Chapter 4

Introduction to stellar photometry

Goal-of-the-Day
Understand the concept of stellar photometry and how it can be measured from astronomical observations.

4.1 Essential preparation

Exercise 4.1
(a) Have a look at www.astro.keele.ac.uk/astrolab/results/week03/week03.pdf.

4.2 Fluxes and magnitudes

Photometry is a technique in astronomy concerned with measuring the brightness of an astronomical object’s electromagnetic radiation. This brightness of a star is given by the flux $F$: the photon energy which passes through a unit of area within a unit of time. The flux density, $F_\nu$ or $F_\lambda$, is the flux per unit of frequency or per unit of wavelength, respectively: these are related to each other by:

$$|F_\nu d\nu| = |F_\lambda d\lambda|$$  \hspace{1cm} (4.1)

Whilst the total light output from a star — the bolometric luminosity — is linked to the flux, measurements of a star’s brightness are usually obtained within a limited frequency or wavelength range (the photometric band) and are therefore more directly linked to the flux density. Because the measured flux densities of stars are often weak, especially at infrared and radio wavelengths where the photons are not very energetic, the flux density is sometimes expressed in Jansky, where $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$.

However, it is still very common to express the brightness of a star by the ancient classification of magnitude. Around 120 BC, the Greek astronomer Hipparcos ordered stars in six classes, depending on the moment at which these stars became first visible during evening twilight: the brightest stars were of the first class, and the faintest stars were of the sixth class. It was not before 1856 that Norman Pogson calibrated the magnitude classification in terms of flux (density). He realised that the magnitude scale reflects the logarithmic response of the receptors in the retina of the human eye (which is why the human eye can see at such a vast dynamical range), and that a difference of five of the
original magnitudes corresponds to a factor $\sim 100$ in flux(density):

$$m = -2.5 \log \frac{F}{F_0}$$

(4.2)

Note that fainter stars have larger magnitudes $m$. The zero point of the magnitude scale, $F_0$, is chosen such that the star Vega ($\alpha$ Lyrae) is of magnitude zero. This is because Vega was one of the brightest stars in the original magnitude classification, and because it appears white: our eye senses that the light from Vega is equally strong at all colours. A major problem arose when it was discovered that Vega emits more radiation at infrared wavelengths than a white star would emit, due to the star being surrounded by warm dust. Hence the infrared magnitudes are calibrated by means of an extrapolation to longer wavelengths of the visible spectrum of Vega, using a Planck curve for an ideal (blackbody) emitter at $T = 10,000$ K.

**Exercise 4.2**

(a) The zero point for magnitude $N$ at wavelength $\lambda = 10 \, \mu m$ is $F_{\nu,0} = 34$ Jy. What is the flux density of a star of magnitude $N = 7.5$?

(b) Show that equation 4.1 also implies $\nu F_{\nu} = \lambda F_{\lambda}$ (remember that $\lambda \nu = c$).

(c) A star has a flux density $F_{\lambda} = 1 \times 10^{-18}$ W m$^{-2}$ $\mu m^{-1}$ at $\lambda = 10 \, \mu m$. Compute its flux density in Jy.

### 4.3 Aperture photometry

*Aperture photometry* entails measuring the brightness of a star by means of a (software) aperture to collect the counts from the star. This is done by summing the pixel values within a circular region centred on the star, the *aperture*. This region includes light from the star as well as light from the sky. To be able to correct for the latter, the sky brightness is measured within an annulus surrounding the central aperture. The star counts are then converted to magnitudes using equation 4.2. The Iraf *digiphot* package contains the *apphot* package with the Iraf tool *qphot* to perform aperture photometry of stars.

The *qphot* tool prompts for the image name, for the width of the centering box that it uses to better centre the aperture on the star, for the inner radius and width of the annulus that it uses to estimate the sky brightness, and for a list of aperture radii. You
must first update the gain parameter \( e_{\text{padu}} \) (here: \( 5 \text{ e}^{-1} \text{ ADU}^{-1} \)), in order to obtain correct error estimates.

A simple recipe to perform aperture photometry using \texttt{qphot} on a few stars in the image is the following: (i) point the mouse cursor at the centre of a star, (ii) press the \texttt{spacebar}, (iii) move on to another star, et cetera. Some output is displayed in the IRAF window: the centre of the star, the sky level (counts per pixel) and the magnitude of the star. The magnitude is calculated using an arbitrary value for the zero point, and such magnitudes are referred to as \textit{instrumental magnitudes}. When satisfied with the measurements, type \texttt{q} in the image display, and then type \texttt{w} in the IRAF window. This stores all information about the parameters and measurements in a text file which is a concatenation of the image name, the extension \texttt{.mag}, and a number which increments each time you run \texttt{qphot} on that image again. It is often convenient to extract a selection of output variables from this file, using the IRAF task \texttt{txdump}.

