



OBSERVATIONAL ASTRONOMY ACTIVITY

Cookie Cutter Astrophysics: Beginning CCD Photometry



http://gtn.sonoma.edu/activity/cookie_cutter_photometry.php





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Credits:

This activity was developed as part of the NASA Gamma-Ray Large Area Space Telescope Education and Public Outreach Program at Sonoma State University, under the direction of Professor Lynn Cominsky.

Contributors to this activity include Dr. Gordon Spear, Tim Graves, Dr. Lynn Cominsky, Dr. Phil Plait, Sarah Silva, and Aurore Simonnet. We would like to acknowledge the American Association of Variable Star Observers for their help.



Stepping Into The Classroom!

Follow the Root Steps:

Elicit	The instructor assesses the learners' prior knowledge and helps them become engaged in a new concept by reading a vignette, posing questions, doing a demonstration that has a non-intuitive result (a discrepant event), showing a video clip, or conducting some other short activity that promotes curiosity and elicits prior knowledge.	
Engage		
Explore	Learners work in collaborative teams to complete activities that help them use prior knowledge to generate ideas, explore questions and possibilities, and design and conduct a preliminary inquiry.	
Explain	Learners should have an opportunity to explain their current understanding of the main concept. They may explain their understanding of the concept by making presentations, sharing ideas with one another, reviewing current scientific explanations and comparing these to their own understandings, and/or listening to an explanation from the teacher that guides them toward a more in-depth understanding.	
Elaborate	Learners elaborate their understanding of the concept by conducting additional activities. They may revisit an earlier activity, project, or idea and build on it, or conduct an activity that requires an application of the concept. The focus in this stage is on adding breadth and depth to current understanding.	
Evaluate		The evaluation phase helps both learners and instructors assess how well the learners understand the concept and whether they have met the learning outcomes. There should be opportunities for self assessment as well as formal assessment.
Extend		Learners should also be given an opportunity to extend their new found knowledge.

Learn More:

Science Teacher: Expanding the 5E Model - by Arthur Eisenkraft, September 2003.

Designing Professional Development for Teachers of Science and Mathematics - Susan Loucks-Horsley, Nancy Love, Katherine E. Stiles, Susan Mundry, Peter W. Hewson - Corwin Press.





Some Technical Details about CCDs

A CCD is constructed in the same manner as a computer chip. The CCD detector is composed of an array of rows and columns of individual light sensitive elements or pixels. An incoming photon of light strikes the detector and produces electrons that are stored in the detector until they are read out. Built-in electronics will organize these electrons as charge packets and a computer can display and record these packets as a digital image. The resulting digital image is composed of numbers that correspond to the relative numbers of photons that struck the individual pixels. These numbers are generally called the “pixel values”.

Figure 1 is a schematic representation of a detector with X columns and Y rows.

