Iranian Journal of Astronomy and Astrophysics
Vol. 10, No. 4, Autumn 2023, 357–364
©Available online at http://ijaa.du.ac.ir
DOI: 10.22128/ijaa.2023.739.1172
Online ISSN: 2383–403X

Iranian Journal of Astronomy and Astrophysics

Research Paper

Astronomy Lab I: Photometric Experiments for Physics Students

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Received: 1 October 2023; **Accepted:** 24 December 2023; **Published:** 31 December 2023

Abstract. As physics laboratories are an integral part of the physics education across the globe, astronomy laboratories are also a necessary part of the astronomy education. However, there have been only theoretical astronomy and astrophysics in Iranian universities. We present for the first time a new laboratory course on observational astronomy for bachelor and master students. In this course, students performed observational experiments and learned how to analyze astronomical data. Data are transformed from the camera RAW to the FITS format and later are analyzed using Python AstroPy packages. In Astronomy Lab I, students learned to polar align equatorial mounts, measure the read and shot noises, estimate the spatial resolution in long exposure images, measure the solar limb darkening, stack a number of images to get a high signal to noise final image, calculate magnitude using aperture photometry, retrieve the absorption coefficient for each filter, correct for the atmospheric extinction and draw a Hertzsprung-Russell (HR) diagram for open clusters.

Keywords: Telescope, Detectors, Photometry, Seeing

1 Introduction

With the inauguration of the Iranian National Observatory (INO), a modern 3.4 m optical telescope, the need for skilled observational astronomers to work in the facility became clear. As the current astronomy courses in universities are theoretical, few students had a chance to perform observations and measure physical parameters in real data. It is necessary to educate students first with small and medium-size telescopes before allowing them to work with meter-class telescopes. To this end, many universities in developed and developing countries have a campus observatory. To address this issue, we developed an astronomy laboratory and proposed three astronomy labs in which students learn stellar photometry, imaging, and spectroscopy. While imaging and spectroscopy require a medium-sized telescope and an astronomical detector in a dark site, it is possible to perform photometry even with small telescopes. Indeed, several exoplanets have been discovered using precise photometry with 8 inch telescopes. Therefore, we compiled a collection of experiments including three numerical and nine observational experiments for the Astro Lab I. The experiments are not focused on a spacial topic. We measure the limb-darkening of the Sun, the spatial resolution in a stellar field, and stellar magnitudes using Johnson-Morgan (UBV) filters by aperture photometry [1]. The UBV filters are about 100 nm wide so even small telescopes can employ them for broadband photometric measurements. Following the first appearance of this course on Spring 2023, we established the Astronomy Lab in the physics department, Sharif University of Technology. In the following, we discuss the hardware and framework of the laboratory.

2 Observations

2.1 Telescopes

Many students had no prior experience of working with telescopes. Therefore we have to teach them in the first experiment on how to align a finderscope with the main optical tube, focus, balance, and polar align each of the three telescopes (Table 1). In order to have a realistic expectation of the image quality, one has to know the principal optical aberration in the Newtonian, Cassegrain, and Catadioptric telescopes [2]. Prior to the first session, we cleaned the optical elements and aligned them using a laser. After that, we performed star testing procedure. The alignment process takes easily an observing night. For each observing session, students moved telescopes from the Astronomy Lab to the roof of the physics department, Sharif University of Technology. Then, they followed the instructions to perform the necessary steps for the polar alignment, and prepare the telescope for measurements.

Table 1: List of the telescopes and mounts used in the Astronomy Lab I.

telescope	mount
Schmidt-Cassegerain 8 inch, f/10	Celestron AVX
Newton 8 inch, f/5	Skywatcher NEQ6 pro
Newton 6 inch, f/5	Skywatcher EQ3

The three telescopes used in the Astronomy Lab I are listed in Table 1. This kind of telescopes exist in many physics departments. They are amateur telescopes with affordable prices. Many astronomy students with a background in the Astronomy Olympiad have a similar telescope. Several universities in Iran have eleven inch telescopes while Universities like Shiraz have their own observatories. So in comparison we started a low-budget project compared to universities with a dedicated telescope.

To track astronomical objects, we need a motorized mount. At least the Right Ascension (RA) direction should have a motor in order to compensate for the earth rotation. All the telescopes mentioned in Table 1 had motorized mounts. The $EQ3$ mount had only one motor for the RA axis while the other two mounts were motorized on both axes. The polar alignment procedure took about an hour for experienced observers: one started from around the Polaris and followed a feedback procedure to polar align the telescope (once for the elevation of the polar axis and once for the azimuth of it).

2.2 Detectors

All experiments in the Astronomy Lab I were based on recorded images. Since we had no dedicated astronomical camera in hand, we used commercial cameras (Table 2). Each camera had a T-adapter to fit into the eyepiece gate of the telescope. The quantum efficiency of the cameras and the full well depth are about 30% and $20\,k$ electron, respectively. The spatial scale for all the cameras were about one arcsec per pixel. The cameras had no temperature control or cooling. We purchased all the cameras from a second-hand market. This shows again that we used basic instruments available to physics departments across Iran.

