Observational Astrophysics
9. Photometry

Rodolfo Smiljanic
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Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences
ul. Bartycka 18
00-716 Warsaw, PL

E-mail: rsmiljanic@camk.edu.pl
Office: 115

http://users.camk.edu.pl/rsmiljanic

1 Introduction

Photometry is the process of making a precise measurement of the brightness of a source. To do photometry, we would like to have a detector of good quantum efficiency that can register the arrival of the source photons in a linear way, so that the instrumental measurement can be related to the physical flux. Mostly, CCD detector are used for that nowadays, at least in the UV, optical, near-IR range. Other options are available depending on what is needed (e.g. "avalanche photodiodes" can be useful for high-speed photometry). Photometry will most often be done using a filter that selects the light in a given passband, which was chosen because the light in that passband gives some useful scientific information about your source.

To do such photometric measurements as precisely as possible, several details have to be taken into account in planning and conducting the observations (e.g., taking care of the sky conditions, observing reference stars, characterising the detector).

2 Read these texts

For an overview of astronomical photometry, please read Stetson (2013)[1]. The text also covers some details on detectors (photographic plates, photomultipliers, and CCDs). We will later cover CCDs in more details, but probably not the others. In any case, it is good to read now something about the detectors since everything connects to the process of doing a good photometric analysis.

Since this is related, for a discussion on Interstellar Extinction see Chapter 9 of Sterken & Manfroid (1992)[2].

[1] This is Chapter 1 of the Volume 2: Astronomical Techniques, Software, and Data, of the series "Planets, Stars and Stellar Systems", see `https://link.springer.com/referenceworkentry/10.1007%2F978-94-007-5618-2_1`. The whole series is actually a very useful resource to have, covering several topics of modern astronomy.

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

3 Summary of concepts

- To be able to do absolute photometry, the astronomer needs what is called a "photometric night" or "photometric observing conditions". This means that the conditions of the atmosphere are stable enough to allow measurements for a length of time, and in several directions, without introducing additional unwanted uncertainty.
- All-sky or absolute photometry is a term used when we are interested in measuring and comparing the magnitudes of objects in different parts of the sky.
- Differential or relative photometry is a term used when we want to measure and compare the magnitude of objects that can be observed simultaneously, in the same image frame.
- Time-domain photometry is a term used when what is needed is to to track changes in magnitude of the same object which is observed periodically.
- Primary standard stars are those that define the magnitude scale in a certain photometric system. They are usually bright, and can not be easily observed with large telescopes. Secondary standard stars are fainter objects whose magnitudes have been carefully measured and calibrated relative to the primary standards. To calibrate the measurements of your target in a given photometric system, you will want to measure standard stars with as close as possible setup and atmospheric conditions (including with similar airmass). Of course, the standard star(s) that you select for observation should be non-variable and close to the star of interest (so it can be observed in the same region of the sky).
- What one measures out of the detector (after applying all necessary corrections to the image) is called the instrumental magnitude ($m_{\rm inst}$). To calibrate the instrumental magnitude into the scale of your photometric system ($m_{\rm std}$), an equation like Eq. 1 is used, with the number of terms adequate to your problem. In this equation, we are taking care of corrections related to the sensitivity of the telescope + detector system (with the coefficient a_0); discrepancies between your instrumental passbands and the passbands of the standard system (with a color term represented by the coefficient a_1); atmospheric extinction (related to the airmass, $\mathbb{X}$, through the coefficient a_2); and, if needed ,a higher order term that introduces a color term dependency of extinction (with the coefficient a_3):

$$m_{\rm std} = m_{\rm inst} + a_0 + a_1\,(B-V)_{\rm std} + a_2\,\mathbb{X} + a_3\,\mathbb{X}\,(B-V)_{\rm std} + ... \tag{1}$$

- As we saw before, the effect of atmospheric extinction depends on the amount of atmosphere that was crossed by the incoming light. This can be expressed by the airmass ($\mathbb{X}$). If the airmass is not too large, it can be approximated as $\mathbb{X} = \sec\ z$, where z is the zenith distance of your object. If $\mathbb{X} \sim 2$ or more (i.e., $z \sim 60$ degrees or more), a better approximation is:

$$\mathbb{X} = \sec z - 0.0018167(\sec z - 1) - 0.002875(\sec z - 1)^2 - 0.0008083(\sec z - 1)^3 \tag{2}$$

- For completeness, the $\sec z$ can be written as a function of the latitude of the observer (ϕ), and the declination (δ) and hour angle of the target (h)[3].

[3] I guess most of you are familiar with right ascension and declination. The hour angle is the difference between

$$\sec z = (\sin\phi \, \sin\delta + \cos\phi \, \cos delta \, \cos h)^{-1} \quad (3)$$

- The terms proportional to the color aim to take into account differences in the spectral response of the equipment. Imagine that the used filter has a longer tail to the blue when compared to the standard filter. If you observe two stars, one that has bluer colors than the other, then this bluer star will be biased to a bluer measurement than it would if the standard filter was used. This is just because the filter response (the weight) is shifted to a region where the bluer star is brighter.

- Differential photometry can be performed also on nights that are not exactly photometric. For this method, target and standard star(s) are observed in the same field during the same exposure. Across the field of view of a detector, the atmospheric conditions should be uniform.

