Utilizing a Low-Cost Telescope to Produce Color-Magnitude Diagrams of an Open Cluster

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ABSTRACT
Hands-on learning is critical for students' education, especially for more complex subjects, such as astrophysics. Astrophysics students are often taught more theoretical concepts than practical research skills, and thus have trouble adjusting to learning methods that produce new astronomical discoveries. This is a complicated problem, as it is difficult to obtain astronomical equipment due to high costs; large telescopes and good camera equipment are expensive. Many schools simply do not have the budget to spend on costly telescopes and cameras. This is an enormous drawback for students' education, as they cannot apply the knowledge they gain in the classroom setting to further their understanding of the astrophysics topics they learn. This paper aims to show that producing scientific data is possible even with low-cost, entry-level astronomical equipment, which can be utilized in classroom settings to help teach students about typical astronomical research methodology through hands-on learning. Many tools exist in astronomy that are either open source or relatively cheap, and this should not go unnoticed by students and educators with a low budget. This paper aims to utilize these tools to show that astronomical data can be retrieved with a great deal of success.

KEYWORDS
Astronomy Education; Hands-On Learning; Education; Accessibility; Low-Cost; Telescope; Photometry; Color-Magnitude Diagram; Open Cluster; Pleiades

INTRODUCTION

Hands-on learning has enormously benefited students' understanding of certain topics.[1] It allows students to both physically do activities and apply the knowledge they have gained, helping them achieve a stronger understanding of the topic at hand.[2] Hands-on methodology is critical for the education and engagement of students worldwide, and Kanwal et al. have shown that inexpensive learning material improves students' ability to learn more through hands-on methods compared to hands-off methods.[3]

Photometry, the measurement of stars' brightnesses, is one of the most important methods of data retrieval in observational stellar astronomy research. Performing photometry can indicate much about the formation and evolution of stars, which can give us a stronger understanding of how our sun will evolve and how it has changed since its initial formation. Performing photometry in different light wavelengths and comparing them can provide strong indications of where a star is along its life and what type of star it is. A common way for astronomers to compare the relative wavelengths of stars is to create a color-magnitude diagram, a graph comparing stars' magnitude in a certain range of wavelengths to a color index, which is the difference between smaller and larger wavelength ranges' magnitudes. This project used red, green, and blue image color channels to generate color indices. The reasoning behind making a color-magnitude diagram is that it strongly correlates with a Hertzsprung-Russell (HR) diagram, an example of which can be seen in **Figure 1**. This graph compares stars' luminosities to their surface temperature, or in some cases, due to the strong correlation, the color index. This correlation implies that a certain relationship exists between the intrinsic brightness and temperature of a star. A more massive star is hotter and brighter than a lower-mass star. Using HR diagrams, astronomers can classify stars by their spectral class, age, and mass, among many other things.

