Observational Astrophysics
8. Magnitude Systems

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1 Introduction

Imaging the sky, or more specifically a given source (or sources), is perhaps the most basic thing an astronomer can do. Imaging is what you do when trying to answer the question of how does your source look like.

If you have a slightly different question, for example how bright is the source, then you need to do a bit more than just imaging. You will need to measure the flux, imaging the source in a given known passband, and calibrating the instrumental measurement into a physical scale. Here is where we enter into the realm of photometry. If you want to ask where the source is, and maybe also measure its movement, then we enter into astrometry. For that, you will need to make other type of measurements from the data and take images of the source more than once (we will come back to astrometry later).

For imaging, you will have a camera and a detector attached to your telescope. At zero order, you could do that with your eye and a piece of paper for drawing. Of course, that's not what most professional astronomers do anymore[1]. We will cover detectors at a later opportunity. Photometry itself is the topic of the next set of notes. Here, let's look first at what a camera does, at different magnitude systems, and at different sets of photometric filters.

We have defined magnitudes before (see note number 01. Astronomical measurements), so I will not repeat everything from there again, just the definition of magnitude:

$$m = -2.5\ \log_{10} \int_0^\infty F_\nu W(\nu)\, \mathrm{d}\nu\ + \text{constant}, \tag{1}$$

where F_ν is the flux (flux density) of the object and $W(\nu)$ specifies the spectral interval of the band and the weights, i.e. how much of the flux at each infinitesimal $\mathrm{d}\nu$ is actually recorded by your equipment (this would essentially be the response function of your photometric filter + detector + telescope).

[1] However, many times amateur astronomers still monitor stars and evaluate magnitudes by eye, and those measuremets can be useful for professional astronomers.

To define a magnitude system, one needs to define the zero point. There are two widely used options:

Vega system: In the Vega system, the star Vega (Alpha Lyrae, of spectral type A0V) is the main reference. This is a bright, unreddened star, the brightest early-type star in the Northern hemisphere. The use of early-type stars as standard comes from the work of Johnson & Morgan (1953)[2], and the definition involved a few more stars than just Vega. The idea was to assume these stars had on average V magnitude = 0 and colors = 0. Vega actually ends up having $V = 0.03$ mag.

Anyway, to put the magnitude of a source in this system, one would just need to observe a standard star (Vega or one of the others). Well, it is actually more complicated than that, as we will see in more detail later. If you want to calibrate your measurements against Vega, you would like to observe it right before or right after your source, to have similar airmass and sky conditions (to accurately take into account the atmospheric effects). Most of the time, Vega will not be available for that. Therefore, photometric systems also need the definition of a number of secondary photometric standards spread over the sky (e.g. Landolt 1983)[3].

In any case, if we are doing a relative calibration with respect to a comparison star, we did not really fix the zero point (i.e., the constant in Eq. 1; doing relative magnitudes we just eliminate the constant from the game). For fixing the zero point, one actually needs to observe Vega (or the other standards) and do a direct comparison against a reference source, i.e. some kind of laboratory reference lamp or black body[4] that will give you the correspondent physical units. One problem, realized after Vega was already extensively used as a reference, is that it is a pole-on fast rotator (Gulliver et al. 1994)[5] with variability between 2-6%, depending on the bandpass (Engelke et al. 2010)[6]. For very accurate work, caution is then needed when using a system based on Vega.

AB system: AB stands for "absolute", in the sense that it does not need an object like Vega as a reference for relative measurements. In this system, it is assumed that the constant is the same for all frequencies and the monochromatic magnitude can be written as:

$$m(AB) = -2.5 \ \log_{10} F_\nu - 48.6, \tag{2}$$

in units of erg s^{-1} cm^{-2} Hz^{-1} (or with a constant $= -56.10$ if the units are W m^{-2} Hz^{-1}). In this definition, a source with a flat spectrum of constant flux per unit frequency has color zero. The zero point has been defined to coincide with the zero point Vega V-band magnitude, $\mathrm{m(AB)}_{5500\text{Å}} = V$

There is an alternative definition, where it would be a source with a constant flux density per unit wavelength that has the same magnitude in all bandpasses. This is sometimes called the **STMAG system**, because it is the definition used for the Hubble Space Telescope photometry:

[2]https://ui.adsabs.harvard.edu/abs/1953ApJ...117..313J/abstract

[3]https://ui.adsabs.harvard.edu/abs/1983AJ.....88..439L/abstract

[4]If interested, you can read Megessier (1995) to know more about the calibration of Vega on the visible and near-infrared (see https://ui.adsabs.harvard.edu/abs/1995A%26A...296..771M/abstract).

