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Today

- Astronomical Observations

Astronomical Observations

Astronomy has historically been (and mostly remains) a field where all our information about celestial and phenomina must be derived from the EM radiation received from it, or by the absorption of light from background sources it causes. There are of course some notably exceptions including neutrino and gravitational wave observations.

We will often characterize the radiation from a source by its spectral energy distribution (SED). This can be written as:

$$f_\lambda d\lambda$$

which is proportional to the total energy emitted in photons in the range $[\lambda, \lambda + d\lambda]$.

The two primary methods of gaining information about the SED are imaging and spectroscopy. In imaging, the fundamental quantity which is measured is the surface brightness distribution. The surface brightness can be denoted as

$$I$$

which is the photon energy received per unit area, per unit time, per unit solid angle. Since "cgs" units are common in astrophysics, units for the surface brightness are

$$\frac{\text{erg}}{\text{s} \cdot \text{cm}^2 \cdot \text{sr}} \qquad 1 \text{ erg} = 10^{-7} \text{ J}$$

Integrating the surface brightness over an entire (assuming only one object is contributing) gives the flux

$$f$$

with units $\dfrac{\text{erg}}{\text{s} \cdot \text{cm}^2}$

Note that both flux and the image surface brightness distribution are both observer dependent quantities. By integrating the flux over a sphere centered on the object with a radius, r, equal to the distance between the observer and the object gives the Bolometric luminosity:

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

Luminosity has units of erg/s. In astrophysics it is common to use solar luminosities as a unit, $1\ L_\odot = 3.846 \times 10^{33}\ \frac{erg}{s}$.

The image size of an object depends on whether it is resolved (extended object) or unresolved (point source). For point sources, the surface brightness distribution depends on the point spread function (PSF). The exact nature of the PSF depends on the telescope optics, instrumentation, and the observing conditions (more on this later).

For extended objects, size is often defined using a characteristic isophotal contour, a line of constant surface brightness. A few example of sizes include:

- The Holmberg radius: The semi-major axis of an isophote of 26.5 mag/arcsec^2 in the B band.
- The core radius: The size of the isophote where the where the surface brightness is half the "central value"
- The half-light radius: The characteristic radius which encloses half the total flux. This is also called the effective radius.

Generally, it is not possible to measure bolometric quantities. In astronomical imaging, measurements are made in fixed "bands". The observed flux in a band from an object is:

$$f_x = \int f_\lambda F_x(\lambda) R(\lambda) T(\lambda) \, d\lambda$$

- $f_\lambda d\lambda$ is the SED
- $F_x(\lambda)$ is the transmission function for the filter defining the x band.
- $R(\lambda)$ is the photon detection efficiency of the telescope + instrument (e.g. CCD).
- $T(\lambda)$ is the atmospheric transmission function

Most quoted observations correct for $R(\lambda)$ and $T(\lambda)$. So, we will usually assume f_x has been corrected in this way.

There are multiple standard filter sets which comprise "photometric systems". These include

- UBVRI, the Johnson + Kron Cousins system. This system has been extended to longer wavelengths.
- SDSS ugriz, the system used on the SDSS.

For historic reasons, flux is usually quoted in "magnitudes". The apparant magnitude in the x-band is defined as:

$$m_x = -2.5 \log_{10}\left(\frac{f_x}{f_{x,0}}\right)$$

note

$\log \equiv \log_{10}$

$\ln \equiv \log_e$

The flux zero-point, $f_{x,0}$, is traditionally defined to be the flux in the x-band of Vega. A more modern system is the "A-B Magnitude" system where:

$$f_{x,0} = 3.6308 \times 10^{-20} \text{ erg} \cdot s^{-1} \cdot cm^{-2}\, Hz^{-1} \int F_x\left(\frac{c}{\nu}\right) d\nu$$

It is very important to know which system was used when comparing magnitudes!

Luminosities are often quoted in absolute magnitudes:

$$M_x = -2.5 \log(L_x) + C_x$$

Here C_x is the zero-point. It is often convenient to give luminosities in $L_\odot$, then,

$$M_x = -2.5 \log\left(\frac{L_x}{L_{x,\odot}}\right) + M_{x,\odot}$$

Here, $M_{x,\odot}$ is the absolute magnitude of the Sun in the x-band.

The absolute magnitude and apparent magnitude are related via the <u>distance modulus</u>,

$$m_x - M_x = 5 \log\left(\frac{d}{d_0}\right)$$

where d is the distance to the object, and d_0 is usually chosen to be $d_0 = 10$ pc.

$\Rightarrow$ The absolute magnitude is the apparent magnitude an object would have if it were 10 pc away.

Surface brightness is often quoted in units of mag/arcsec^2.

$$\mu_x = -2.5 \log\left(\frac{I_x}{L_\odot \, pc^{-2}}\right) + 21.572 + M_{x\odot}$$

Things to remember about magnitudes:

1. if $m_1 > m_2$, then $f_1 < f_2$
2. magnitudes are not additive (flux is)
3. $\Delta m = 1$ corresponds to a flux ratio of 2.5

Finally, the term "color" is the difference in magnitudes between two bands.

The color index:

$$(x-y) \equiv m_x - m_y = M_x - M_y$$

For example the B-V color is

$$(B-V) \equiv m_B - m_V = M_B - M_V$$

This quantity is related to the slope in the SED between the two bands.