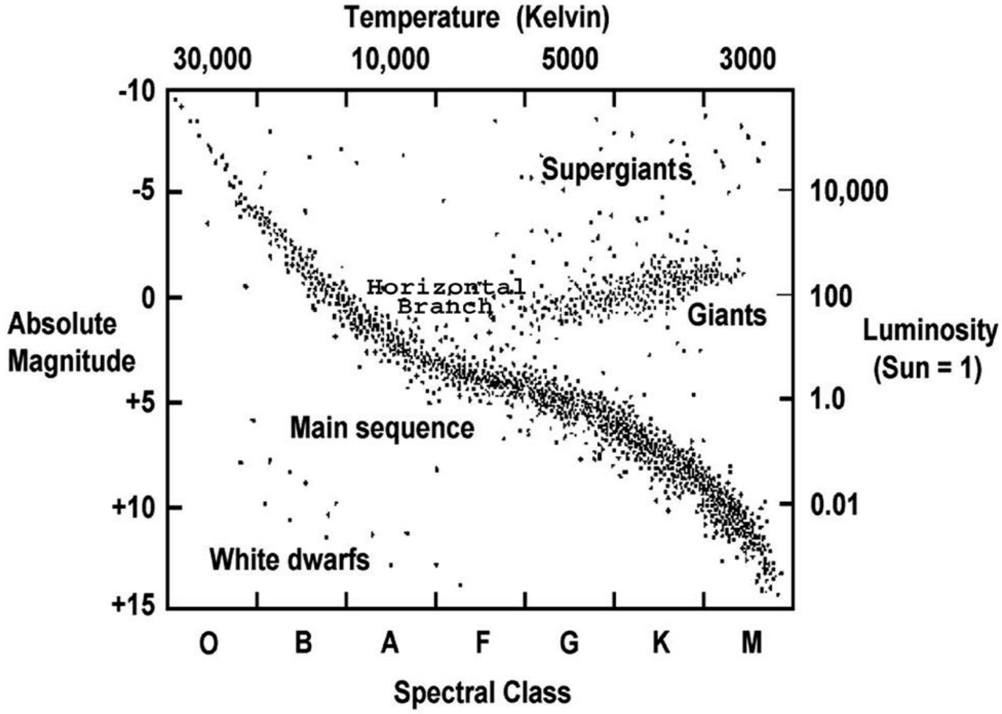


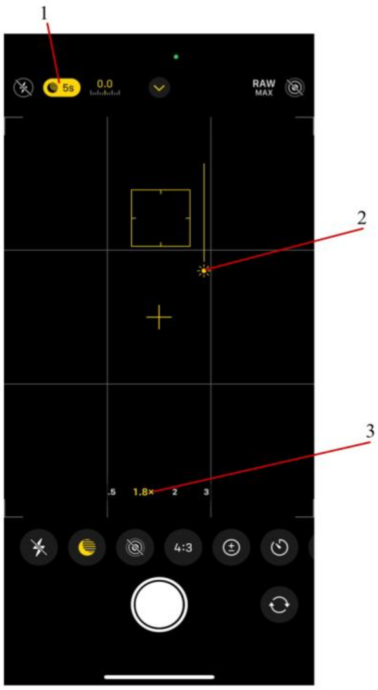
Figure 1. HR diagram with temperature and spectral class on the x-axis, and absolute magnitude and solar luminosity on the y-axis. Image credit goes to the Harvard-Smithsonian Center for Astrophysics.[4]

This project uses a low-cost telescope to generate a color-magnitude diagram for the Pleiades (also known as Messier 45, or M45) open cluster. It is the closest (400 light years away), young (125 million years old), and rich open cluster, with 2000 known members. The Pleiades were chosen due to their high brightness and relatively young age of about 100 million years, meaning that a larger majority of the bright stars are still within the main sequence, allowing a more obvious trend to be seen in the color-magnitude diagrams.[5] The goal of this project is to show that it is possible to use low-cost equipment in order to teach students about the processes that go into observational astronomy research and produce results that are generated with data gathered by the students themselves. This project will encourage the idea that astronomy is accessible to students and teachers with a relatively low budget.

METHODS AND PROCEDURES

Several steps were involved in this project. The primary objectives were observing, image preprocessing, performing the photometry, and generating a color-magnitude diagram from the magnitudes.

Observations were performed at Iron Horse in Watkinsville, Georgia. This location was chosen due to its relatively short distance from the University of Georgia campus and relatively low light pollution, with a radiance value of 0.90nW/cm^2 as of 2023, and no information regarding recent anti-light pollution efforts since then could be found, so it likely has not decreased much more than this if at all.[6] The telescope used was the Celestron FirstScope with an aperture of 76 mm and a focal length of 300 mm, and photographs were taken using the 20 mm eyepiece that comes with the telescope. The camera used for imaging M45 was the iPhone 15 Pro, using its 24 mm lens and the native Apple camera app, as shown in **Figure 2**. The iPhone 15 Pro's camera has a 48-megapixel complementary metal oxide semiconductor (CMOS) sensor that utilizes a quad Bayer color filter array (CFA). The typical telescope and camera setup can be seen in **Figure 3**. Camera exposure was set to a minimum to minimize the International Organization of Standardization (ISO) sensitivity, and exposure times ranged from 1/16 second to 1.1 seconds using 1.8x digital magnification, and the images were taken with the ProRAW camera mode. Everything else was left as the default option. Observations were done over five nights, and the images taken were put into an observation log, as shown in **Figure 4**. When performing a saturation check on the obtained target images, the stars in the images have relatively consistent saturations with brightness values typically well below 100, implying that they are not oversaturated.



Key Features

1. "Night Mode" – exposure time control, 0-10 second exposure time range
2. Exposure – set to a minimum to minimize ISO
3. Magnification – Set to 1.8x for all gathered images

Figure 2. The iPhone 15 Pro's camera app interface.

Figure 3. The telescope setup consists of the Celestron FirstScope, an iPhone 15 Pro, a Celestron phone mount, and a folding table.

Date	EST Time Range (HH:MM)	Image Types	Exposure Time Range (s)	Usability (good/bad
9/8/2024	21:45-22:50	Tests	1.1-10.0	25 test
9/20/2024	21:23-21:33	Tests	1.1	60 test
10/10/2024	05:34-05:52	Science, Bias, Dark	1/16-1.1	48/3 science, 0/10 bias, 5/0 dark
10/23/2024	00:59-01:00	Bias	1/18-1.1	0/10 bias
11/12/2024	00:50	Bias	1/16	10/0 bias

Figure 4. The observation log. This includes the date, the 24-hour time range in which images were gathered, what types of images were gathered, the ranges of exposure times for the images, and how many of each type of image were usable for this project.