[5]https://ui.adsabs.harvard.edu/abs/1994ApJ...429L..81G/abstract

[6]https://ui.adsabs.harvard.edu/abs/2010AJ....140.1919E/abstract

$$m(AB) = -2.5 \ \log_{10} F_\lambda - 21.1, \tag{3}$$

The definition of the AB system is based on the work by Oke (1974)[7].

2 Read these texts

For a basic introduction on camera systems (and why not, we can look also at coronographs now) see Sections 2.1 and 2.2 of McLean et al. (2013)[8]. And to complement, three pages with a few words on cameras and photometers (Sections 2.1.1 and 2.1.2) from the book "The design and construction of large optical telescopes" (Bely 2003)[9].

For a discussion on the photometric systems that have been around for a long time (e.g., Johnson UBV, Strömgren $uvby$) see Chapter 16 of Sterken & Manfroid (1992)[10].

3 Summary of concepts

- For the simplest type of imaging, one would put the detector directly at the focal plane of the telescope. This avoids additional optical elements and maximizes throughput. In this case, filters will be located in the converging beam from the telescope. However, consider that each filter might introduce a different change in optical path. This means each filter might change the place where the beam converges. In this case, one might need to refocus the telescope each time the filter is changed.

- An alternative is to use a collimator lens after the focal plane, and position the filters in the parallel (collimated) beam. A second lens (or mirror) can then re-image the beam onto the detector.

- The visual photometric system is based on observation made by eye. There is of course a limit of accuracy possible with eye observations and a personal factor is introduced.

- Photographic plates were the first detectors used (other than the eye). Probably the first to photograph a star was John Adams Whipple, American inventor, working together with the American astronomer William Cranch Bond[11] at the Harvard College Observatory[12]. George Phillips Bond[13], son of W. C. Bond, is also regarded as one of the pioneers in this area[14].

[7] https://ui.adsabs.harvard.edu/abs/1974ApJS...27...21O/abstract

[8] https://link.springer.com/referenceworkentry/10.1007%2F978-94-007-5621-2_12

[9] https://link.springer.com/book/10.1007%2Fb97612

[10] https://link.springer.com/book/10.1007/978-94-011-2476-8

[11] https://link.springer.com/referenceworkentry/10.1007/978-1-4419-9917-7_180

[12] See Hoffleit (1950) in https://babel.hathitrust.org/cgi/pt?id=mdp.39015011394940&view=1up&seq=11 for a historical account.

[13] https://link.springer.com/referenceworkentry/10.1007/978-1-4419-9917-7_179

[14] See Bond (1858) for an early report of his experiments, https://ui.adsabs.harvard.edu/abs/1858AN.....49...81B/abstract.

- Several photometric systems were defined using photographic plates. The plates offered the possibility of longer integration and thus the detection of fainter objects. Also, they provided permanent records of the observations. However, their analysis was difficult, they suffered with non-linearity in the response, and had low quantum efficiency (the ratio of detected photons over incident photons). The first attempts to define two-color photometric systems can be traced back at least to the work of Karl Schwarzschild[15] (Schwarzschild 1912)[16], John A. Parkhurst[17] (Parkhurst 1912)[18], and Edward S. King[19] (King & Pickering 1917)[20].

- Photoelectric stellar photometry appeared with the introduction of the photocells and then photomultipliers. A photocell is a resistor that changes resistance depending on the amount of light incident on it. Photomultipliers (electron multiplier phototubes) detect photons through the photoelectric effect. They are still used for a few applications, like in Cherenkov radiation detectors. See the book Astrophysical Techniques (Kitchin 2020) for more details on these types of detectors.

