ASTROEDU
Peer-reviewed Astronomy Education Activities

Street Lights as Standard Candles

Understand standard candles using street lights.

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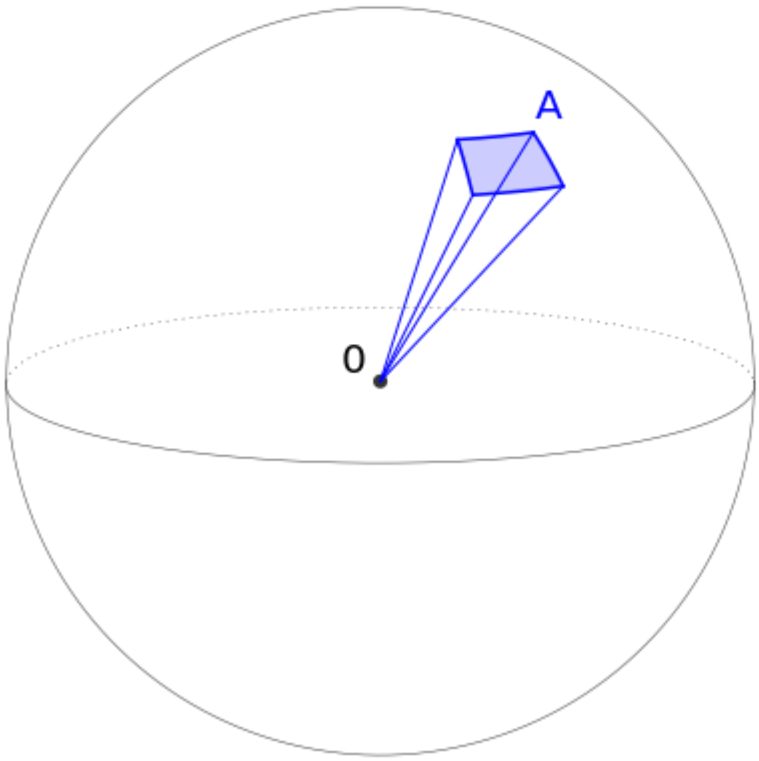


AGE

14+

LEVEL

Secondary, University, Informal

TIME

3h

GROUP

Group

SUPERVISED

No

COST PER STUDENT

Low Cost

LOCATION

Outdoors

CORE SKILLS

Developing and using models, Planning and carrying out investigations, Analysing and interpreting data, Using mathematics and computational thinking, Constructing explanations

TYPE(S) OF LEARNING ACTIVITY

Technology-based, Modelling, Simulation focussed

KEYWORDS

Inverse square law, Standard candle, Distance measurements

SUMMARY

GOALS

- Understand the concept of standard candle distance measurements in astronomy.
- Perform such measurements using everyday objects (namely street lights).
- Lay the foundations for understanding a type of distance measurement crucial for physical interpretation of astronomical observations of distant astronomical objects.
- Learn about important kinds of systematic error (obstruction, intrinsic variations) in astronomical observations.
- Learn the basics of digital image processing, including simple photometry (activity can thus serve as a first step in a development that includes more challenging astrophotography projects).

LEARNING OBJECTIVES

- Recognise the relation between an object's intrinsic brightness, apparent brightness and distance.
- Explain how this relation can be used to determine the distance of astronomical objects of constant (more generally, of known) brightness, namely standard candles.
- Understand how a digital camera can be used not only to take pictures, but to perform quantitative measurements of object brightness.
- Use a digital camera and image analysis software to measure the brightness of street lights, assumed to be standard candles.
Recognise and describe systematic errors that can (partially) invalidate the simple standard candle interpretation.

EVALUATION

Overall success of the measurements can be tested by inspecting students' results, in particular linearity of the curve plotting distances derived by the standard candle method against distances measured by a conventional method (e.g. on Google maps or via direct measurement).

Some specific criteria:

- Have the images been taken correctly (in focus, no internal reflections, light sources not saturated)?
- Has the basic formula for the inverse square law been applied correctly?

Advanced: Have the students found suitable explanations for outliers that do not lie on the expected inverse-square curve?

Student understanding can be gauged by asking students about their derivation (which should start with a brightness measurement and use the inverse square formula) and about deviations between distances as measured by the standard candle and conventional methods. Sensible models for error sources (intrinsic brightness variations, [partial] obscuration) are indicative of advanced understanding.

MATERIALS

- Digital camera (capable of taking raw format images)
- Computer with internet access (The cost estimate assumes that a camera and computer are already accessible.)
- Software used for analysis: Basic image processing software allowing for the measurement of pixel brightness such as ImageJ (available for free at http://imagej.nih.gov/ij/) or AstroImageJ (available for free at http://www.astro.louisville.edu/software/astroimagej/)
- For calculating distances from brightness values and producing plots, spreadsheet software can be used, such as Microsoft Excel (available commercially), Open Office Calc (available for free at https://www.openoffice.org/), or Google Sheets (available for free at https://www.google.com/sheets/about/).

