Low-Cost Astrophotography with a Smartphone: STEAM in Action

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Astrophotography has been responsible for the discovery of planets, solar systems, stars, and several other celestial objects, which directly helps with expanding our knowledge about the universe and creating scientific models for nature. Practical techniques have been extensively described,[1,2] including Covington,[3] who has published an extensive guide to amateur astrophotography. Furthermore, aiming to introduce such important scientific activity among students, several authors have described possibilities of using the technique in physics and astronomy teaching.[4-10] However, the proposed activities and methods normally need expensive equipment, such as telescopes, professional cameras, mounts, tripods, optical components, and other items not commonly owned by teachers, students, or the general public. The ubiquity of the smartphone, especially among students, makes it interesting for educational purposes. The device can be used as a mobile laboratory due to the several integrated sensors.[11] Furthermore, the possible uses in classroom are extensive,[12-13] including the ones involving astronomical subjects, especially with the use of its camera for sky imaging.[15-17] In this work, we propose a simple and low-cost technique for the practice of astrophotography using the smartphone. Moreover, we suggest teaching activities involving the STEAM disciplines (science, technology, engineering, the arts, and math), including the analysis of the Earth's rotation and the artistic treatment of the astrophotographs.

A simple and low-cost technique for astrophotography

Astrophotographs were taken using a single smartphone, a low-cost stand (assembled by the authors), and a remote-control system. The second and third items are necessary to avoid trembling in the images caused by hand shaking. The equipment is shown in Fig. 1.

The 37-mm 0.45x wide-angle eyepiece lens clipped on the camera lens in Fig. 1(a) is optional and serves to enlarge the camera field of view. This is used when one wants to capture a broader area of the sky. The stand was assembled using a broken pedestal consisting of several ~40-cm length metal rods (only five were used), a base, and a holder for cell phones with an adjustable claw, the same used for fixing such devices to a car's panel. The holder was adapted to the vertical metal rod through a piece of wood fixed with a screw. Despite there being very cheap stands for sale, this do-it-yourself approach can also be used in the classroom, stimulating the students' creativity.

Controlling manually the settings of the smartphone's camera is the most important part of the technique. We used the smartphone native camera application (in Android system version 9) to change the following relevant photograph parameters available in PRO mode [Fig. 1(d)]: exposure time or shutter speed (*S* button) and sensor sensitivity (*ISO* button). In other Android versions or other operational systems, the installation of an additional application, such as Camera FV-5 for Android (free), ProCamera for iOS (free), among others, might be necessary to access the camera's manual settings. Moreover, the name of the manual setting parameters can be slightly different in other applications. To capture sharper images of the stars that have a weak brightness in the sky, it is necessary to open the shutter for a long period, i.e., to choose long values for *S*. We used $S \geq 8$ s. However, as is known, the stars apparently move in the sky (since Earth is rotating), forming a trail in the astrophotograph. With this exposure time, the rotation angle is only $0°4'$ (4 minutes of arc) and in wide field astrophotographs it is not noticeable. On the other hand, when one wants to photograph the Moon, which is a bright object in the sky, *S* needs to be smaller, on the order of ms (1/1000 s) to avoid a big blur in the image. *ISO* is a parameter for the sensitivity of the camera sensor. The lower the *ISO*, the less sensitive the sensor is and the more light is needed to make the photo sharper. In contrast, the photograph is less noisy. This is the case of photographing well-illuminated or bright objects (daytime photographs or the full Moon, for example). Moreover, several environmental conditions, such as cloudiness, pollution, and the presence of luminous objects from the city, have influence on the star visibility, and thus in the *ISO* value to be chosen. In the teaching project, teachers can include photography sessions using daily life scenes and objects to practice the procedures with the students.