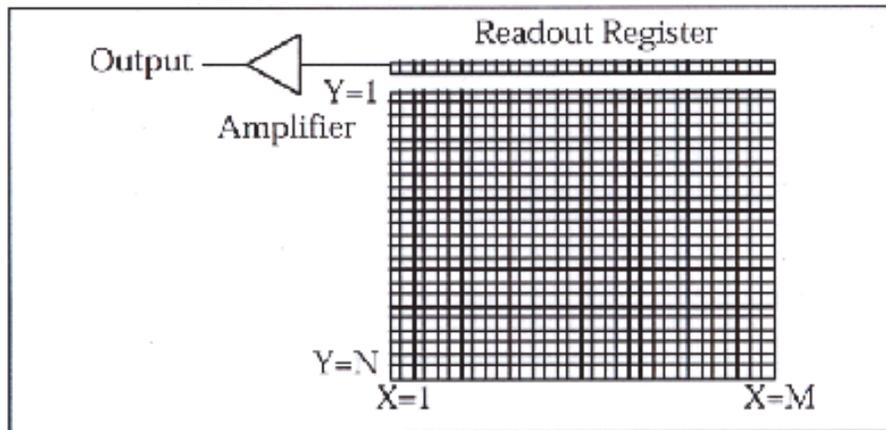


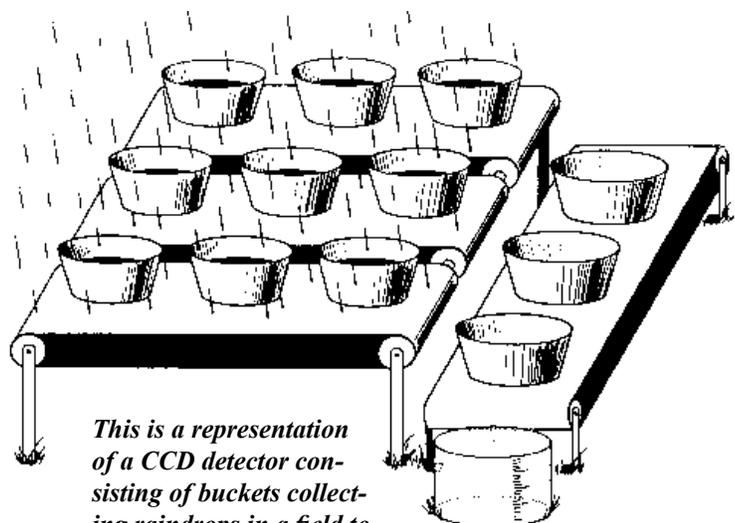
Fig. 1

The classic description of how this all happens was eloquently described in a paper by James Janesik and Tom Elliott of the Jet Propulsion Laboratory. This was first published as “History and Advancements of Large Area Array Scientific CCD Imagers,” by the Jet Propulsion Laboratory, California Institute of Technology, CCD Advanced Development Group.

Imagine an array of buckets covering a field (see fig. 2). After a rainstorm, the buckets are sent by conveyor belts to a metering station where the amount of water in each bucket is measured. Then a computer would take each of these data and display a picture of how much rain fell on each part of the field. In a CCD the “raindrops” are photons, the “buckets” the pixels, the “conveyor belts” the CCD shift registers, and the “metering system” an on-chip amplifier.

Technically speaking, the CCD must perform four tasks in generating an image. These functions are:

1. Charge generation
2. Charge collection
3. Charge transfer
4. Charge detection



This is a representation of a CCD detector consisting of buckets collecting raindrops in a field to produce a picture of how the rain was distributed as it fell.

Fig. 2

The first operation relies on a physical process known as the photoelectric effect – when photons strike certain materials free electrons are liberated. In the second step the photoelectrons are collected in the nearest discrete collecting site or pixel. The collection sites are defined by an array of electrodes, called gates, formed on the CCD. The third operation, charge transfer, is accomplished by manipulating the voltage on the gates in a systematic way so the signal electrons move down vertical registers from one pixel to the next in a conveyor-belt like fashion. At the end of each column is a horizontal register of pixels. This register collects a line at a time and then transports the charge packets in a serial manner to an on-chip amplifier. The final operating step, charge detection, is when the individual charge packets are converted to an output voltage. The voltage for each pixel can be amplified off-chip and digitally encoded and stored in a computer to be reconstructed and displayed on a computer monitor.

Even though stars are technically point sources of light, a real star image will have some physical size due to the blurring by the earth's atmosphere (technically known as seeing) and the diffraction and interference of the light waves that produce the image. A real star image will appear as the so-called seeing disk (see figure 3). This pattern will be brighter at the center of the disk and approach the sky background at the edges of the pattern.