BACKGROUND INFORMATION

Astronomical distances

Image: The constellation Orion. Each of the seven principal stars of this constellation, forming Orion's shoulders, belt, and feet, is between a few thousand and a few hundred thousand times more luminous than the Sun. Credit: Mouser, deep sky image of the constellation Orion, CC BY-SA 3.0 https://creativecommons.org/licenses/by/3.0/legalcode

Astronomers are distant observers. With very few exceptions inside our own solar system, we cannot travel to our objects of study. Instead, we need to infer the properties of stars, nebulae and planets from our observations. Knowing an object's distance is key to such cosmic detective work. If all we knew were an object's apparent brightness in the sky, we couldn't distinguish between objects that are fairly near but not very bright and those that are far away but emit lots of light!

This is evident when it comes to some of the most basic celestial objects: stars. Our direct experience on a clear night is that stars are tiny pinpricks of light. A simple flashlight will give us much more illumination than all the thousands of stars we see in a starry night taken together. But the Sun is a star, too, and it is the brightest object most of us will ever experience – so bright that it poses a danger to our eyes, and we shouldn't look at it directly! Yet some of the stars we see at night emit much more light than our Sun. The key factor that makes them appear much less bright, for an
observer here on Earth, is distance. The only difference is distance. Even the closest star, Alpha Centauri, is more than 265 000 times far away from us compared to the Sun.

Estimating cosmic distances is a difficult task. Even distances within our own Solar System are sizeable by everyday standards. The astronomical unit, corresponding to the average distance of the Earth from the Sun, is about 150 million kilometres.

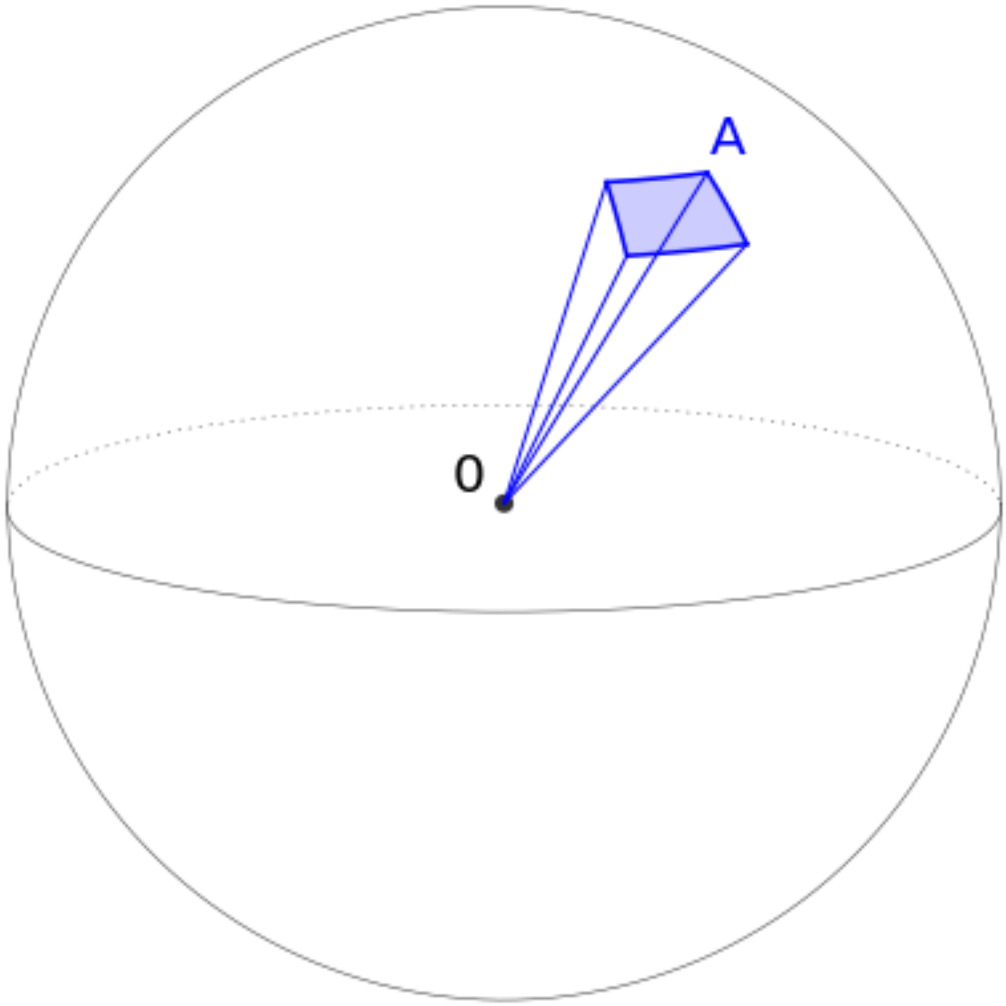
The nearest star, Alpha Centauri, is $4{\cdot}10^{13}$ km away. Such giant numbers are unwieldy, and astronomers have introduced an alternative way of stating distances. Nothing moves faster than light, and astronomers have taken to using light travel times as their measure of the distances to the nearest stars (parsecs, and its derivatives, as well as redshifts are used for greater distances). The Sun, for instance, is about 8 light-minutes away from us: light takes 8 minutes to travel from the Sun to us. Alpha Centauri is 4.2 light-years away.