After preparing the equipment and learning the astrophotography technique, one needs to know what to shoot in the sky. Thus,
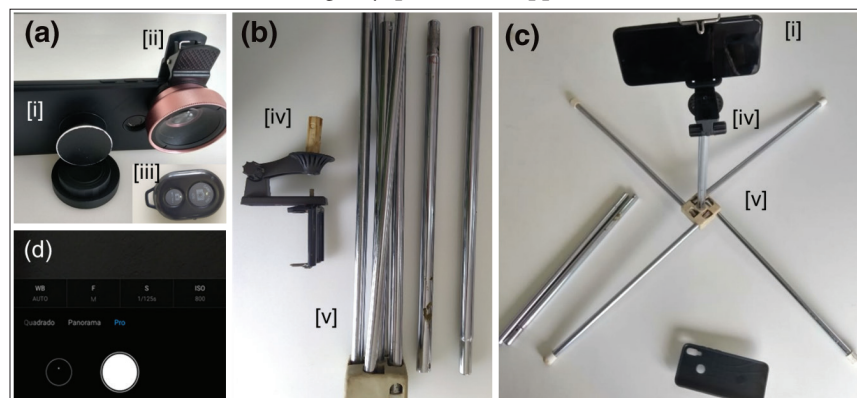

Fig. 1. Low-cost equipment used in astrophotography: (a) [i] smartphone with [ii] an eyepiece lens mounted (optional), and [iii] a Bluetooth remote control; (b) parts to assemble the low-cost stand: [iv] a phone holder, [v] metal rods and a base. In (c), we see the setup in its final form ready for operation (without the eyepiece lens), and in (d) a screenshot of the camera control application showing the main menu.
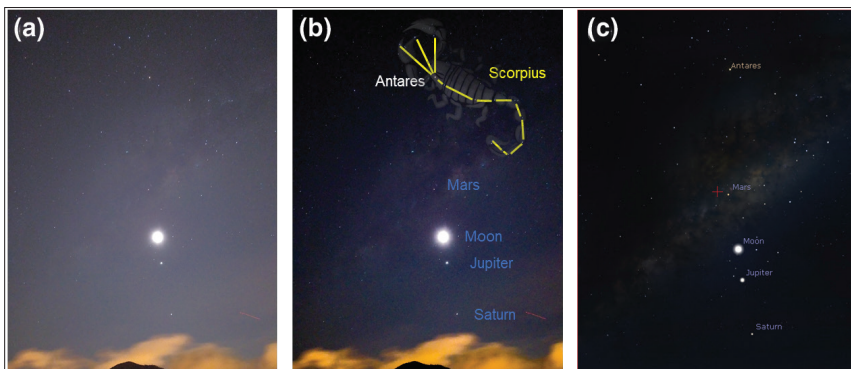
Fig. 2. (a) Original astrophotograph taken with *S* = 8 s and *ISO* = 1600 from the Southern Hemisphere in the southern direction on February 19th, 2020, at 4:39 a.m. (GMT-3). In (b), we see it after editing and in (c), we see a Stellarium screenshot showing the same sky scenario.
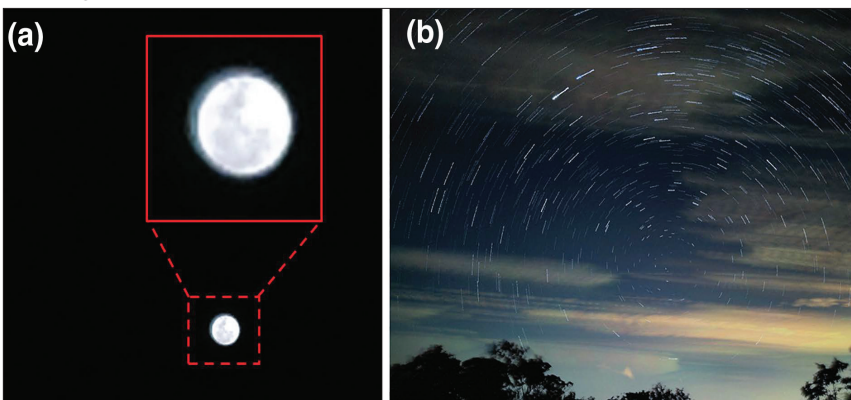

Fig. 3. (a) Astrophotograph of the full Moon taken with *S* = 1 ms and *ISO* = 100 and (b) a time lapse taken for 23 minutes with *ISO* = 100.

it is important to plan the astrophotography session before going to the field by consulting astronomical tables and planners published by official agencies, such as NASA,[18] or using a sky simulation software/application. In this work, we used the computer version of Stellarium[19] for this task. Beyond planning the sessions with it, teachers can additionally explore and discuss the sky objects and their movements. Once in the field, computer software or smartphone applications[20] are also helpful in finding sky objects. Many of them have the function to guide the user live through the sky based on GPS and other sensors.