- Another consideration when doing photometry, particularly of faint objects, is the night sky brightness. This is an additional source of noise that adds photons on top of the counts that you are measuring in the direction of your source. Technically, you will try to estimate the night sky background using the same CCD image that contains your target. You will measure it in a free patch of the sky, close to the image of your target. An important source of sky brightness is scattered light from the Moon. Because of that, observing nights of "dark time", i.e. nights near the new Moon, are the ones that face strongest competition.

- One of the methods to obtain photometry out of the data is called "aperture photometry". In this method, one attempts to measure the signal inside a certain region (usually circular) around the position of the center of the object. Difficulties include how to find the center of the image, how to define the optimal size of the aperture, and how to treat the square pixels that are only partially included inside the aperture.

- Another method is the PSF fitting. The idea is to try to model the image and not only sum the signal over where you think the image is. The PSF of the stellar image is usually taken to have a Gaussian profile. PSF-fitting photometry is a better option than aperture photometry in crowded fields. In such cases, it is difficult to define an aperture that contains signal of only one object in your field. In addition, subtracting the profile of a bright object might help in revealing the signal of fainter objects.

- Interstellar extinction is not neutral but selective, meaning that the effect has a wavelength dependency. We talk about extinction because the objects look fainter than they are. We also talk about reddening, because with the wavelength dependency, the objects also look redder than they really are.

- The total absorption in a given band is usually represented by $A_{\rm band}$; so $A_{\rm V}$ is the amount that the V-band magnitude of the source increased because of extinction: $V_{\rm obs} = V_{\rm true} + A_{\rm V}$.

- We can define the so-called colour excess, the effect of interstellar reddening in a certain color (m_1 - m_2) as E(m_1 - m_2) = (m_1 - m_2)$_{\rm obs}$ - (m_1 - m_2)$_{\rm true}$ = ($m_{1\,\rm obs}$ - $m_{1\,\rm true}$) - ($m_{2\,\rm obs}$ - $m_{2\,\rm true}$) = $A_{\rm m_1}$ - $A_{\rm m_2}$.

your local sidereal time and the right ascension of the object. Your local sidereal time is the right ascension of an object that is currently crossing your meridian. Your meridian is the great circle connecting the celestial poles and your zenith. Confused?

- The ratio of total-to-selective absorption, R, is used to characterize the interstellar extinction law, usually with respect to B and V bands in the Johnson system: $R = A_V/E(B-V)$. This ratio depends on the nature of the absorption grains causing the extinction.

4 Surface photometry

These notes, and the recommended reading material, focus on stellar (point-source) photometry. If you are interested in resolved objects (e.g. galaxies, nebulae) then you do not want to measure magnitudes but surface brightness profiles. I am not very familiar with the subject, but I found the following references that might be useful:

1. Okamura (1988)[4]: it is an old test, but seems to give a review of the methods.
2. Milvang-Jensen & Jørgensen (1999)[5]: also old, this are lecture notes from a summer school on photometry.
3. Schombert & Smith (2012)[6]: a more recent summary of the surface photometry techniques.
4. Pignatelli et al. (2006)[7]: describes a software used for the analysis of galaxy surface photometry (and thus discusses the methods).

And the short discussion on deconvolution in Chapter 2 of Kitchin (2020)[8] might also be of use.

5 Further reading

The book "Astronomical Photometry: Past, Present, and Future" (Milone & Sterken 2011)[9] presents a series of articles that summarize the historical development and some practical elements of modern photometry. Of particular interest are the Chapters on differential photometry by Milone & Pel (2011) and on absolute photometry by Cohen (2011). The book "An Introduction to Observational Astrophysics" (Gallaway 2016)[10] presents, in its Chapter 10, the practical steps that one would need to take, to do the photometric analysis of an image.

The Schlegel et al. (1998)[11] maps are widely used to estimate reddening. Some care is however needed, as these maps give integrated effects in the line of sight, which might overestimate the

[4] https://ui.adsabs.harvard.edu/abs/1988PASP..100..524O/abstract
[5] https://ui.adsabs.harvard.edu/abs/1999BaltA...8..535M/abstract
[6] https://ui.adsabs.harvard.edu/abs/2012PASA...29..174S/abstract
[7] https://ui.adsabs.harvard.edu/abs/2006A%26A...446..373P/abstract
[8] https://www.google.com.br/books/edition/Astrophysical_Techniques_Sixth_Edition/fU3BAQAAQBAJ?hl=en&gbpv=0
[9] https://link.springer.com/book/10.1007%2F978-1-4419-8050-2
[10] https://link.springer.com/book/10.1007/978-3-319-23377-2
[11] https://ui.adsabs.harvard.edu/abs/1998ApJ...500..525S/abstract

reddening for Galactic sources (e.g. Bonifacio et al. 2000)[12]. The Stilism[13] database is an online resource that can provide reddening values in a given direction, as a function of distance, based on 3D maps of the local ISM (Lallement et al. 2014)[14].

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[12] `https://ui.adsabs.harvard.edu/abs/2000AJ....120.2065B/abstract`
[13] `https://stilism.obspm.fr/`
[14] `https://ui.adsabs.harvard.edu/abs/2014A%26A...561A..91L/abstract`