(Do not be confused by the occurrence of words like 'minute' or 'year' in these units. Light-minutes and light-years are measures of distance, not of time.)

The most distant objects we know are much farther away. Light takes billions of years to cover the distance between those objects and us, so these objects are billions of light-years away (corresponding to tens of sextillions, or 10^{22}, of kilometres). No single method can cover this immense range of distances. Instead, astronomers rely on what they call the cosmic distance ladder: a set of complementary methods of determining distances, where methods applied to more distant objects are calibrated using methods applicable to less distant objects.

Apparent brightness: inverse square formula

A number of key methods of measuring astronomical distances involve the following basic principle: Assume that we know how much light an object emits (this is called 'luminosity'). We can measure the object's apparent brightness in the sky. Comparison of luminosity and apparent brightness is directly related to the object's distance from us. Quantitatively, assume that the objects emits energy per second L, and that this emission does not favour any particular direction (isotropic emission). L is called the object's luminosity. At a distance d from the object, this total energy will have spread out over a spherical surface of area 4 pi d^2. Imagine that our detector – for instance, our telescope mirror – covers an area A, as shown in the following figure, which is at a distance d from the radiating object O:



Since the object's light emission is spread evenly over the whole sphere, our detector will only receive a fraction $A/(4 \pi d^2)$ of that emission; in other words, our detector will receive energy per second

$$F = L \cdot A/(4 \pi d^2)$$

from the object. We can rewrite this formula by dividing out the detector area to yield the intensity of the radiation

$$I = F/A = L/(4 \pi d^2),$$

that is, the amount of energy per second per unit detector area reaching us from a particular object. This is the famous 'inverse square law' for radiation. Typical classroom demonstrations of the inverse square law involve a photodetector, such as a small solar cell, placed at varying distances from a light source (e.g. Stanger 2008).

Standard candles

Image: Supernovae of type Ia, such as this one in 1994 in the galaxy NGC 4526, are standard candles that allow astronomers to deduce the distance of far-away galaxies. Credit: NASA, ESA, The Hubble Key Project Team, and The High-Z Supernova Search Team. CC BY-SA 3.0 https://creativecommons.org/licenses/by/3.0/legalcode

The inverse square law links the quantities I, L, and d. Imagine a class of objects whose members all have the same luminosity L. Such objects are called standard candles. Whenever we observe a standard candle, we know its luminosity L, can measure the intensity I, and use the inverse square law to calculate the object's distance.

So-called supernovae of type Ia are the most important standard candles for very distant galaxies, in the context of cosmology, the science of the universe as a whole. These supernovae are violent, thermonuclear explosions of white dwarf stars. They are extremely bright, and visible over great distances. A supernova's type can be identified from the properties of the light we receive from the explosion (more concretely, from the spectrum of the supernova). Once it is clear that one is indeed observing a supernova of this type, the (maximum) luminosity of the explosion can be deduced.

For most astronomical standard candles, L is not constant for all objects within the class, but instead is correlated with a measurable property of objects of this kind. The most famous example are Cepheid variable stars, which show periodic changes in brightness. The period of these changes is correlated with the luminosity of the stars; measure the period, and you can deduce the luminosity L. This correlation was first noticed and exploited by Henrietta Swan Leavitt in 1908-1912.

Standard candles like this have played a key role in the history of astronomy. In the early 20th century, Cepheids were used to show that our galaxy is just one among many. And in the final years of the 20th century, type Ia supernovae were used to show that cosmic expansion is accelerating – the discovery of 'Dark Energy', which was rewarded with the 2011 Nobel Prize in Physics.