In astrophotography, image editing[21] is useful to highlight some star cluster or other detail of the sky, such as the milky strip representative of the Milky Way, as the raw images are normally not appealing. This will be further discussed in a coming section, but we emphasize that this is an important part of the teaching project that highlights its artistic branch. In a post-processing step, sky simulation software/application also aids in the identification of the sky objects contained in the astrophotographs. If an astrophotography session is not viable, the treatment of astrophotographs and their analysis is still possible by using images previously selected by the teacher from a public repository.[22]

Results: Some examples of astrophotographs

In this section, we present the astrophotographs taken by the authors from the coordinates (22°29'12" S, 43°10'52" W).

Readers may find them and many others from the authors in a public repository and are welcome to use them freely.[23]

Figure 2 presents an astrophotograph in which it is possible to see the Moon, the planets Mars, Jupiter, Saturn, and the constellation of Scorpius vertically aligned in the sky. In addition, part of the Milky Way is observable in the background.

The sequence presented in Fig. 2 shows the original astrophotograph [Fig. 2(a)], the same image after editing [Fig. 2(b)], and a Stellarium-cropped screenshot for the same date, time, and location. It is possible to notice the great similarity between the software screenshot and the astrophotograph. This sequence, not necessarily in the same order, can be used by the teacher in the classroom in which he/she can explore the scientific content of the image with the students and also stimulate artistic skills in the treatment of the pictures.

Figure 3 shows interesting astrophotography possibilities by using different time configurations: (a) an ordinary single shot astrophotograph taken with a short exposure time and (b) a time lapse taken for several minutes.

Figure 3(a) shows an astrophotograph of the full Moon obtained with the shortest exposure time, *S* =1 ms. Those who have tried photographing the Moon may already realize the difficulty of framing and focusing it under the correct brightness. The enlarged inset photograph appears blurred due to its apparent movement of 0°0'0.015" (15/1000 sec of arc), only noticeable with such large zoom-in. Even so, it is still possible to observe details of the satellite's surface. In Fig. 3(b), it is possible to observe a time-lapse astrophotograph. To achieve this effect, 40 photographs taken for 23 minutes with *S* = 16 s were superimposed in a post-processing step. From this image, it is possible to observe and extract interesting information, such as the identification of the celestial south pole and the calculation of Earth's angular velocity, as discussed in the next section.

Scientific teaching activities with astrophotography

All the discussions brought by astrophotography involving the sky objects and their movements, and the historical aspects of astronomy related to the ancient cultures, among others, enrich scientific classrooms. Additionally, we present in this section a quantitative analysis of the time-lapse astrophotograph shown in Fig. 3(b) that allows for the analysis of Earth's rotation and the calculation of its angular velocity. This analysis can be used in introductory physics courses, expanding the pool of scientific activities that can be done in the classroom.

In Fig. 4(a), we repeat Fig. 3(b) but with the superposition of an arbitrary scale for distances and angles. First, we identify the center of symmetry of the lines traced by the stars during
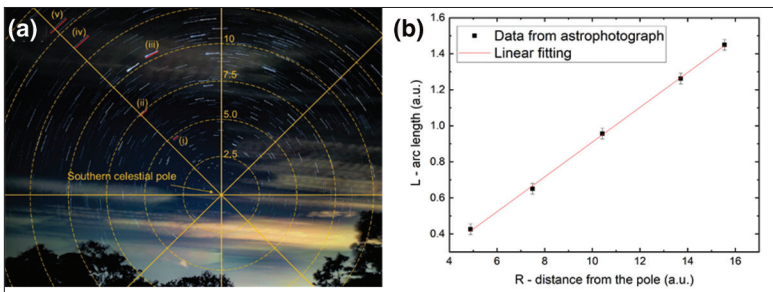
Fig. 4. Analysis of a time lapse astrophotography in the context of physics teaching: (a) the original image shown in Fig. 3(b) with an arbitrary superimposed scale and (b) a plot of the trace length as a function of the distance to the pole.

their apparent movement in the sky, the southern celestial pole. From the figure, it is possible to notice that the traces are larger the farther they are from the pole. To further investigate the relation between the trace lengths (L) and the distance from the pole (R), we measured such quantities for some selected traces [shown in red in Fig. 4(a)] in relation to the scale and plot them in Fig. 4(b).