Table 2: List of cameras and their properties.

camera	# of pixels	storage media
Canon EOS 400D	10 M	CF card
Canon EOS 1200D	18 M	SD card
Nikon D90	12 M	SD card

The second experiment was about characterization of detectors. Students learned to operate each camera and recorded a seri of dark current images. All the recorded images were first converted from RAW to the FITS format using *dcraw* tool. Students investigated the difference between mean and median in astronomical data and studied how to deal with the traces of cosmic rays in long-exposure images. They also learned about the bias images, overscan region and similar issues in astronomical detectors. Students used the AstroPy module and develop their own Python codes to read, reduce, and write FITS data.

2.3 The solar limb darkening

As the third experiment, we used a Mylar solar filter in the pupil of one of the 8 inch telescopes. Mylar filters are planes of dielectric mesh with aluminum powder on both sides. They are available in two grades: for human eye and silicon detectors. In absence of Mylar filters, exposed X-ray films or other natural density filters can be used. A rule of thumb is that we have to decrease the intensity by a factor of one million. We stress that the filter should be placed at the entrance of the telescope and not after the eyepiece or in front of the camera. Mylar filters like other natural density filters are broad band. A solar disk with a Mylar filter is slightly bluish and loses its yellow color. Figure 1 shows a single image of the Sun recorded around the noon. In our solar image, we resolve sunspot umbra and penumbra showing that the spatial resolution was about 1 arcsec in our observation, although the typical seeing in the roof of the physics department was about $4-5$ arcsec. The limb darkening in visible light is clearly seen in Figure 1. It is a result of the temperature stratification in the solar atmosphere and is automatically reproduced in empirical solar models. A radial profile from the center to the limb (away from sunspots) is then compared with the Eddington approximation [3].

2.4 Photometry

Aperture photometry has a wide range of applications: study of variable stars, search for exoplanets, or construct a HR diagram of a stellar cluster. Therefore, several experiments of the Astro Lab I are about photometry. This include estimating an instrumental magnitude, a differential magnitude (with respect to a known source), magnitude of the background sky, and the atmospheric absorption coefficient. The principal approach is the aperture photometry [4]. For instrumental magnitude one had to find an appropriate radius for integration of star light (star zone), take a separation zone of comparable size, and finally use an annular region to estimate the average sky background. With these two quantities, we can define the instrumental magnitude

$$m_{inst} = -2.5 \log(\text{star} - \text{background}), \qquad (1)$$

where star corresponds to the integrated star signal and background corresponds to the total background signal that falls into the area of the star zone i.e., median of the background area times number of pixels in the star zone. Star and background signals are normalized by the exposure time in seconds.

Observations to measure the absorption coefficient in different filters required at least a few hours to monitor a standard star at different air mass values. The atmospheric extinction is to first order a product of the absorption coefficient and the air mass [5]. The absorption coefficient itself roughly follows the Rayleigh scattering law (in a clear site, it decreases from about 1.0 mag in the U filter to about 0.1 mag in the V filter). Beside molecules, aerosols, ozone and dust grains also contribute to the total extinction in the atmosphere. Following a correction for the atmospheric extinction, we measured the magnitude outside the earth atmosphere. Different group of students measured B and V filters and as a result constructed an observational HR diagram of the IC 4665 open cluster. Having the (B-V) color index of each star, they transformed it into a color temperature using an empirical formula [6]

$$T_c = \frac{7300}{(B-V)+0.73}, \tag{2}$$

where $T_{\rm c}$ is the color temperature and $(B-V)$ the color index from the blue and visible Johnson-Morgan filters. This empirical relation corresponds to main sequence stars (dwarfs). The color index in this relation can have values from -0.32 to $+2.0$, corresponding to a temperature of 38 000 to 2660 K, respectively.

Like previous experiments, students developed their own Python programs to read the data, measure parameters and find magnitudes. A necessary issue in working with data is to perform an error analysis. As we mostly deal with the photon noise (shot noise) and the thermal noise, students estimated the signal to noise ratio and the uncertainty in the reported magnitudes [7]. Considering the shot noise and thermal noise, we achieved a magnitude accuracy of about 0.2 mag. Part of this uncertainty is due to light pollution while variation of the camera temperature has also a contribution. We anticipate that with a dedicated astronomical camera and an observation from a dark site, uncertainty in the measured magnitudes will reduce significantly.

To have an idea about exposure times, we note that we could easily record 9th magnitude star (in the V filter) with an 8 inch telescope and with an exposure time of one second from the light-polluted Sharif campus in the Azadi avenue. For fainter targets like star clusters, we accumulated several exposures to have a total exposure of a few minutes. Alignment, registration and stacking of individual frames were programmed in Python.