- In 1892, the Irish astronomer William Monck[21] became the first person to make astronomical measurements with a photovoltaic cell. These cells were produced by the Irish mathematician and physicists George Minchin Minchin[22], see Monck (1892)[23] and Minchin (1895)[24]. After that, it seems only in 1907 photoelectric astronomical observations were attempted again, by American astronomer Joel Stebbins[25]. Joel Stebbins and the German astronomer Paul Guthnick[26] pioneered the use of photoelectric methods for photometry (Stebbins 1910; Guthnick 1913)[27].

- Although we are not discussing detectors here, let me add for completeness. Charge-coupled devices (CCDs) were invented in 1969 by Willard Boyle, Canadian physicists, and George Smith, American physicist, originally for use as computer memory[28]. It seems the first astronomical image using a CCD was of the planet Uranus, taken by scientists from the Jet Propulsion Laboratory (Janesick & Blouke 1987)[29].

- Filters are used to select specific regions of the electromagnetic spectrum for observation. They are described by their spectral transmission and reflection curves. The normalized

[15] German physicist and astronomer, well-known for his contribution in many areas, see https://mathshistory.st-andrews.ac.uk/Biographies/Schwarzschild/.

[16] See https://www.bibliotekacyfrowa.pl/dlibra/publication/105138/edition/100212/content for a scan of the original in German.

[17] https://www.encyclopedia.com/science/dictionaries-thesauruses-pictures-and-press-releases/parkhurst-john-adelbert

[18] https://ui.adsabs.harvard.edu/abs/1912ApJ....36..169P/abstract

[19] American astronomer, see http://articles.adsabs.harvard.edu/pdf/1932MMAAR..30...10.

[20] https://ui.adsabs.harvard.edu/abs/1917AnHar..80...91K/abstract

[21] https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_971

[22] https://academic.oup.com/plms/article-abstract/s2-13/1/1/1612338

[23] https://books.google.com.br/books?id=bYzpAAAAIAAJ&ots=SSbYedyqR9&dq="astronomy+and+astrophysics"+1892&pg=PA843

[24] https://royalsocietypublishing.org/doi/10.1098/rspl.1895.0019

[25] https://link.springer.com/referenceworkentry/10.1007/978-1-4419-9917-7_1313

[26] https://link.springer.com/referenceworkentry/10.1007/978-1-4419-9917-7_560

[27] https://ui.adsabs.harvard.edu/abs/1910ApJ....32..185S/abstract and https://ui.adsabs.harvard.edu/abs/1913AN....196..357G/abstract

[28] W. Boyle and G. Smith received the Nobel prize in physics of 2009 for the invention of CCDs, see https://www.nobelprize.org/prizes/physics/2009/summary/.

[29] https://webhome.phy.duke.edu/~kolena/sky_on_a_chip.pdf

photometric response of some broad- and intermediate-band filters are compared to the eye response in Fig. 1.

- The passband where a filter transmits is usually characterized by its central wavelength and a band-width that corresponds to about 50% of the transmission.
- Colors are magnitude differences between two different bandpasses; e.g. given the magnitudes B and V in the Johnson system, one can define the color $(B - V)$.
- Broad-band filters are usually considered those with a band-width between 30 to 100 nm (but definitions vary). Many of those were defined before a good astrophysical understanding of different sources existed.
- Intermediate-band filters are usually those with a band-width between 9 to 30 nm. Mostly, such filter systems have been designed to sample carefully selected regions of the stellar spectrum, to obtain relevant physical information.
- Narrow-band filters, with band-width smaller than $\sim$ 9nm, are designed to cover some selected spectral feature, like the Hα line.
- Interference filters are something different. They are systems where light suffers multiple reflections, to change the phase of the wavefront and create constructive or destructive interference. The principle can be used for the selection of a narrow wavelength range.
- A different concept of filter is that of rejection or cutoff filters, which are used to remove unwanted wavelength ranges that were maybe leaked by other filters.
- Neutral density filters are not exactly used for photometric measurements by themselves. Such filters have the property to attenuate light over a broad wavelength range. They are needed when observing very bright objects.

4 Further reading

To see details of about 200 different photometric systems, have a lok at the Asiago Database on Photometric Systems[30] presented in Moro & Munari (2000)[31].