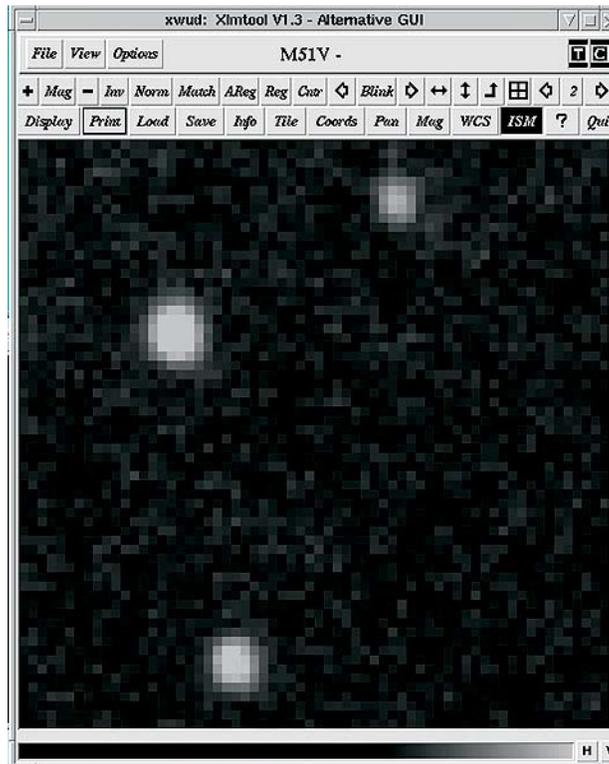


Fig.3 - This is a real astronomical image showing three stars. Note the pattern of light, which is bright in the middle and fades near the edges

Some Apparent Magnitudes

Some Bright Things

sun -26

full moon -12

Venus (at brightest) -4

Jupiter, Mars (at brightest) -2

brightest star (Sirius) -1.5



Some Faint Limits

average of brightest stars 1

naked eye limit 6

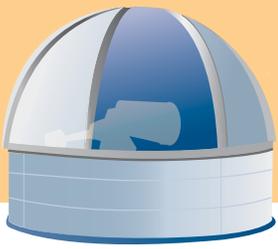
binocular limit 9

14 inch telescope 14

36 inch telescope 17

200 inch telescope 20

HST (80 inch) 29



Cookie Cutter Photometry

Duration:

Introduce concepts: 1 hr

Perform activity: 1 hr

Background Information

Digital images

Digital images are produced by special detectors. The most common detector available today to produce digital images is based on the concept of the Charge Coupled Device (CCD). In addition to being the detector of choice throughout much of modern astronomy and astrophysics, CCD detectors are the detectors in consumer level digital cameras and video camcorders.

A CCD is constructed in the same manner as a computer chip. The CCD detector is composed of an array of rows and columns of individual light sensitive elements or pixels. Incoming photons of light strike the detector and produce electrons that are stored in the detector until they are read out. Built-in electronics will organize these electrons as charge packets and a computer can display and record these packets as a digital image. The resulting digital image is composed of numbers that correspond to the relative numbers of photons that struck the individual pixels. These numbers are generally called the “pixel values.”

When astronomers use CCDs to detect photons, they are usually focusing light from the astronomical object with a telescope. Even though stars are technically point sources (because they are so far away), atmospheric effects, as well as other optical effects, blur the star into a disk. Astronomers call this “seeing,” and the apparent size of the blurred star is called the “seeing disk.”

Here is a highly magnified digital image of a real star (figure 4).

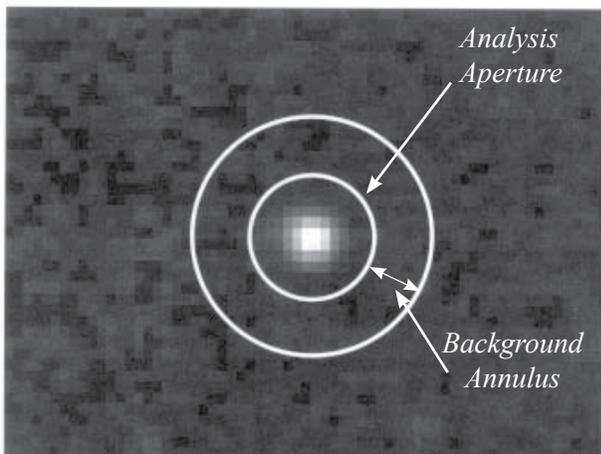


Fig. 4

we will have a number that represents the brightness of the star. (This number is ultimately directly related to the number of photons coming from the star that struck the detector during the time the exposure was being made.)

Notice that you can see the individual pixels in the star image, as well as in the background. The inner circle represents the region within which effectively all the light from the star has struck the detector. For determining stellar brightness this is termed the “analysis aperture.” If we add up all the pixel values in this analysis aperture

Essential Question

How can we measure the brightness of a star?