2.5 Numerical experiments

We anticipated that on some weeks, the weather condition does not allow us to perform night observations. To address this issue, we prepared three numerical experiments. It consisted of fitting a straight line to the data in presence of the measurement error in one or two axes, fitting a histogram to the observed data, and fitting spectral lines to retrieve spectral parameters. Through these experiments, students learned to upgrade their skills in error propagation, create high quality figures, draw a colorbar next to 2 D maps, and have a second x or y axis in some plots. This resulted in decent publication grade figures, much better than the ones students created during the elementary labs.

3 Data Analysis

In the first experiment, students were instructed to convert raw camera data to FITS files (using *dcraw* command in a Linux shell). Using different Python packages like NumPy, SciPy, Matplotib, and AstroPy, students gradually developed their own program for photometric data reductions. Some students also posted those programs as a packages on the git webpage. As an example, students used the $\sigma-$ clip technique to remove cosmic rays and artifacts in the dark images.

Another experiment was about the astronomical seeing. Students had to estimate the spatial resolution. They learned to cut-out a star in the map and fit a Gaussian function to measure the Full Width at Half Maximum (FWHM) of stars. They fitted a 1 D or 2 D Gaussian function to individual stellar profiles, after removing a constant or a linear background and normalization of the stellar profiles to the unity. The estimated sigma of the Gaussian function was retrieved for about 20 stars. A statistical mean value was then reported which correspond to the long-exposure Point Spread Function (PSF). This is one of the basic methods to estimate the astronomical seeing. More advanced methods like using a power spectrum will appear in the Astro Lab II.

4 The course work

Although the Astro Lab was designed as a two unit laboratory like optics or laser labs, we had a weekly two hour class to discuss observational details in addition to the four hour lab observation. As a few examples, the following topics were discussed during the classes: different ways to record a flat field, how to deal with a gradient or cosmic ray in an image, the procedure to drift align an equatorial telescope, optical aberrations, solar observations in continuum and spectral lines, the ephemeral time, the nautical procession, coordinate transformation, detection limit, and significance of a measurement. These issues are not fully covered in introductory courses in Astronomy or in Astrophysics lectures. Therefore, we found it necessary to have a two hour class prior to conduct any observations. It was also helpful to show the telescopes in the daylight before the first observation so students learned where each screw is located. We performed ten experiments depending on the weather condition. A final exam was also executed in the Astro lab I.

5 Astro Lab I notes

For each experiment, the text was prepared and typed using the SiPersian Latex tool. In addition, several appendices including definition of magnitudes, optical aberrations, sky chart, etc were also included in the Astro lab I book of nearly 135 pages. Physics students did bulk of the job of typing and language improvements of the manuscript. A complete list of all experiments were listed in Table 3.

6 Summary and outlook

We presented for the first time an astronomical laboratory in Iran. We showed how we constructed a low-budget astronomical lab in the physics departments, Sharif University of Technology. Bachelor and master students with a minimum knowledge of astronomy and computer programming skills attended the course. They learned diverse techniques from polar alignment of the telescopes to estimating the astronomical seeing and measuring

Figure 1: The solar white light image recorded at 10:00 UTC on July 11, 2023. The image was recorded using a Mylar filter and the 8 inch Newton telescope with a focal length of 1000 mm. Note the clear separation of the umbra and penumbra of the large sunspot. Students measured the limb-darkening effect in a radial profile.

Table 3: List of all experiments in the Astro Lab I.

#	title
1	Drift polar alignment
2	Chracterization of detectors
3	Estimation of the Hubble constant (numeric)
4	The solar limb darkening
5	Spectral parameters (numeric)
6	Astronomical seeing
7	Differential photometry
8	Sky background magnitude
9	Atmospheric extinction
10	Construction of observational HR diagram
11	the color temperature
12	the main-sequence fitting

magnitudes of stars. Even if we had only three small telescopes (which means three lab "tables"), we grouped students to access the telescopes in a row. Following the first few experiments, students had improved skills to navigate the telescope, record long exposure images and for instance take note on the meridian flip of the targets. We plan to continue our efforts by establishing the Astro Lab II, in which students deal with more challenging targets, narrow band filters, and imaging techniques. We hope that this manuscript on Astro Lab I motivates colleagues in other physics departments to contribute in educating skillful observers for the INO telescope.

Acknowledgment

We are grateful to the students of the Sharif University of Technology who helped us during preparation of the lab book (N. Khosravani Nejad), borrowed us their telescopes (S. Pashaee, G. Safari), and helped other students to improve their reduction programs (A.H. Amiri, K. Hajyian). Their skills and patient was the key in night-long observations at dark sites. The substantial support of the colleagues at the Physics department, the astrophysics group, and in particular Dr. S. Moghimi is greatly appreciated. We are thankful to several colleagues including Dr. N. Seyed Reyhani and Dr. M. Bahman Abadi who allowed us to access to their labs.

Authors' Contributions

The author contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all aspects of this work.

Data Availability

No data available.

Conflicts of Interest

The author declares that there is no conflict of interest.

Ethical Considerations

The author has diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

Funding

This research did not receive any grant from funding agencies in the public, commercial, or non profit sectors.

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