An old review about the attempts to establish an absolute photometric scale in the times of photoelectric measurements can be found in Oke (1965)[32]. This review is also interest for the outline of the AB magnitude system. A more recent review, which discusses the realization of photometric systems in the era of CCDs (but giving also the historical overview) is that of Bessell (2005)[33].

Nowadays, some of the most important all-sky photometric surveys (that were not mentioned in the reading material recommended above) include: 2MASS[34] (Two Micron All Sky Survey, Skrutskie

[30] http://ulisse.pd.astro.it/Astro/ADPS/
[31] https://ui.adsabs.harvard.edu/abs/2000A%26AS..147..361M/abstract
[32] https://ui.adsabs.harvard.edu/abs/1965ARA%26A...3...23O/abstract
[33] https://ui.adsabs.harvard.edu/abs/2005ARA%26A..43..293B/abstract
[34] https://old.ipac.caltech.edu/2mass/

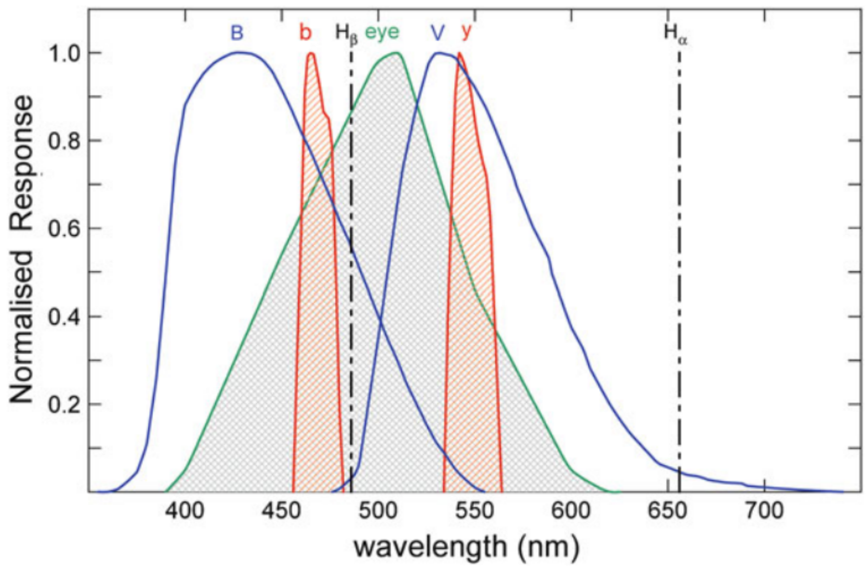

Figure 1: Normalized photometric responses of the B and V broad-band filters, b and y intermediate-band filters, and of the eye. Credit: Figure 4 from Sterken et al. (2011).

et al. 2006)[35], offering magnitudes in three near-infrared bands (J at 1.25 microns, H at 1.65 microns, and Ks at 2.17 microns; the Sloan Digital Sky Survey *ugriz* system, see Fukugita et al. (1996)[36] for the SDSS photometric system, Gunn et al. (1998)[37] for details on the instrument, and (York et al. 2000)[38] for a technical overview of the survey; and finally also the *Gaia* photometric system. Although the *Gaia* passbands are very wide, the data is avaiable for an uncomparable number of objects. See Gaia Collaboration et al. (2016)[39] for a description of the *Gaia* mission, Riello et al. (2018)[40] for an overview of the photometric data processing, and Riello et al. (2021)[41] for details of photometric data content in Gaia's early data release 3.

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[35] `https://ui.adsabs.harvard.edu/abs/2006AJ....131.1163S/abstract`
[36] `https://ui.adsabs.harvard.edu/abs/1996AJ....111.1748F/abstract`
[37] `https://ui.adsabs.harvard.edu/abs/1998AJ....116.3040G/abstract`
[38] `https://ui.adsabs.harvard.edu/abs/2000AJ....120.1579Y/abstract`
[39] `https://ui.adsabs.harvard.edu/abs/2016A%26A...595A...1G/abstract`
[40] `https://ui.adsabs.harvard.edu/abs/2018A%26A...616A...3R/abstract`
[41] `https://ui.adsabs.harvard.edu/abs/2021A%26A...649A...3R/abstract`

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