Science Concepts:

- Stars have different brightnesses, which can be measured using digital detectors
- Digital detectors measure brightnesses more accurately than the human eye
- Astronomers use the magnitude system to measure star brightnesses.

Objectives: Students will...

- learn about digital images.
- learn about the astronomical magnitude system.
- understand how to determine brightness for astronomical objects.
- gain experience using logarithms.

However, other sources of light also reach the pixels in the analysis aperture. We must correct our star brightness in the analysis aperture for this effect. For more information on this, see the section *Background Correction* below.

It can be useful to think of a digital star image in terms of a three dimensional histogram of pixel values (see figure 5).

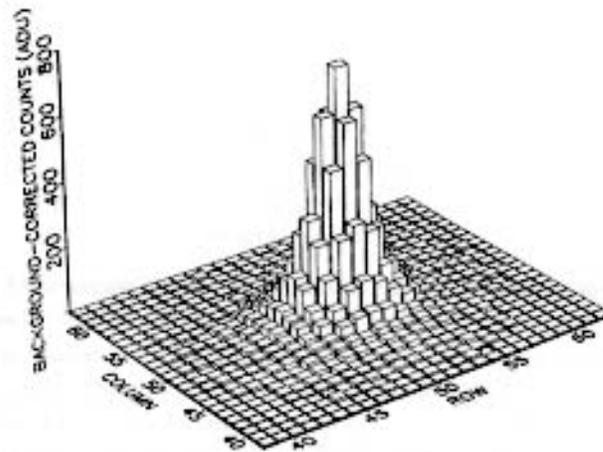


Fig. 5

Here the height corresponds to the value at a particular pixel and the rows and columns correspond to the location on the detector. If we could actually construct a 3D model of this pattern (say, out of blocks or clay) and then weigh the part caused by the star we could also use this number (the weight) to represent the brightness of the star. Of course, we would also need to correct this approach for the contribution due to the background.

Background Correction

When making a measurement of a star's brightness, we must be careful to correct for any other sources of light. These can contaminate the values of the star brightness. These sources include light from the sky and from the detector itself. Together these are called (for obvious reasons) "background counts."

Even under the most ideal circumstances the sky is never truly black, that is, without any light. Of course, in an urban or even a suburban environment light pollution from artificial light sources will illuminate dust and molecules in the atmosphere. The atmosphere itself emits some light resulting from interactions of solar wind particles with the upper atmosphere. Another source is the integrated light from faint and distant stars. All of these sources from the sky are recorded by the detector, and are collectively called the "sky brightness."

A final important source results from the detector itself. Even in the total absence of light a detector will produce electrons that get placed into the pixels. For an electronic detector this is termed "dark current."

In order to accurately measure the brightness of a star, the observer must correct for these background counts. The "background annulus" formed by the inner and outer circles represents a region we can use to estimate the average background brightness reaching each pixel. This factor may be used to correct the pixel sum from the analysis aperture depending on the number of pixels in the analysis aperture.

In this exercise, you will determine a method of doing this, and then determine the brightness of a star using the magnitude system.

The astronomical magnitude system

Astronomers measure the brightness of stars, galaxies, and even the sky itself using the “magnitude system.” Historically, the magnitude system is based on a concept first introduced by the Greek astronomer Hipparchus in about 129 B.C. Hipparchus produced the first well-known star catalog in the western world. In this catalog Hipparchus ranked stars by what he called “magnitude.” Since brighter stars tend to look bigger, Hipparchus called the brightest stars he could see those of the first magnitude. Stars not so bright he called second magnitude. Using this system he called the faintest stars he could just barely see sixth magnitude. This basic system has survived to the present time.

Galileo forced us to change this system slightly. When Galileo used a telescope to view the sky he discovered there were fainter stars. As Galileo expressed his finding...

*Indeed, with the glass, you will detect below stars of the sixth magnitude such a crowd of others that escape natural sight that it is hardly believable. ... The largest of these... we may designate as of the seventh magnitude: **Sidereus Nuncius, 1610.***

A new term was introduced (“seventh magnitude”) and the magnitude scale became open ended. As telescopes became bigger and better astronomers kept adding more magnitudes to the bottom of the scale.