Spectroscopy is a more direct method of measuring the SED. A spectra is a direct measure of

$$\underbrace{f_\lambda \, d\lambda}_{\substack{\text{flux received in} \\ \text{a range } [\lambda, \lambda + d\lambda]}} \quad \text{or} \quad \underbrace{f_\nu \, d\nu}_{\substack{\text{flux received in} \\ \text{a range } [\nu, \nu + d\nu]}}$$

Recall that for EM radiation $\lambda = \frac{c}{\nu}$. The frequency and wavelength SEDs can then be related

$$f_\lambda = \frac{\nu^2 f_\nu}{c} \quad \text{and} \quad f_\nu = \frac{\lambda^2 f_\lambda}{c}$$

There are three major methods of obtaing spectra for astrophysical objects:

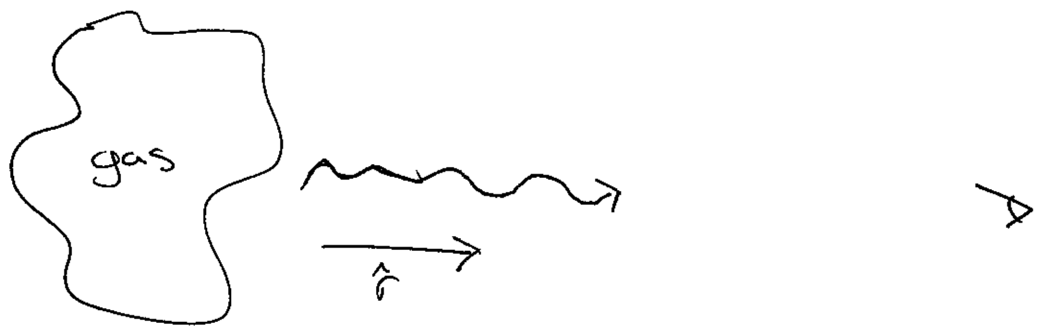
1. Slit spectroscopy
2. fiber spectroscopy
3. Integral Field Unit (IFU) spectroscopy

Slit spectroscopy places a thin slit directly on the focal plane of the telescope. Each point along the slit passes through a dispersive element to produce a 2-D image. One dimension is the spatial dimension corresponding to the slit orientation. The other is the λ or frequency dimension.

Fiber fed spectrographs place individual optical fibers on the focal plane. Any spatial dimension is then lost in the resulting 1-D spectra.

IFU spectrographs place bundles of fibers on objects. Each fiber produces a spectra.

The detailed SEDs obtained from spectrosopy provide a wealth of information. Critical to astrophysics is information about the thermal or dynamical state of a system. For example, consider a cloud of gas in space



Photons produced by a quantum transition between two states, E_1 and E_2, are emitted with a frequency ν_{12} $(E_2 > E_1)$:

$$\nu_{12} = \frac{(E_2 - E_1)}{h} \qquad h \equiv \text{plank's const.}$$

If the atoms in the gas are moving with some velocity, $\vec{v}$, relative to the observer, then the observed frequency will be shifted:

$$\nu_{obs} = \left(1 - \frac{\vec{v} \cdot \hat{r}}{c}\right)\nu_{12}$$

Note that if the source is moving away from the observer, then $\nu_{obs} < \nu_{12}$, i.e. the photons will be redshifted. If the source is moving towards the observer, then the photons will be blueshifted, $\nu_{obs} > \nu_{12}$.

In astronomy, redshift "z" is used to characterize this doppler shift.

$$z \equiv \frac{\nu_{12}}{\nu_{obs}} - 1$$

Similarly, in terms of λ,

$$z \equiv \frac{\lambda_{obs}}{\lambda_{12}} - 1$$

Redshift is related to the velocity (in the non-relativistic) limit as:

$$z = \frac{\vec{v} \cdot \hat{r}}{c}$$

For example, if the atoms in this gas cloud have random motions along the line-of-sight (LOS) drawn from some velocity distribution $f(v)dv$, the observed frequency distribution is given by:

$$F(\nu_{obs})\,d\nu_{obs} = f(v)\,(c/\nu_{12})\,d\nu_{obs}$$

v is related to the observed frequency via the doppler shift equation,

$$v = c\left(1 - \nu_{obs}/\nu_{12}\right)$$

$$\Rightarrow \frac{dv}{d\nu_{obs}} = \frac{-c}{\nu_{12}}$$

From the observed frequency distribution one can infer $f(v)$. If $f(v)$ is caused by thermal effects, then one can infer the temperature of the gas.

If instead of a thermal gas we are observing a cluster of stars, we can infer the LOS velocity distribution.

Given some spectral line in spectrum of a star with a profile given by $S(\nu)$

$$F(\nu_{obs}) = \int S(\nu) f(v)\,dv$$

remember that $\nu_{obs} = \left(1 - \frac{v}{c}\right)\nu$

$$\Rightarrow \nu = \nu_{obs}(1 + v/c)$$

Distance Measures

- Parallax is the apparent change in position of an object wrt a distant background when viewing the object from two different positions

If instead of a thermal gas we are observing a cluster of stars, we can infer the LOS velocity distribution. Given some spectral line in the spectrum of a star with a line profile given by $S(\nu)$

$$F(\nu_{obs}) = \int S(\nu) f(v)\, dv$$

note that $\nu = \nu_{obs}\left(1 + \frac{v}{c}\right)$