 10^{0.4} = 2.512$$

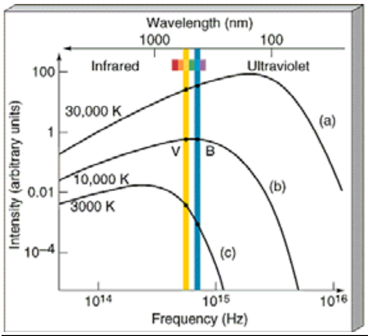
Add 1 to both sides: $\frac{f_A}{f_B} + 1 = \frac{f_A + f_B}{f_B} = \frac{f_C}{f_B} = 3.512$

So

$$m_B - m_C = 2.5\log(f_C/f_B)$$

$$m_C = m_B - 2.5\log(f_C/f_B) = 4 - 2.5\log(3.512) = 2.64 \quad .$$

Color and temperature



Note that a given ratio of flux within the *B* and *V* wavelength ranges (see below) is characteristic of a certain temperature of **blackbody**, and that continuous stellar spectra are approximately blackbodies.

Figure: Chaisson and McMillan, *Astronomy Today*

High opacity and the appearance of stars: blackbody emission

Because stars are **opaque** at essentially all wavelengths of light (as we'll prove in a week or so), they emit light much like ideal **blackbodies** do.

Blackbody radiation from a perfect absorber/emitter is described by the Planck function:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}$$

Dimensions: power per unit area, bandwidth and solid angle.

For a small **bandwidth** (wavelength interval) $\Delta\lambda$ (<< λ) and solid angle $\Delta\Omega$ (<<4π), the flux f emitted by a blackbody is

$$f = B_\lambda(T)\Delta\lambda\Delta\Omega \quad .$$

Blackbody emission (continued)

The total flux emitted into all directions at all wavelengths by a blackbody is

$$f = \iint d\lambda d\Omega \cos\theta B_\lambda(T) = 2\pi\int_0^\infty d\lambda \int_0^\pi d\theta \cos\theta \sin\theta B_\lambda(T)$$

$$= \sigma T^4 \quad , \quad \text{where}$$

$$\sigma = 5.67\times10^{-5}\ \text{erg cm}^{-2}\ \text{s}^{-1}\ \text{K}^{-4}$$

is the Stefan-Boltzmann constant. **(See PHY 227.)**

Luminosity of a spherical blackbody:

$$L = 4\pi R^2\sigma T^4 \quad .$$

The Sun's luminosity indicates a $T_{\odot e} = 5800$ K blackbody.

Blackbody emission (continued)

Wavelength of the Planck function's maximum value changes with temperature according to

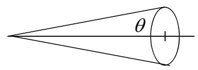
$$\lambda_{max} T = 0.29 \text{ cm K} \quad .$$

(see this week's workshop problems).

Reminders about solid angle:

- Solid angle for cone with small apex angle θ is

$$\Omega = \pi\theta^2 \quad .$$



- Differential element of solid angle in spherical coordinates:

$$d\Omega = \sin\theta d\theta d\phi \quad .$$

Blackbody emission (continued)

Solid angle, still:

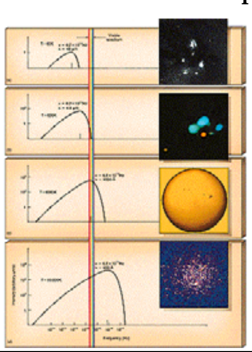
- In general, in spherical coordinates:

$$\Omega = \int_0^{\phi_0}\int_0^{\theta_0} \sin\theta d\theta d\phi$$

$$\int_0^{2\pi}\int_0^{\pi} \sin\theta d\theta d\phi = 4\pi \quad \text{(sphere)}$$

$$\int_0^{\pi}\int_0^{\pi} \sin\theta d\theta d\phi = 2\pi \quad \text{(hemisphere)}$$

Color and temperature (continued)



ρ Ophiuchi. a molecular cloud at T = 60 K.

A young stellar object. The star's surroundings have T = 600 K.

The Sun's surface, T = 6000 K.

Evolved stars in ω Centauri, at T = 60,000 K.

Figure: Chaisson and McMillan, *Astronomy Today*.

Color and effective temperature

Color index is the difference between the magnitudes of an object at different wavelengths, or 2.5 times the logarithm of the ratio of fluxes of the object in the two bands.

- An oft-used index is the color between the visible B and V bands, at wavelengths 430 and 540 nm (blue and green):

$$B - V = m_B - m_V = M_B - M_V$$
$$= 2.5 \log\left(f(V)/f(B)\right)$$

- Note that if $B - V$ is large and positive, it means the object's B magnitude is much larger than its V magnitude, so it's much brighter at V than B.
  (Large $B - V$ means a redder color, small $B - V$ means a bluer color.)

Color and effective temperature (continued)

In the absence of extinction, color is an index of the effective temperature T_e of stars.

- …meaning the surface temperature of stars: T_e is the temperature of the blackbody of the same size as a star, that gives the same luminosity:

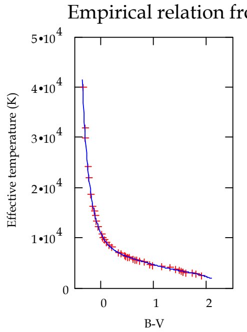
$$T_e = \left(\frac{L}{4\pi R^2 \sigma}\right)^{\frac{1}{4}}$$

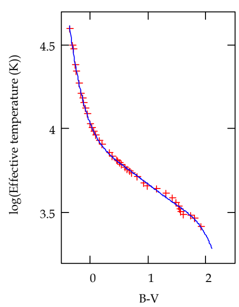
- For T_e < 20000 K, taking stellar spectra as perfect blackbodies, and taking $U = B = V = R = 0$ at T_e =10000 K,

$$B - V \cong -0.71 + 7090\ \mathrm{K}/T_e \qquad \text{(empirically)}$$

B-V and effective temperature

Empirical relation from H.L. Johnson (1966)





Bolometric correction

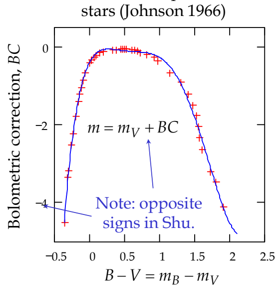
Usually stars are observed a finite bandwidth about some specific center frequency, and one observation thus determines the flux and apparent magnitude within that band:

Band	Wavelength λ (nm)	Bandwidth $\Delta\lambda$ (nm)
U	360	70
B	430	100
V	540	90
R	700	220

To obtain bolometric magnitudes, one must either observe at lots of wavelengths or make a **bolometric correction** for flux at wavelengths not observed.

Bolometric correction (continued)

Bolometric correction for main sequence stars (Johnson 1966)



Shape of spectrum, and this correction factor, can be determined if one knows the color of the star (difference between apparent magnitudes at two wavelengths).

A scaling factor for flux is the same as an offset in magnitude. This offset is called the bolometric correction, *BC*, and is determined **empirically** from observed stellar spectra.

Color and bolometric correction example

Two stars are observed to have the same apparent magnitude, 2, in the V band. One of them has color index B-V = 0, and the other has B-V = 1. What are their apparent bolometric magnitudes?

From the graph, *BC* = -0.4 and –0.38 in these two cases, so their bolometric magnitudes are practically the same, too, 1.6 and 1.62.

- That these magnitudes are both less than the *V* magnitude is a sign that these stars produce substantial power at wavelengths far outside the *V* band. The bluer star (with *B-V* = 0) turns out to be brightest at ultraviolet wavelengths; the other one is brightest at red and infrared wavelengths.