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Catching Cosmic Rays with a DSLR

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Abstract

Cosmic rays are high-energy particles from outer space that continually strike the Earth's atmosphere and produce cascades of secondary particles, which reach the surface of the Earth, mainly in the form of muons. These particles can be detected with scintillator detectors, Geiger counters, cloud chambers, and also can be recorded with commonly available photographic equipment. Many current digital single lens reflex (DSLR) cameras contain complementary metal oxide semiconductor chips that are sensitive to these charged particles at long exposures and high light sensitivity settings. Suggestions are given on how to incorporate this method of capture and display as a teaching tool for physics. DSLR high-energy particle capture could be used as a classroom demonstration, as a laboratory experiment to accompany a high-energy particle physics discussion, or presented as an inquiry-based research project for advanced undergraduates.

1. INTRODUCTION

Historically, charge-coupled device (CCD) cameras used for astronomical purposes have been susceptible to the effects from cosmic ray strikes, creating dots and streaks on images when long exposures were taken. More recently, cosmic rays have been responsible for problems with computer equipment such as those on satellites and power grids (Friedlander 2002) and possibly causing failure in the acceleration systems for some vehicles (O'Neill 2010).

On the AstroLrner listserv, sponsored by NASA's Center for Astronomy Education (2009), C. Renee James posted a question on 3 November 2009 asking, "Does anyone know whether the CCDs in store-bought digital cameras can detect cosmic rays?" An extensive and interesting discussion continued in subsequent posts.

The main reason that it would be difficult to find cosmic rays with an inexpensive digital camera, such as that on a cell phone, is because you do not have much control over shutter speed and other settings. However, with a digital single lens reflex (DSLR) camera that has a "bulb" setting, the photographer has greater control over the exposure time. Being unable to find information on the Internet about using DSLR cameras to study cosmic rays, an attempt was made to detect them using a Nikon D90.

2. THEORY

Cosmic ray studies are an accessible way of bringing high-energy particle physics into the classroom. The term "cosmic ray" is a misnomer because, instead of rays, cosmic rays are comprised mainly of particles. These particles are mostly energetic protons that hit the nuclei of atmospheric gases and produce showers of secondary radiation. These collisions produce short-lived mesons, mostly pions, which in turn produce muons (Friedlander 2002). In addition, neutrinos, electrons, and gamma rays are produced in an ever-changing cascade or shower of interactions. To help students visualize these complex interactions, an instructor may wish to refer to the three-dimensional computer simulation movies that were created for the Pierre Auger Observatory in Argentina (Landsberg, Surendran, and SubbaRao 2005).

The muons produced are the most numerous energetic charged particles at sea level, and it is estimated that the average muon cosmic ray flux at sea level is approximately 1 $\text{muon}/\text{cm}^2/\text{min}$ (Kliewer 1997). The Earth's magnetic field deflects the primary particles, and this, as well as different path lengths for the particles, causes differences in cosmic radiation intensity dependent on altitude, azimuth angle, latitude, longitude, and direction from which they seem to originate (East-West effect) (Friedlander 2002). Although there may be significant variation in cosmic ray flux among different locations throughout the country, the flux at an individual site remains relatively constant. Cosmic ray flux variation of less than 10% at a given location has been used to study solar effects and changes in the Earth's climate (Svensmark 1998).

From the specifications of the Nikon D90 camera (Nikon Corporation 2010) that was used in this study, the sensor chip is 15.8 $\text{mm} \times 23.6$ mm. This camera uses a complementary metal oxide semiconductor (CMOS) chip rather than a CCD, but it also is susceptible to the ionizing muons produced by the cosmic ray showers. This would mean about two counts should strike the sensor per minute, a 5-min run would produce about ten counts, and a 10-min run should yield about 20 counts.

3. METHOD AND FINDINGS

To simplify the system, the lens was removed from the body of the camera and was replaced by a light-tight body cap. To keep the shutter open for several minutes, a digital timer accessory was attached to make use of the bulb function of the camera. The International Standards Organization (ISO) setting for digital cameras is similar to the old American Standards Association (ASA) light sensitivity settings for film cameras. The first image was exposed for 5 min and set at a high sensitivity, 3200 ISO. The higher the ISO, the more sensitive it is, the higher the amplification, and the more noise you will have on your image. This is why photos appear grainy if taken at a high ISO. When the ISO was set at 3200 for a 5-min exposure, it produced a consistent reddish color on the right side of the frame [as seen in the following image (Figure 1)]. This dark noise image is highly repeatable for the given settings.