Preprocessing in this project involved three major steps: stacking, bias subtraction, and dark correction. Stacking is the process of adding each spatially calibrated image array to obtain larger brightness values for stars. Bias subtraction removes any imperfections that are caused by defections in CMOS cameras and helps to reduce noise in the images. Dark correction removes unwanted signals caused by hot pixels and electronics inside the camera by subtracting a median-combined dark image. The observations yielded 5 dark images, 10 bias images, and 51 target images. The preprocessing was done using DeepSkyStacker, which contains algorithms that find stars in images to rotate, adjust, and stack them and perform the proper preprocessing (calibration, bias subtraction, dark subtraction, and bad pixel masking). Users must import the proper unprocessed target images, such as the one in **Figure 5,** as well as calibration frames. These calibration frames being bias images, gathered by covering your camera with something dark, such as the lens cap, and taking zero (or as close to as possible) second-exposure images, dark images, gathered by repeating the setup for bias images, but choosing the same exposure time and environment as the data images that you are gathering, and flat frames, gathered by imaging a uniformly lit surface, such as a white blanket or a clear sky at twilight. This project did not use flat calibration. DeepSkyStacker uses these input images to create a single final preprocessed image that can then be exported as a Flexible Image Transport System (FITS) file, such as the one in **Figure 6**. This final image had an effective exposure time of 13 seconds.

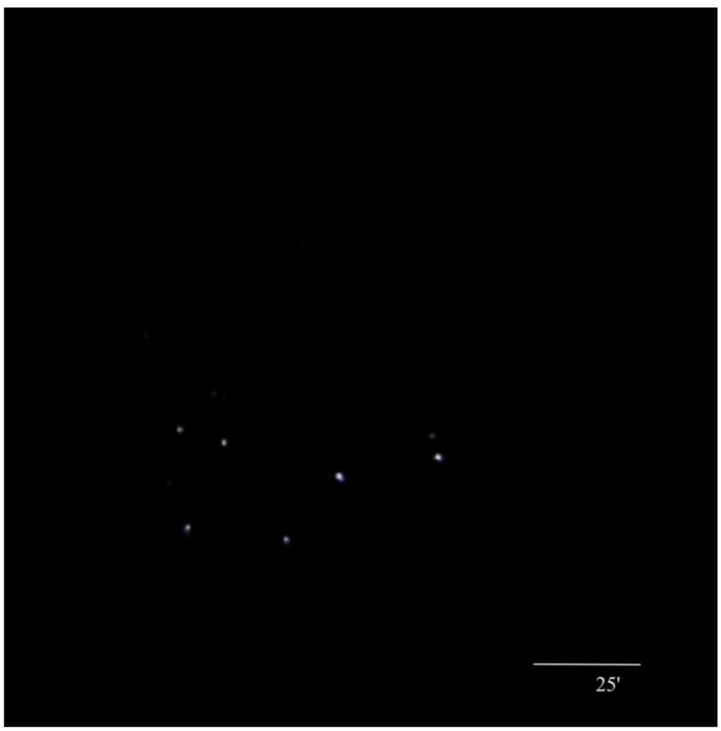


Figure 5. An unprocessed DNG image of M45 cropped and edited to make the stars more visible. This editing was not done for the actual data. The total field of view is approximately two degrees.