It is well known that the apparent movement of the stars in the sky is caused by Earth's rotation. Some evidence for this is provided by the fact that all elements in the sky seem to be moving together with the same angular velocity ω. Moreover, this angular velocity matches exactly that of Earth, ω_E, as will be shown. Therefore, one would expect the apparent movement of the stars to follow the equations of the uniform circular motion, as in Eq. (1):

$$\omega = \frac{\Delta\theta}{\Delta t}, \tag{1}$$

in which $\Delta\theta$ is the apparent rotation angle of the objects and Δt is the duration of the movement. The relation between the apparent distance L traveled by an object in such a system [represented by the traces in Fig. 4(a)] and the distance R from the center is stablished in Eq. (2):

$$L = \Delta\theta \cdot R. \tag{2}$$

Equation (2) represents a linear relation between L and R, which is also observed in Fig. 4(b). Thus, the angular coefficient σ obtained from the linear fitting of the L x R graph gives $\Delta\theta$. From the fitting, we extracted $\sigma = (0.097 \pm 0.001)$ rad, and using the duration of the movement (the same of the time lapse) $\Delta t = (0.383 \pm 0.004)$ h, we obtained $\omega = (0.253 \pm 0.015)$ rad/h, which is in agreement with the expected value for the Earth sidereal angular velocity

$$\omega_E = \frac{2\pi \text{ rad}}{23\text{h } 56\text{ min } 4\text{ s}} = 0.263\,\text{rad/h}.$$

Artistic teaching activities with astrophotography

The artistic potential of astrophotography can be explored from the beginning of the teaching project, but it is more pronounced in the editing of the images. In Fig. 2, we presented an example of an astrophotograph and its comparison to a sky simulation software screenshot showing good agreement. Figure 5 presents another example of an astrophotograph and the sequence of steps performed in its artistic treatment. The image, in which it is possible 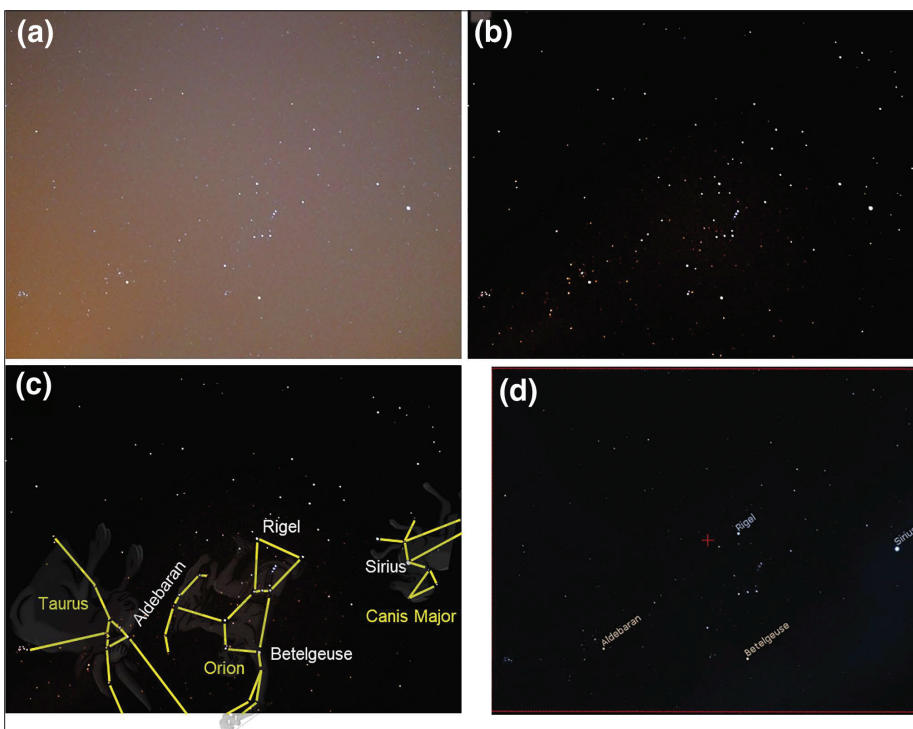to identify three constellations visible in the sky during spring/summer, was taken with $S = 16$ s and $ISO = 1600$ from the Southern Hemisphere in the northeast direction on Oct. 4, 2019, at 2:57 a.m. (GMT-3).