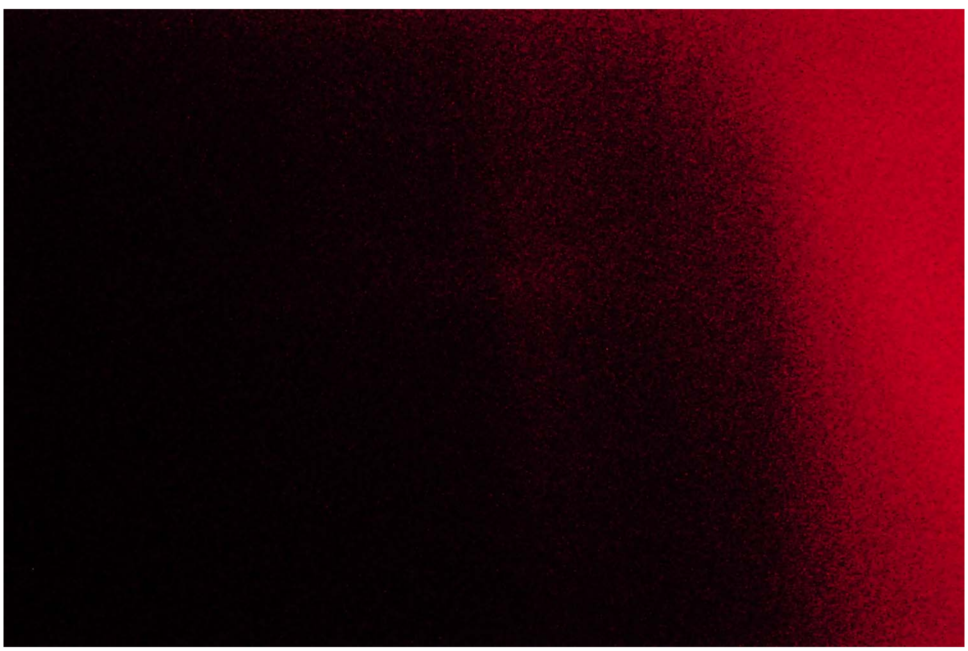

Figure 1. Photo taken by Kendra Sibbernsen, Omaha, Nebraska (2009)

Two common photo file formats for the newer DSLR cameras are JPEG and RAW. The image in Figure 1 was taken in RAW format at high resolution. Some professionals use RAW and others shoot in JPEG exclusively, but this is a matter of personal preference. When the image was examined at high magnification, there were several white dots and a few streaks visible that are distinctly different from the red blotches on the right-hand side of the image. See the cropped and enlarged images below (Figures 2(a) and 2(b)).