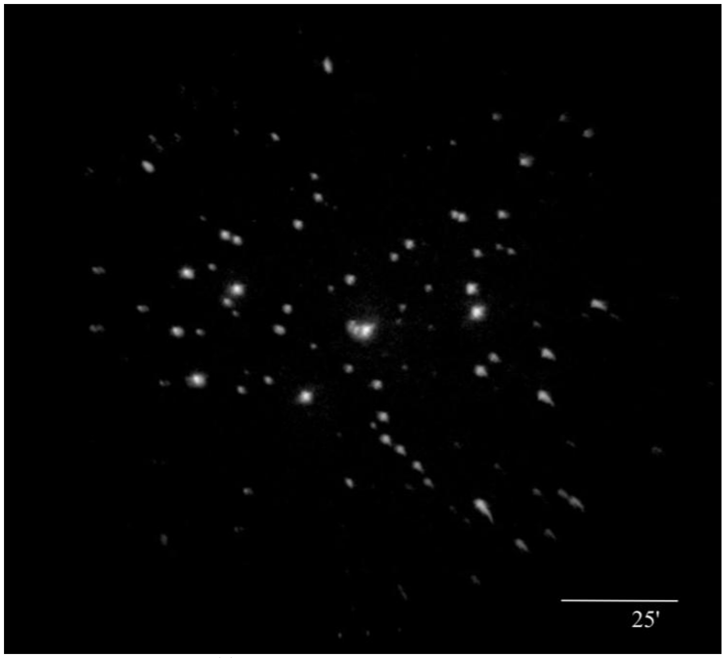
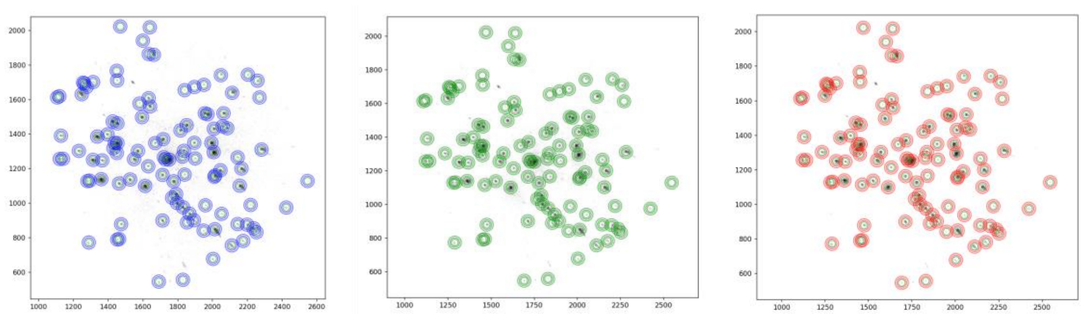


Figure 6. The stacked and preprocessed image of M45.

Once the preprocessed image was obtained, analysis was conducted using a Python script to perform the photometry. Python was chosen due to its large number of statistical and astronomical libraries. The four used in this project were NumPy, photutils, Astropy, and matplotlib. Using photutils' Image Reduction and Analysis Facility (IRAF) star finder, it was possible to locate stars in the image and perform aperture photometry on the located stars, as shown in **Figure 7.** To detect stars, the settings for IRAF star finder were a full-width half maximum (FWHM) of 5.0 pixels and a threshold of 5×10^{-5}. The FWHM is a measure of how sharp or blurry a star looks in an image, and it is measured as the pixel width of a typical stellar image at half of its peak brightness. The threshold describes the minimum possible value for pixel brightness that the IRAF star finder would use to distinguish stars from background noise. The rest of the inputs were left as default. The sources found with IRAF star finder were from the red image channel; there seemed to be some background noise in both the green and blue channels that interfered with star detection in the blue and green channels. The radii used for the aperture were 20 pixels, and the inner and outer radii for the annuli were 28 and 38 pixels, respectively. These values were chosen because they appeared to minimize the statistical error in the resultant data while maintaining a large enough set of apertures to contain every star and also have enough background subtraction not to include other sources for the most part. The result of the photometry was a flux that could be converted to a magnitude by using **Equation 1,** where M is the magnitude, f is the flux, and t is the exposure time. In the script, the zero point was chosen to be zero, as this project focused on performing relative photometry rather than absolute photometry.

$$M = zeropoint - 2.5log_{10}(f/t) \quad \textbf{Equation 1.}$$



Pixel Count Pixel Count Pixel Count

Figure 7. The images with the stars located and the apertures & annuli around them.

After the photometry was performed and errors were calculated, creating a color-magnitude diagram was relatively simple. Using matplotlib's subplot function, the individual magnitudes of each star in red, green, and blue on the y-axis and the difference between the different magnitudes were plotted.

RESULTS

The result of this project is the set of color-magnitude diagrams for M45 shown in **Figure 8**, created from data gathered with a low-cost telescope. Since the errors involved with these images are unquantifiable with our methodology, we opted to take the standard error of the flux for each data point using **Equation 2**, where N is the count of data points, in this case, being pixels within the apertures. From there, the errors were propagated to convert these errors to magnitude errors for each star using **Equation 3**, where dM is the magnitude error, f is the star's flux, and df is the flux error.

$$Standard\ Error\ = (Standard\ Deviation)/\sqrt{N}$$

Equation 2.

$$dM = (2.5/f) * df$$

Equation 3.