By the middle of the 19th century astronomers realized it was necessary to define a more rigorous magnitude system. It had been determined that a 1st magnitude star was approximately 100 times brighter than a 6th magnitude star. Accordingly in 1856 Norman Pogson proposed that a difference of five magnitudes be defined as exactly a factor of 100 to 1. Since at this time in the western world it was believed that all human senses were logarithmic, it seemed perfectly reasonable to define a magnitude difference between two sources in the following manner...

$$m_2 - m_1 = 2.5 \log \left(\frac{L_1}{L_2} \right)$$

Here the L 's are the amount of light from object 1 (the bright object) and 2 (the faint object). This gives the magnitude difference between the faint object and the bright object. Keep in mind that fainter objects will have larger magnitude numbers and brighter objects will have smaller magnitude numbers. (Very bright objects will even have negative magnitudes). This relationship became known as Pogson's rule. This rule describes how brightness measured by some instrument sensitive to light can be represented as astronomical magnitudes.

It is particularly convenient (and even easy) to determine the magnitude of a star with respect to a nearby star for which the magnitude is known. That is, we can determine the magnitude difference between an unknown star and a reference star or standard star with a known magnitude. This type of magnitude determination is termed “differential photometry.” Of course, in the final analysis all magnitude determinations are differential since the stars themselves (or at least a set of standard stars) effectively determine the entire magnitude system.

Materials for each student:

- Clay model star field (modeling clay or Play-Doh)
- Plastic knife
- Pencil
- Triple beam balance or kitchen scale (for measuring mass)
- Ruler
- Paper Plates
- Wax paper

Engage and Explore!

Procedure:

1) Pre-class: Prepare the clay star field models for each group of students. Have the students read about CCD detectors for homework (student handout).

Explain!

2) In class: Go over the vocabulary. (digital image, pixels, CCD, background, photometry, astronomical magnitudes). Stress that the clay models are representations of the light striking the detector. The thicker (or higher) the clay, the more light reached that particular part of the image. Also stress that virtually all astronomical measurements are relative (or differential) with respect to some known standard objects or sources. Discuss with the students the concept of a pixellated detector. Also discuss the magnitude system, giving them examples of magnitudes of different objects in the sky. Have students calculate a few magnitude differences given star brightness measurements (say, in number of electrons produced, of the volts produced by some detector). Instructors may need to help students make a connection between the height of the clay model star fields and brightness. A good example would be topography maps for mountains.

3) Post-class: Look at some digital images of astronomical sources. Zoom in to see the pixels. Demonstrate the use of software used to analyze astronomical images.

Preparing the clay star fields:

Elaborate!

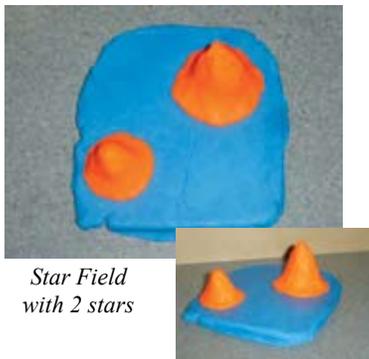
Option 1: Instructor prepares the star field models.

For best results the mass of the clay or dough should be about: Be sure to record accurate masses of each star.

- larger star ~40g
- smaller star ~15g
- background should weigh out to be ~155g



Star Field



Star Field with 2 stars



Cutting out the stars and background



Stars and background cut out

Start with three fingers of modeling clay. Flatten it out using a pencil, a rolling pin, or your fingers. Make the sheet about 6 inches by 6 inches and about 1/4 inch thick. The sheet does not need to be perfectly flat or smooth. Then take a strawberry sized piece of clay. Form this clay into a cone. Measure and record the mass of the cone so you know what to expect for results. Lightly press the cone onto the sheet with the flat side of the cone down. Take more clay, of a different size, and form another cone. The second cone should be either larger or smaller than the first cone. Measure and record the mass of the second cone. Lightly press this second cone onto the clay sheet. You now have a model star field with two stars. Of course, you could add another star or two if you wish.

Option 2: Instructor prepares the cones that represent the stars. Students prepare the clay sheet that represents the background brightness. Instructor then adds the stars.

Option 3: Each pair of students or student team prepares a model star field. Students then trade models with another team. Each student team must record the measurements of their star field that they create for their classmates.