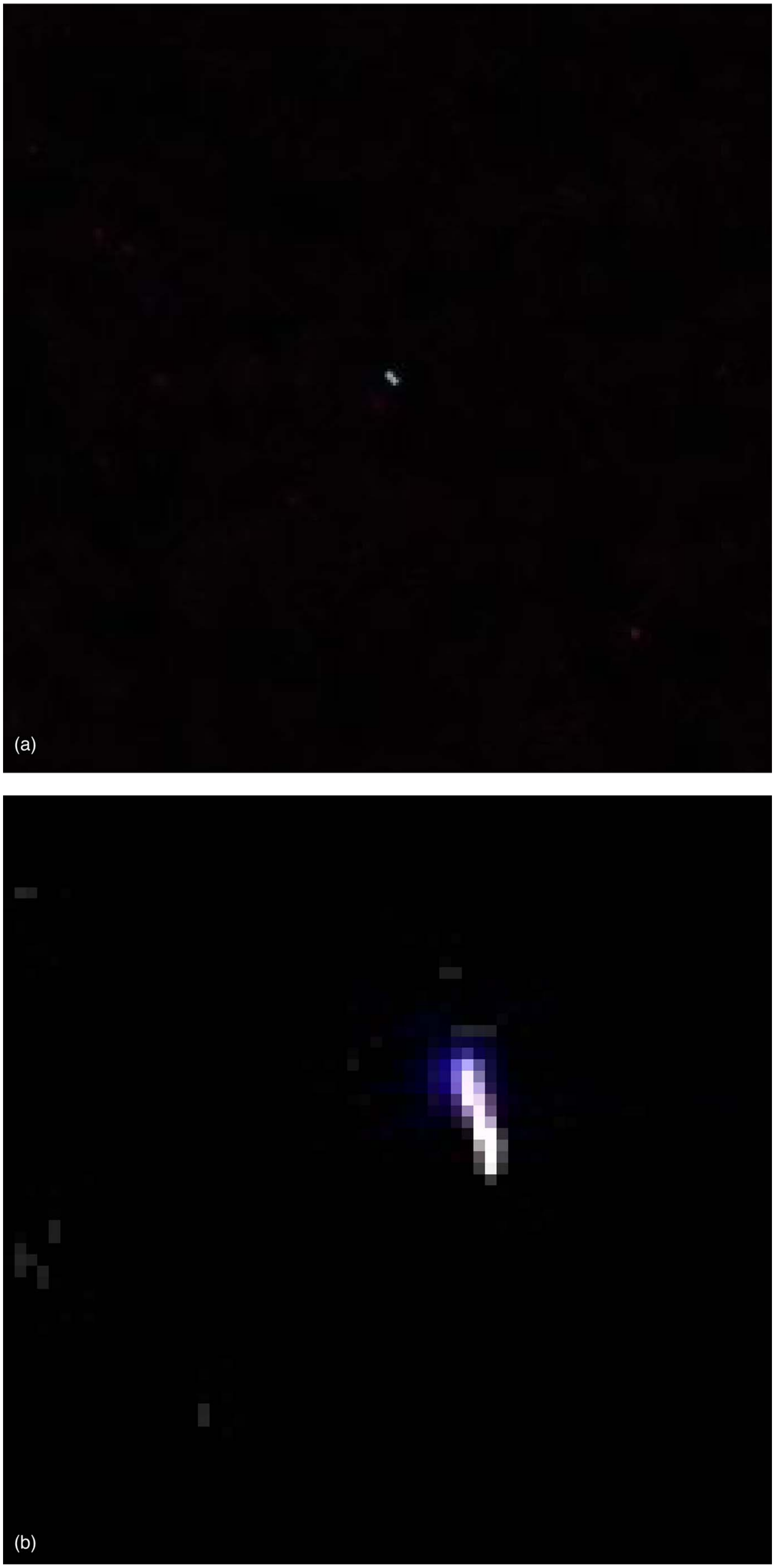

Figure 2. Close up images of streaks. Photos taken by Kendra Sibbernsen, Omaha, Nebraska (2009).

Because these dots and streaks are in different positions from image to image, this discounts the possibility of them being caused by bad pixels on the chip. In addition, occasionally a few of the incident streaks were pointed in the same direction, indicating that they possibly could have been produced by the same shower of secondary particles.

Roy Lorenz, an AstroLrner contributor, attempted to reproduce these results by using his Canon XTi with 1600 ISO, the highest setting, for 10-min exposures. He processed the images using freeware called GNU Image Manipulation Program, version 2, and circled the white dots to count the hits. One of his large images and a close up are attached with permission (Figures 3 and 4).

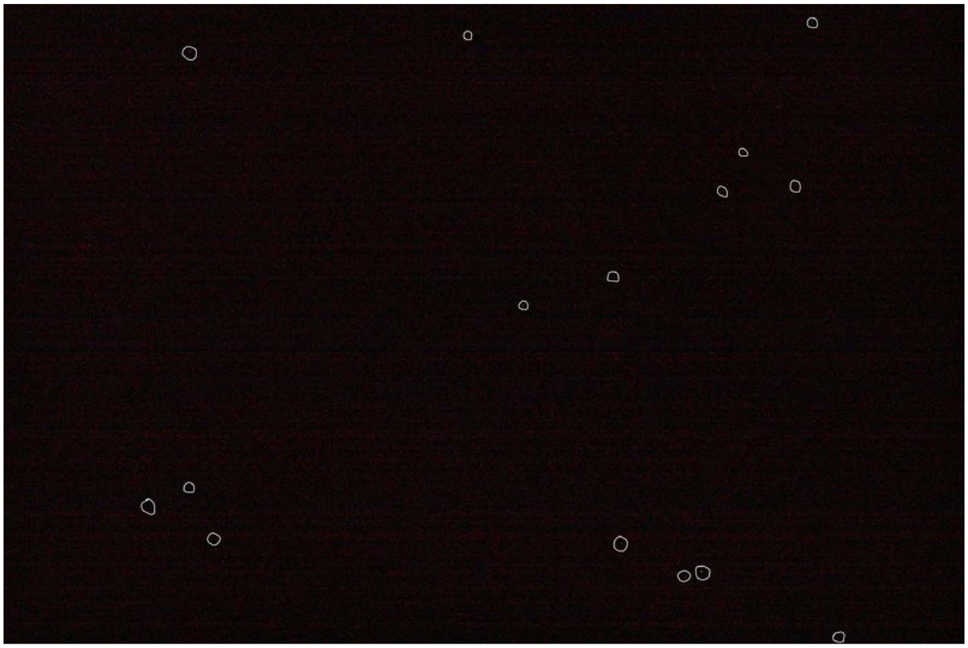

Figure 3. Photo taken by Roy Lorenz, Tuscon, Arizona (2009)