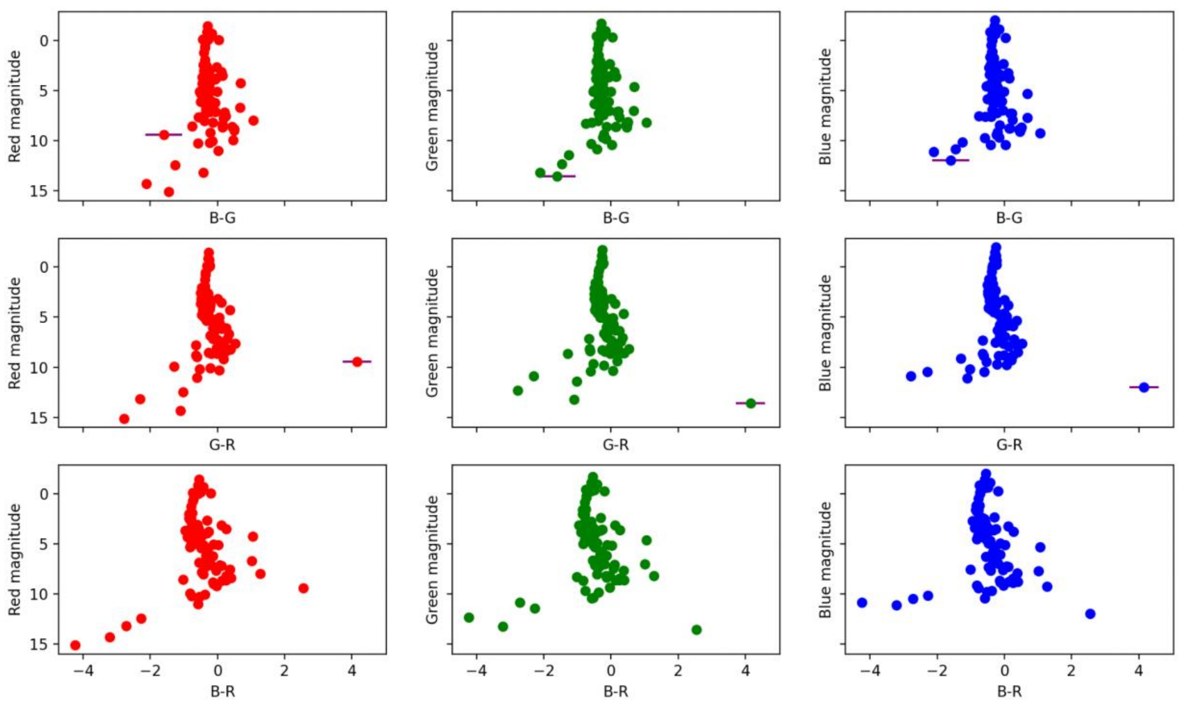


Figure 8. The resulting color-magnitude diagrams. The colors of the plot symbols correspond to the specific band (R, G, B band) plotted in the vertical axis in each column of subplots.

Not including personal costs, such as the iPhone 15 Pro and the computers used to write and run the code, the only necessary expenses were the telescope itself, and the mount used to place the phone on the telescope for more stable data. The total cost of this project was just under $100, not including personal equipment, such as the phone, or computers involved.

DISCUSSION

The maximum statistical errors for the red, green, and blue magnitudes are 0.055, 0.037, and 0.207, respectively, which include all data points. When removing data points that are dimmer than the maximum magnitude that a telescope can theoretically detect, also known as the "limiting magnitude," the maximum red and green magnitude statistical errors decrease slightly, being 0.055 and 0.031, respectively, but the maximum blue magnitude statistical error decreases to 0.047. These errors are low enough for strong confidence in the data, especially when investigating limiting magnitude-corrected data points, as they are four orders of magnitude below the range of the data. Despite the low error, there are some potential reasons for the larger errors that appear in some data points. One of which is the annuli and contamination from other stars. Some stars' annuli contain another star within them. In these cases, when the background is subtracted, it is subtracting another star's flux entirely, which may drastically affect the true value of the flux. This can be adjusted by changing the radius size of the annuli, but finding a sweet spot for annulus size can be difficult. For this research, the code was run with several annulus sizes, and a radius of 20 pixels minimized the data's maximum statistical errors.

These color-magnitude diagrams show a decently strong trend in line with the main sequence, which can be seen in **Figure 9**. The main sequence is the central downward trend on an HR diagram that corresponds to stars that are actively burning hydrogen. All young stars, such as members of M45, lie along the main sequence, so this is a point of evidence that the data is realistic. Some stars appear outside the main sequence, which are most likely either foreground or background stars, and not members of M45. It is also possible that these are stars that are close to the edge of the telescope's view and thus have a significant amount of streaking in the image. This would drastically affect the background subtraction aspect of the aperture photometry and may be the cause of these outliers. Another possibility is that these stars may be red giants. If this is the case, it is likely that they are foreground or background stars, as the brightest members of M45 are all B-type stars according to the Montreal Open Clusters and Associations database. As stars begin to run out of hydrogen, they cool and expand, leading to an overall rightward and upward deviation from the main sequence. In the data, these stars are brighter in red magnitudes than blue or green, which further supports this hypothesis. Many stars with lower magnitudes appear to have a large spread, which is likely caused by a low signal-to-noise ratio, causing more noise than stars with larger magnitudes. Many causes of noise are difficult to remove, especially after data has already been gathered. Despite this, it is possible to qualitatively remove some of the data points due to this telescope having a limiting magnitude of 11.2 as calculated by **Equation 4**, where M_{lim} is the limiting magnitude, and d is the telescope aperture in inches.