Activity Results:

The goal is to determine the magnitude difference between two model stars. Students must measure the mass of each model star. This includes determining how much mass is being contributed by the background and subtracting this background for the final results. The ratio of the masses for the model stars can then be used in the magnitude difference equation to compute a magnitude difference. If the masses of the star cones are measured before being placed on the clay sheets the true value for the magnitude difference that students should obtain can be known in advance.

Note: The students are not allowed to simply pull or separate the stars from the flat surface. You must encourage the students to figure out how to “subtract the background” from the star.

Extension Activities:

1. Use binoculars or small telescopes to measure the brightness of some variable stars. The AAVSO provides excellent resources for such activities:

<http://aavso.org>

2. Obtain digital images using a local telescope system with CCD detector. Local amateur astronomers often have telescopes and CCDs that could be used to obtain some images. It may be possible to arrange a demonstration of the equipment and to obtain some images. Local universities or colleges may also have astronomy programs and may be willing to provide demonstrations and images.

3. Obtain digital images using a remote robotic telescope system. Several organizations maintain robotic telescope systems and allocate at least some time for educational purposes. Such organizations include the Global Telescope Network (GTN), Telescopes In Education (TIE), and Hands On Universe (HOU). Several companies and organizations maintain telescope systems which may be reserved and used for a modest fee.

4. Analyze astronomical images to determine magnitudes for variable sources. University researchers and research organizations may have image data that students could learn to reduce and analyze. Some organizations, such as the GTN, maintain image archives of variable objects that could be analyzed as student projects.

Lesson Adaptations:

Visually impaired students could touch the star model and describe what they feel.

Assessment:

Points	Parts 1 and 2: Description of star field	Part 3: Mass determinations	Part 4: Magnitude difference	Part 5: Magnitude values for stars
4	Answers are complete and correct	Calculations are all accurate	Explanation is thorough and accurate	Calculations are all accurate
3	Answers are mostly correct and complete	Most calculations are accurate	Explanation is accurate, but not thorough	Most calculations are accurate
2	Answers are somewhat correct and complete	Some calculations are accurate	Explanation is somewhat accurate	Some calculations are accurate
1	Answers are incorrect and incomplete	Calculations are inaccurate	Explanation is inaccurate	Calculations are inaccurate
0	None turned in	None turned in	None turned in	None turned in

Answer Key for *Cookie Cutter Photometry*:

This will depend on the actual masses used for the cone shaped star models. The required magnitude difference can be computed using the magnitude difference equation and the known ratio of the masses.

The magnitude for the “unknown” will depend on the magnitude difference and the magnitude selected by the instructor for the reference star.

For 40g and 17g stars, the magnitude difference ($m_2 - m_1$) is 0.929.



Additional Information:

- Obtaining astronomical images using small telescopes:

An activity is available that is designed to introduce students to designing an observing program and collecting image data using a remote robotic telescope. You can examine this activity at:

<http://gtn.sonoma.edu/activity/oa/index.php>

- Software for analyzing astronomical images and determining magnitudes:

Some of the available software systems that can process astronomical images include:

AIP4WIN - MaximDL - CCDSoft
Mira - Iris - Canopus - SIP



Cookie Cutter Photometry

Student Handout

Introduction

“Photometry” is the common term used for measuring the brightness of astronomical objects. Approximate brightness measurements can be made using the human eye. We humans are very, very good at determining which of any two objects is the brighter. With some experience and with two or more objects of known brightness we can even learn how to estimate how much brighter one object is than another. But truly accurate brightness measurements must be made using some kind of instrumentation. Photography has been used to record the brightness of objects, and then the photographs could be measured to determine reliable brightnesses.

However, today electronic detectors that produce digital images provide one of the most reliable ways to determine the brightness of astronomical objects. Of course, these very same detectors are the devices inside a digital

camera, or a camera in a cell phone, or in a video camera. These electronic detectors have very small light sensitive elements called pixels. When light falls on these pixels, electrons build up. When the pixels are read out to a computer, an image can be displayed on its screen. Pixels that received more light would have more electrons, and more electrons would be displayed as a brighter spot on the digital image on the computer screen. Each pixel in a digital image has a number associated with it that ultimately can be related to the number of electrons at the detector. Thus, if we can add up the numbers in the pixels in the image of a star, that number will correspond to the brightness of the star. Of course, this same approach can be applied to other objects that can be imaged, such as planets, moons, and galaxies.