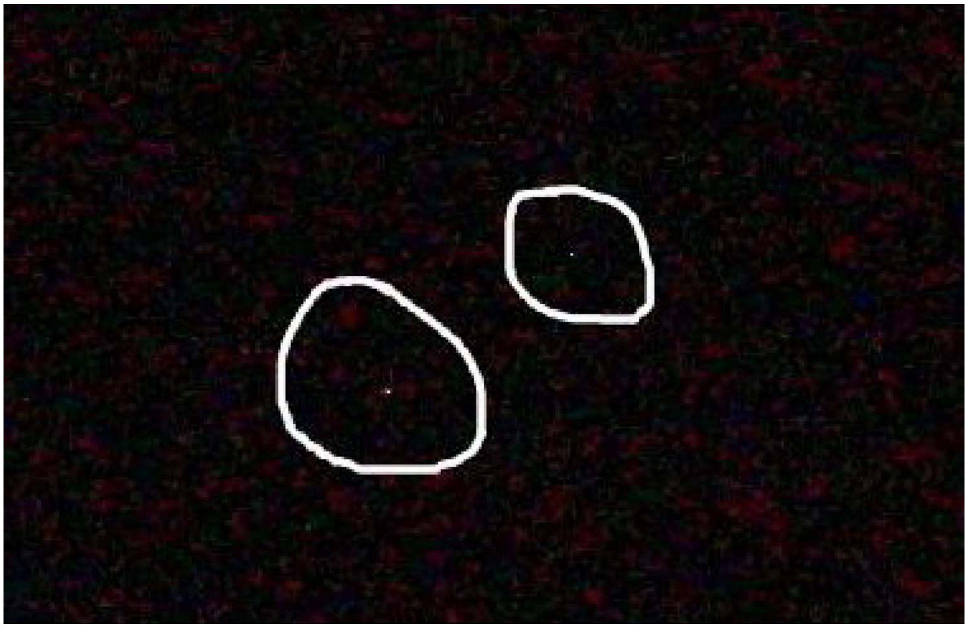

Figure 4. Photo taken by Roy Lorenz, Tuscon, Arizona (2009)

Lorenz counted ten hits in his first image and 15 in his second. Similar settings for a 10-min exposure using the Nikon D90 in a different part of the country produced 16 hits with a few additional spots that were questionable. Therefore, it seems that the cameras are detecting slightly fewer hits than the average muon cosmic ray flux of the previous section, about 20 hits in a 10-min exposure. The Canon XTi CMOS chip is slightly smaller than the Nikon D90; the same estimations used before would yield approximately the same number of hits in a 10-min exposure. Using Poisson counting statistics, the standard deviation should be about equal to the square root of the number of counts. Therefore, a typical error of approximately three out of ten counts and between four and five out of 20 counts is expected.

4. CONCLUSIONS AND RECOMMENDATIONS FOR EDUCATIONAL USES

The CCD or CMOS chips in DSLR cameras seem to be able to detect cosmic ray hits with sufficiently high ISO settings at long exposures. This technique could be used to bring high-energy particle physics to students. It could be used as a demonstration for astronomy or physics classes, a semester-long field project for an advanced student, or to develop a laboratory experiment. If an online astronomy student was an amateur photographer and had access to a DSLR camera, he or she could do a project and upload the images to share with the class. Students could develop their own inquiry-based research questions, such as:

Does it make a difference if I have the lights off or on?

Does it make a difference if I have the camera on its side or on its back?

Does it make a difference if I take the pictures inside the building vs. outside?

Can I find anything that will shield the camera from the cosmic rays?

Does it make a difference if I wrap my camera in tin foil?

Does it make a difference if you get near a weak radioactive source?

Does it make a difference if you take an image while on an airplane in flight?