$$M_{lim} = 8.8 + 5log_{10}(d) \quad \textbf{Equation 4.}^{7}$$

This limiting magnitude is the dimmest possible value that a telescope can detect with a given aperture. Taking the limiting magnitude into account by removing stars with $M_{lim} > 11.2$ eliminates a majority of this noisy region. As well as this, changing the chosen data area to exclude data that appears to be streaked significantly in the final image removes the foreground and background star region and reduces the data spread significantly, as shown by **Figure 10**.

The main sequence is visible in the resulting color-magnitude diagrams, shown in **Figure 11**. This fact shows that even with low-cost equipment, astronomical data can be retrieved with a good deal of accuracy. Entry-level astronomers can observe the stars for enjoyment while learning and understanding how astronomy is done in the actual academic field. By understanding how to go through an astronomy research project and observing good results, students can have a more positive outlook on astronomy. From this, students could be more likely to observe and produce data on other objects, such as variable stars, globular clusters, and general star-forming regions, which can be done with a low entry cost. Accessibility is key to engagement, and the easier it is to access tools to perform astronomical observations, the more likely students will be inclined to become involved with the astronomical community as a whole.

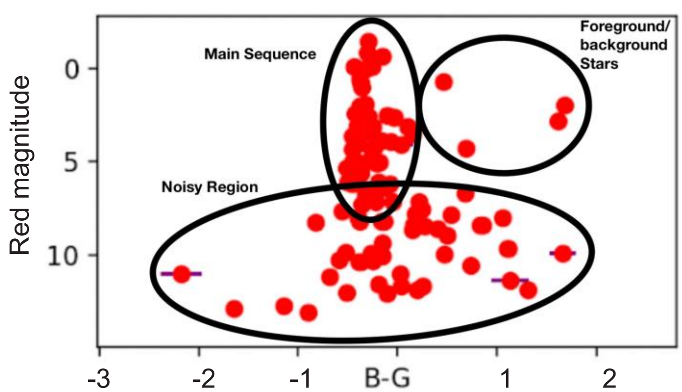


Figure 9. The apparent trend in the Red magnitude, Blue-Green color index subplot with the Main Sequence, as well as non-member/outlier stars, and noisy sources.

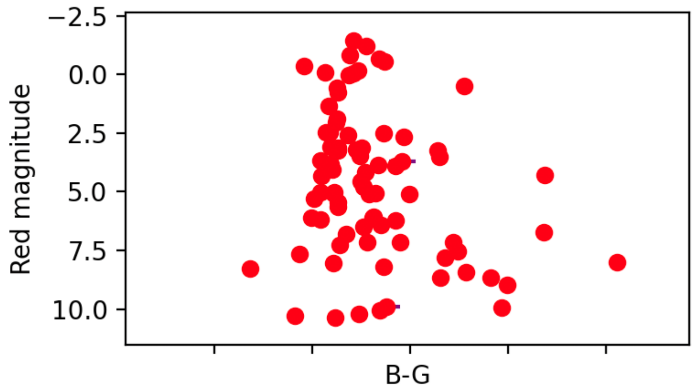


Figure 10. The same subplot as **Figure 9** with streak cropping and the magnitude limit taken into account for comparison.