Procedure:

1 You will be provided with a clay model of a star field. This model represents an image of a small part of the sky. Your model will have two or more mounds of clay that represent stars. The higher the mound, the more light reached the image at that point. The sheet of clay on which the mounds are located represents the brightness of the background. Is your background perfectly constant (flat)? How many stars are in your model star field? Make a sketch of your star field.

2 It is your task to determine the difference in brightness between two of the stars. You will determine this difference as a difference in astronomical magnitudes. If you have more than two stars, your instructor will indicate which two stars to measure. Which of the two stars is brighter? Label the stars on your sketch that you will measure as **Star 1** for the bright star and **Star 2** for the faint star.

3 Determine the brightness by determining the mass of the star mounds. The more mass that is present implies more light struck the detector at that point. However, there are some rules for determining the mass of the star mounds!

Rule 1: **You cannot physically separate the star from the background.** That would be cheating. After all, in real life, you cannot take a star off the sky.

Rule 2: You can draw on, cut, or weigh any part of the image.

Note that you must somehow correct your determination for the background brightness. You will need to describe in words how you decide to correct for the background and make your mass determinations.

What are the units for the masses you determined?

4 Determine the magnitude difference for your two stars using the magnitude difference equation.

$$m_2 - m_1 = 2.5 \log \left(\frac{L_1}{L_2} \right)$$

Here L denotes the bright object and 2 denotes the faint object. Use your masses as indicators of the light L coming from each star. What is the magnitude difference between your two stars?

L = brightness of star = mass of star
 m = magnitude of star.

5 Your instructor may know the actual stellar magnitude for one of your stars. Ask your instructor. This will be your reference object. Use this known magnitude and your measured magnitude difference to determine the magnitude for the unknown star in your star field. What is the magnitude for your unknown star?

6 How accurate are you? Find the percent error for the real masses of your stars and the calculated masses. Your instructor will have the real star masses.



Cookie Cutter Photometry Student Worksheet

Name _____

Date _____

1) How many stars are in your star field? _____

Is your background brightness perfectly constant everywhere in your field?

Make a sketch of your star field here.

2) Label your sketch with the names Star 1 and Star 2 for your stars.

3) Record your mass determinations in the following table:

Star 1	
Star 2	

What are the units for the masses you determined?

Describe in your own words how you corrected for background brightness.

4) What is the magnitude difference for your two stars?

5) Record the magnitudes for your stars in the following table:

Object	Name	Magnitude
Reference		
Unknown		

6) How accurate are you? Find the percent error for the real masses of your stars and the calculated masses. Your instructor will have the real star masses.



National Science Standards

Specific Science Standards:

Content Standard A: Science as Inquiry

- *Abilities necessary to do scientific inquiry*
- *Understanding about scientific inquiry*

They will test their hypotheses by direct experimentation. Students will mathematically convert their measurements to magnitudes. The students will see that the physical model and the procedure that they use directly correlates to the actual procedure used by scientists to measure the brightness of stars with CCDs.

Content Standard E: Science and Technology

- *Abilities of technological design*

Students will use the clay star field models to represent a real digital image taken from a telescope. They will apply this technology by removing background noise from a simple clay model of a digital image. They will employ clay and knives to solve the problem.

- *Evaluate the solution and its consequences.*
- *Communicate the problem, process, and solution.*

The students are asked to draw their models and label their drawing as a scientist would if using a real digital image. Students will describe the method used to determine the clay weight with the background subtracted.

- *Understandings about science and technology*

Students will see that astronomers ask very different questions about their surroundings than other scientists. The students will also get a better understanding of the use of technology and how it changes over time. Students will see specifically that digital detectors are changing the way modern astronomy is done, making measurements of brightness more accurate.

ITEA Technology Content Standards

The Designed World

- *Standard 17:* Students will develop an understanding of and be able to select and use information and communication technologies.