4.1. Classroom Example

A cosmic ray laboratory exercise, such as the one described, was performed by a small group of physics students in their last laboratory of the year. Each laboratory group used either a Nikon D90 with a CMOS chip or a Nikon D70 with a CCD chip. Because it was not expected that students would know how to use a DSLR camera or the image processing program, it was important to design the laboratory to scaffold their laboratory experience so that they eventually could ask interesting questions about cosmic rays. A backward-faded scaffold design (Slater, Slater, and Shaner 2008) was used in the development of the laboratory exercise. This design provides the framework to allow students to perform an open-inquiry exercise. It begins with giving a student the question, method, data, and conclusion; subsequent activities require the student to perform more of these tasks themselves. The reason it is called “backward” is because the final step is to have the student independently ask a research question, which is usually the beginning of the scientific process.

The first phase was an exploration using the DSLR camera with a lens. Students were instructed to have each laboratory group member take photographs of each other with the camera on the “AUTO” setting. Under this setting, the camera will automatically set the exposure, ISO, and the focus. With a large memory card, the cameras can record hundreds of photographs that can be deleted quickly and easily if the images are not to their liking. Students generally had an enjoyable time posing and taking photos, and, as a bonus, the instructor had a digital record of the teams. The next step was to have students download the images of their classmates to the computer with the cable provided. Students were then instructed to remove the lens, replace it with the body cap, set the camera to “M” (manual), and plug in the timer/bulb mechanism. They were then to take a 10-s image, a 1-min image, and a 5-min image and examine the results. The 10-s image was completely dark. Few hits, if any, were viewed on the 1-min image, but there were some visible artifacts on each 5-min image.

The second phase was designed to have students think critically about a conclusion given certain evidence. Rather than telling them how to discern the difference between bad pixels, thermal noise, and actual cosmic ray hits, the students are asked if they agree or disagree, based on their previous observations, with someone who generalizes that “there is no way to determine the difference between bad pixels or random noise and cosmic rays." Most students will say that bad pixels will be at the same position each time and cosmic rays will be at random places on each image. They may also mention that the thermal noise produces "blotchy" faint colors, while the cosmic rays seem to strongly affect only a few pixels and produce white dots or streaks.

The third phase of the exercise presents the given research question as well as a given set of data, and the students are to determine a conclusion based on the evidence presented. This question is asked: "How many cosmic rays hit the sensor chip per minute?" Different techniques could be used to answer this question, and the students are asked to explain their reasoning. General Studies students likely would take averages, where more advanced students may graph the data and find the slope of the regression line.

The fourth phase gives students the research question only and asks for them to develop a procedure. They do not have to perform this procedure but would explain in detail how they would answer the question "How many cosmic rays fall in one square meter per second in your city?"

The fifth phase gives the students the opportunity to design their laboratory experience by asking an appropriate research question, determining the procedure, taking the data, analyzing it, and coming to a conclusion. Each group may ask valid questions; however, as often happens in professional science situations, the results may not be quite what they anticipated. This can produce a teachable moment about the nature of science and how these unanticipated results should not be considered failures. It also provides an opportunity to discuss how the students would remedy any problems they encountered, additional studies they would perform if they had more time, and how much error they would expect. At the end of the exercise, each student summarizes what was learned in the laboratory session in a critical reflection. Students may express that they particularly enjoyed this laboratory because they had the freedom to design their own research.

4.2. Tips for Digital Image Manipulation and Attaining Equipment

For the described laboratory exercise, students used the Photo Viewer and Microsoft Paint program on Windows PCs that were standard on the college network. This is not recommended because of the program limitations, especially with the limits in the ability to zoom.

If iPhoto for the Mac is used, under the "Edit" mode is the "Adjust" control. Rather than using the "Exposure" slider bar that brightens or darkens the image uniformly, increasing the "Shadows" slider bar darkens the dark background and brightens the bright spots making them easier to view and count in a large image. If there are any streaks on the image, these become very prominent.

In an image manipulation program such as Photoshop Elements, the drawing tool can be used to create circles, using the "pencil," by creating a white line around the hits (while zoomed in) to make them easier to count on a large image. Another possibility is to use the invert tool and the negative image will be shown. This would provide a white background with dark spots, and this may make it easier to count the spots.

If a faculty member does not have access to a personal DSLR camera with a bulb feature, one may be available for checkout from the Photography Department if such a program is available. Another affordable alternative is to rent a DSLR camera body from a quality photography store or an online photo equipment rental service. Because every model of DSLR camera may have different characteristics, it is suggested that an instructor become well acquainted with the camera before using it in the classroom to find the best settings.

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