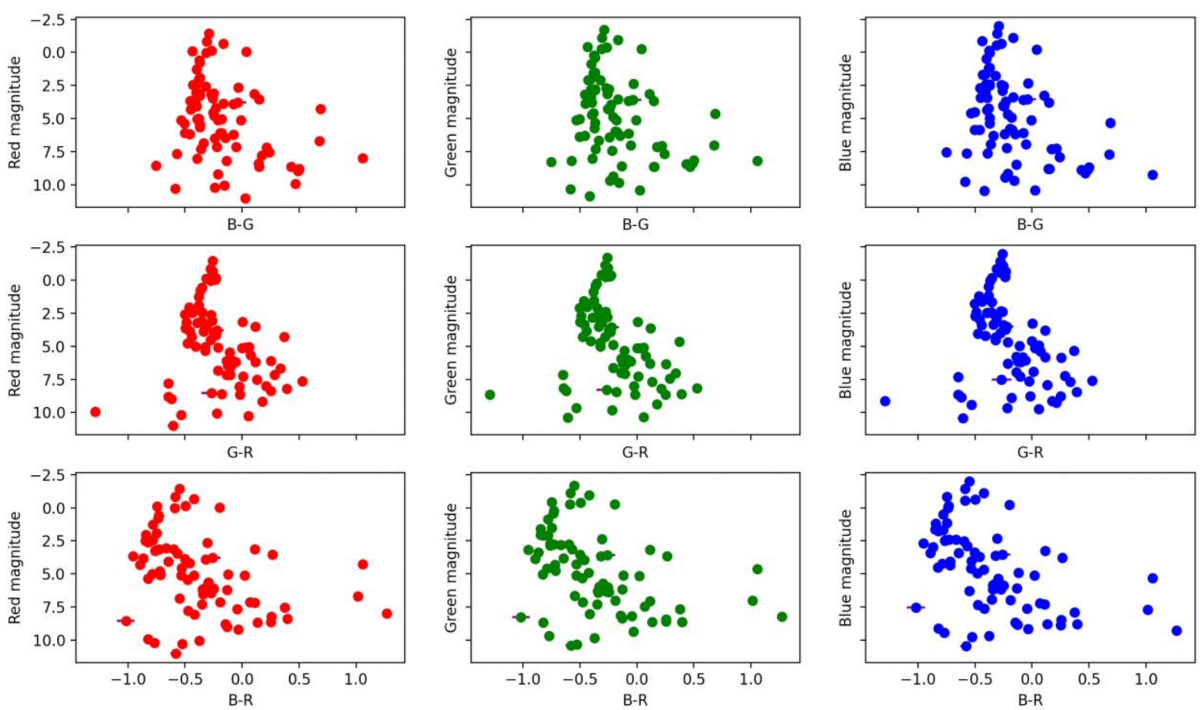


Figure 11. The resulting color-magnitude diagrams with streak cropping and magnitude limitation taken into account.

With this project, some approximations were made that could impact the accuracy of the results. For one, the observations were not done with any filters, so the color index, as previously mentioned, was blue-green rather than blue-visual, and instead of infrared, just red was used. The impact of this is likely that the magnitudes of blue and red, especially, are less extreme than they would have been had filters been used. For more accurate results, the project should be repeated with at least blue and infrared filters, which should be purchased for future iterations of this project, though one of the goals is to minimize cost, so this can be disregarded. These results also do not include any standardization to correct for extinction (absorption and scattering) caused by telluric contamination in the atmosphere known as the airmass effect. For any ground-based observation, the least amount of extinction can be obtained by observing a target along the direction of altitude of 90 degree where the airmass is defined as 1.0. Airmass value can be approximated as $Airmass = 1/cos(90° - altitude)$. The average airmass of M45 during the observations was low at 1.10, which has a definite, but relatively low impact on the results. It is also worth mentioning that the iPhone 15 Pro's camera uses a quad Bayer color filter array, meaning that a given image can be broken up into four-pixel squares where the color value is accurate. The other colors that are seen are interpolated from the surrounding pixels. The results of this project are consistent across each color, though, so the impact of this is likely small.

One thing that was quite troubling with the camera was the inability to have full control over the exposure times or ISO. The images were taken using Apple's "Night Mode" with a 5-second exposure time, but the resulting images' descriptions claimed that the maximum exposure time was 1.1 seconds. When investigating this, there was no primary documentation as to why this is. We brought the issue up to Apple photography forums, and the consensus was that the Apple camera app stops the actual data intake early for its ProRAW images to save on storage space. This is something that is troublesome and lacks a credible explanation, but it is unavoidable when using the native iPhone camera app. The iPhone's camera app also lacks direct control for the ISO, which makes it impossible to have a single ISO value for all of the images. The way to minimize the ISO was to turn the exposure down as low as it would go, but this provided an ISO of 100-400, which could theoretically be lower. Apple also uses DNG format files rather than RAW files, meaning that there was some level of processing on the images. This app was chosen because it comes predownloaded onto all iPhones, and as a result, is the most widely used camera app for iPhone users. For this reason, it is likely the app with which most people would be familiar. Despite this, it may be viable to use a different camera app that can take DNG or RAW image files without being as problematic with the exposure time or ISO. Some options are Nightcap, which is exclusive to iOS, or ProCam X, though neither is free, which would add to the overall cost of the project. If cost is not as significant an issue, one could even use an inexpensive camera that is intended for astronomical use, such as the ZWO ASI662MC USB3.0 Color Astronomy Camera. Future iterations of this research could also benefit by observing some standard astronomical object(s) and performing standard transformations on the magnitudes of the star cluster of choice to achieve higher accuracy in magnitude calculations. It would also be better in a future iteration of this project to opt not to use any digital magnification, as this diminishes the quality of the image.