Figure 5(a) is not an appealing image. The cloudiness and public city lighting have an impact on its brightness and colors. Thus, this explains the high value needed for the ISO parameter. As the most important information from this image is the star positions, we performed an edit on it, applying some color filters (reduce exposition, increase whites, remove fog, increase contrast, reduce brightness, among others) in order to make the background darker and the stars more visible. The result is Fig. 5(b). As every single astrophotograph will always be unique due to local particular climate and lighting conditions as well as the photography parameters used, it is not instructive going through all the steps taken.[25] Additionally, we superimposed graphical elements to the

Fig. 5. Sequence performed in the editing of an astrophotograph and its comparison to a sky simulation software screenshot: (a) original photo, (b) after filters, and (c) after addition of graphical elements. In (d), we see a Stellarium screenshot showing the same sky scenario.

image, such as lines and drawings illustrating the constellations, and text identifying the main stars and constellations, resulting in Fig. 5(c). We obtained the drawings from Stellarium's root installation folder in Windows.

We believe that freedom should be given to the students in the artistic treatment of the astrophotographs as long as the physics behind the images is not altered, such as including stars in the images. Another interesting activity would be leaving the students free to create their own constellation from the stars presented in an astrophotograph.

Conclusions

In this work, we presented a low-cost and accessible technique for astrophotography based on the smartphone and different teaching possibilities involving STEAM disciplines. A STEAM approach requires that at least two disciplines are integrated in an educational activity. Here, we proposed classroom activities using astrophotography that can be integrated in the science, math, and arts disciplines preferentially in a multidisciplinary approach. The full process involving astrophotography in (i) preparing the equipment, (ii) learning the techniques, (iii) planning the shoot sessions, (iv) framing the sky scenarios, (v) post-processing the images, and (vi) performing the corresponding analysis shows the potential for engagement of such activities in all disciplines.

In the classroom activities proposed, we emphasize the identification of celestial objects and constellations using sky simulation software that allows for further understanding of the sky and its movements throughout the year, stimulating its observation, a practice unfortunately lost over time. Moreover, we showed that the quantitative analysis of a time-lapse astrophotograph allows for the calculation of Earth's angular velocity and discussions about Earth's motions.

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19. Stellarium is a well-known software in the astronomy community. Its computer version is open source and free of charge and is available at http://stellarium.org/pt/. The authors used this software due to previous experience, but any other having the same functions can be used, such as Celestia, KStars, C2A, and many others.
20. Examples of free applications for smartphones are: Star Tracker (Android and iOS) and Star Walk (Android and iOS).
21. Examples of image editing applications are Fotor and Photoshop Express, both available for free in Android and iOS.
22. Wide-field astrophotographs can be found in Astrobin at https://www.astrobin.com/, in Flickr at https://www.flickr.com/, in Pinterest at https://www.pinterest.com/, and many other image repositories.
23. The astrophotographs from the authors are available at https://flic.kr/s/aHsmMLDCJf.
24. We used the free computer software Sequator for this purpose, but there are also camera applications with a time-lapse built-in function that can facilitate this work.
25. To help the reader gain insight with image editing, we prepared a demonstrative video with the step-by-step process used to prepare Fig. 5(b) from Fig. 5(a). It is available at https://flic.kr/p/2jJUQbM/.

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