\textbf{Exercise 4.3}

(a) Load the photometry packages by typing \texttt{digiphot} and then \texttt{apphot};
(b) Change the gain parameter in the task \texttt{qphot}; the IRAF command \texttt{epar qphot} should be used for this;
(c) Using \texttt{imexamine} with the radial profile option (\texttt{r}), choose a inner radius and width of the sky annulus appropriate to perform photometry with a 6-pixel aperture radius;
(d) Measure the instrumental magnitude of a bright star, using the choices made in (c);
(e) Extract the output values for the following: the sky level per pixel \texttt{msky}, the sum of the counts within the aperture \texttt{sum}, the area of the aperture \texttt{area}, the magnitude \texttt{mag} and the error in the magnitude \texttt{merr};
(f) Compute the number of counts due to the star, \( N_\star \), from \texttt{msky}, \texttt{sum} and \texttt{area};
(g) Show that \( \texttt{merr} \simeq -2.5 \log \frac{N_\star - \sigma_\star}{N_\star} \), where \( \sigma_\star \) is the standard deviation in counts;
(Hint: \texttt{merr} is the magnitude difference between stars with “fluxes” given by \( N_\star - \sigma_\star \) and \( N_\star \) counts.)
(h) Hence, estimate the \textit{signal-to-noise ratio} on this measurement, \( N_\star / \sigma_\star \).

If the noise in the measurement of a star’s brightness is dominated by the noise in the sky level, which may happen in the case of faint stars and/or a bright sky, then the measurement is said to be \textit{background-limited}. In the opposite case of a bright star against a faint sky, the noise is dominated by the Poisson-noise in the counts from the star.

\textbf{Exercise 4.3}

(i) Show that in the background-limited case, the signal-to-noise ratio \( N_\star / \sigma_\star \propto N_\star \);  
(j) Show that for bright stars against faint sky, the signal-to-noise ratio \( N_\star / \sigma_\star \propto \sqrt{N_\star} \).

\subsection{Point Spread Function}

Stars on the image appear as round(ish) disks of light. The radial profiles we have looked at show how stellar profiles are centrally concentrated and star counts fall off with increasing distance to the star’s centre: the \textit{Point Spread Function (PSF)}. The shape of the PSF is the result of a convolution of the true apparent diameter of the star — which is usually (much) smaller than the pixel size\(^1\) — the seeing, the diffraction pattern of the

\(^1\)The apparently largest star in the night sky, the nearby red giant R Doradus measures \( \theta \sim 0.06^\circ \).
optics, and the sampling by the CCD pixels. A more centrally concentrated PSF provides a higher sensitivity to detect faint stars and a greater ease to resolve closely-spaced stars. Often the shape of the PSF is characterised by its Full Width at Half Maximum (FWHM).

If the shape of the PSF is determined by the telescope optics, then the images are said to be diffraction-limited: the stellar image appears as a central maximum — the Airy disk — surrounded by concentric minima and maxima (diffraction rings). The size of the central disk depends on the wavelength of the light, \( \lambda \), and on the diameter of the entrance pupil of the telescope, \( D \). Two equally bright stars are resolved if they are separated by at least the size of the Airy disk (Dawes’ criterion), which is given by the distance from the centre to the first minimum (diffraction limit, in radians):

\[
\theta = 1.22 \times \frac{\lambda}{D} \tag{4.3}
\]

However, the shape of the PSF is often dominated by the seeing (seeing-limited), and a measure for the seeing is then given by the FWHM of the PSF.

**Exercise 4.4**

(a) For a seeing of FWHM= 1″ at a wavelength of \( \lambda = 550 \text{ nm} \) (yellow light), what is the telescope diameter, \( D \), for which the diffraction limit equals the seeing?

(b) In such seeing conditions and for the same wavelength, why is it still useful to have a telescope of \( D = 8 \text{ m} \)?

When performing aperture photometry, if the aperture does not embrace all of the PSF, the brightness of a star will be under-estimated. It is therefore necessary to measure how much of the stellar light falls outside of the aperture, the aperture correction. This can be derived from measurements of isolated bright stars with several apertures. If the brightness of these bright stars is known in real physical units (standard stars), then the brightness of the other stars can be inferred and absolute photometry is obtained.

The core or central part of the PSF often resembles a two-dimensional Gaussian, in which case the FWHM can be readily related to the \( \sigma \) of a Gaussian distribution. In practice, however, the PSF has a different shape in particular in the wings.

**Exercise 4.4**

(c) Estimate the FWHM of the PSF (Hint: use imexamine to look at radial profiles);

(d) Using aperture photometry measurements, estimate what fraction of the stellar light falls within the FWHM;

(e) Show that the FWHM and the \( \sigma \) of a Gaussian-shaped PSF are related by:

\[
\text{FWHM} \approx 2.35 \sigma \tag{4.4}
\]

\(^2\)The position of the first minimum for the diffraction pattern of a circular aperture can be derived in an analogous way as the first minimum for the Fraunhofer diffraction pattern.