Something that is also worth bringing up is the fact that flat calibration was not performed for this project. Because of this, it is possible that pixel sensitivity variation across the image is causing problems with the accuracy of the pixel brightnesses. It is also possible that the dark correction is imperfect as the exact times that the dark frames were taken was up to a few minutes apart from when some science frames were captured. To try to balance this, dark frames were taken in the middle of capturing science frames, so that the temperature when the dark frames were gathered was colder for the last science frames, but warmer than the first science frames. The conditions at the time of observation may have also been not perfectly photometric, which could impact the overall results. Even using the identical setup of this project, future students may be able to achieve a better result by implementing the full, standard digital photometric data reduction scheme used in astronomical imaging observations. This entails all the corrections already included in our project (bias, dark, stacking, etc.) plus flat correction and the standardization of the observation. The standardization step involves the observation of known brightness calibration stars, known as the photometric standard stars, to transform the measurements into the standard filter system brightness scales widely used in astronomy.

CONCLUSION

This project's broader scope can be seen in the opportunities it helps provide, especially for the astronomy education environment with a limited budget. The use of inexpensive astronomical equipment, such as the Celestron FirstScope, is an important tool for teaching the next generation of aspiring astronomers about space, astronomy research, and data science as a whole. This is supported by the apparent "main sequence" trend, as well as the low amount of error involved with the data itself. There is often a stigma with astronomy that a great deal of high-level equipment is a necessity to retrieve any reliable data. The results of this project help support the idea that this is not always the case. Students, and more generally, people interested in astronomy, can utilize low-cost equipment to perform photometry to gain a better understanding of how the brightness of stars affects our understanding of them. Astronomy, and science as a whole, should be open to anyone interested in the field and should have opportunities for those who seek them, not just those with high-grade equipment or those at the professional level. Educators should not dismiss the use of such low-cost equipment, as it holds great opportunity to be used as a tool for hands-on learning.

REFERENCES

1. Ates, Ö. & Eryilmaz, A. (2011) Effectiveness of hands-on and minds-on activities on students' achievement and attitudes towards physics. *Asia-Pacific Forum on Science Learning and Teaching, Volume 12, Issue 1, Article 6, p.1 (Jun., 2011). https://www.eduhk.hk/apfslt/v12_issue1/ates/index.htm*
2. Deslauriers, L., McCarty, L. S., Miller, K., & Kestin, G. (2019) Measuring actual learning versus feeling of learning in response to being actively engaged in the classroom. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(39). *https://doi.org/https://doi.org/10.1073/pnas.1821936116*
3. Kanwal, W., Shahid, S., & Jabeen, F. Effectiveness of Low Cost Material to Teach Science at Primary Level. Journal of Management Practices, Humanities and Social Sciences. *https://doi.org/10.33152/jmphss-6.2.12*
4. Harvard-Smithsonian Center for Astrophysics. (2012, April 9) *Educational materials :: Pulsating variable stars and the hertzsprung-russell diagram*. Chandra X-Ray Observatory. *https://chandra.harvard.edu/edu/formal/variable_stars/HR_student.html*

5. Center for Astrophysics Harvard & Smithsonian. (2014, Sept, 19) Retrieved February 15, 2025 from *https://www.cfa.harvard.edu/news/how-far-are-pleiades-really#:~:text=The%20Pleiades%20is%20a%20relatively,Jurassic%20dinosaurs%20passed%20into%20history*
6. Light Pollution Map. Retrieved February 15, 2025, from *https://www.lightpollutionmap.info/#zoom=15.33&lat=33.7267&lon=-83.3006&state=eyJiYXNlbWFwIjoiTGF5ZXJCaW5nUm9hZCIsIm92ZXJsYXkiOiJ3YV8yMDE1Iiwib3ZlcmxheWNvbG9yIjpmYWxzZSwib3ZlcmxheW9wYWNpdHkiOjYwLCJmZWF0dXJlc29wYWNpdHkiOjg1fQ==*
7. Bowen, I. S. (1947) Notes From Observatories. *Publications of the Astronomical Society of the Pacific*, *59*, 253. *https://doi.org/10.1086/125959*

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PRESS SUMMARY

Hands-on learning is crucial for students' understanding of complicated topics, such as astrophysics. Astrophysics students are often taught more theoretical concepts than practical research skills, and as a result, often do not have the opportunity to reap the benefits of hands-on education. This is a complicated problem, as it is difficult to obtain astronomical equipment due to high costs; large telescopes and good camera equipment are expensive. This is an enormous drawback for students' education, as they cannot apply the knowledge they gain in the classroom setting. This paper aims to show that producing astronomical data is possible even with low-cost, entry-level equipment, which can be utilized in classroom settings to teach students about typical astronomical research methodology through hands-on learning.