The ideal standard candle would be exceedingly bright, and thus visible over large distances, it would be easily identifiable (e.g. via the determination of a spectrum), and it would be reasonably common to allow for a wide range of distance determinations. Ideally, we would have some very close examples of this type of standard candle in our cosmic neighbourhood, which allows for calibrating the standard candle (that is, measuring its luminosity L) and many very distant examples that allow for distance determinations of galaxies as well as for cosmological measurements.

In reality, no single standard candle meets all the criteria at once. Instead, astronomers have built a distance ladder of standard candles. For instance, for nearly 300 Cepheid variables, their distance can be measured directly using basic geometry (stellar parallax). These known distances can be used to calibrate the Cepheid period-luminosity relation. Once this relation is known, we can examine nearby supernovae of type Ia in galaxies that harbour Cepheids. Using the Cepheid distances, we can determine the peak luminosities of supernovae of type Ia. Once we know these luminosities, we can use supernovae of type Ia as standard candles that are so bright they can be seen to substantial extragalactic and cosmological distances.

The activity presented here allows your students to discover and explore the key principles of standard candles for themselves, using a simple example in an everyday setting.

Standard candles and the inverse square law

In practice, quantitatively measuring intensities is a challenging task, which requires careful calibration of one's instruments markedly beyond the scope of this activity. Instead, we will make use of the fact that we are making our measurements of various sources with one and the same piece of equipment, our digital camera.

Assuming that we receive light of intensity I from an object, our camera will gather a total amount of light per second corresponding to $P = I \cdot A \cdot \eta$, where A is the collecting area of the camera and $\eta < 1$ is a dimensionless constant that allows us to encode (a) that some light will be absorbed within the camera lens and (b) some light might not reach the camera chip but be scattered elsewhere. The total energy deposited on the chip is $E = P \cdot t$, where t is the exposure time. Assume that in our image the object in question spans a certain pixel region and assume a linear response of the chip and linear processing, then E will be proportional to the sum S of the pixel values for that region. (An optional part of the activity involves testing this linearity.)

What greatly simplifies our task is that the pixel value sum S depends linearly on the intensity I. As long as we take care to take all our images under the same conditions (same exposure time, same lens, same settings), this linearity means that we can compare the intensities $I_{1,2}$ of different sources by comparing the sums $S_{1,2}$ of the pixel values for the images of these sources,

$$S_1/S_2 = I_1/I_2.$$

It does not get simpler than this, and this simple formula, together with the inverse square formula linking luminosity, intensity and distance, will be the foundation of the following activity.

How to undertake this activity?

This activity can be undertaken at different levels, depending both on the degree of independence of the activity (i.e. how much is prepared beforehand by the teacher) and on the level of analysis.
As far as preparations are concerned, at the most basic level, the teacher scouts one or more likely locations, takes care to set up the necessary software and prepares simplified recipes for using the software. Students can then concentrate on the science, namely on the measurements and their evaluation. This level of preparation allows for the quickest completion of the exercise. If, on the other hand, the exercise is set up as a completely free inquiry, students need to find their own location, do research on what software they need (e.g. to convert raw images either to FITS or another suitable format for their analysis) and install what they need. This makes for a much more realistic experience, as such preparations are a standard part of astronomical research. Naturally, it also makes the exercise that much more time-intensive.
The most basic level of analysis directly uses the inverse square formula to relate measured brightness to distance, using a reference object for which the distance has been measured by conventional means (either directly or using a map, e.g. Google Maps). This version of the exercise concentrates on the fundamental concept to be learned and allows for quickest completion.

As an additional activity, the role of the digital camera can be explored. As shown above, use of the camera to measure apparent brightness via simple ratios of pixel value sums relies on a linear relation between the amount of light received from a certain region of the scenery and brightness values for the corresponding image pixels. This linearity can be checked in optional supplemental activities that, at the same time, can be the first steps towards more advanced astrophotography activities. At a more advanced level, students should be encouraged to think about causes of the deviation of their derived distances from the directly measured distances. Two fundamental causes they are likely to encounter are intrinsic brightness variations (that is, deviations from the standard candle assumption) and obscuration (an object's light being dimmed by intervening matter). Both have their analogues in astronomy, where the simple standard candle assumption (same intrinsic brightness) often needs to be refined (e.g. for Supernovae of type Ia, by making use of a correlation between the supernova light curve's evolution over time and its peak brightness), and where dust and gas clouds can dim the light of a distant source. In this exercise, we are in the fortunate situation of being able to get close to ('travel to') our light sources, and measure their intrinsic brightness directly. Students can make these measurements and apply a corresponding correction to their distance derivation; this should reduce the deviation considerably. We can also identify obstructions in the worked-out example; for instance, those street lights that appear dimmer than expected indeed turn out to be obscured by tree branches. While the more advanced level takes considerably more time, it teaches valuable skills in analysing data and error sources.

A worked-out example with brightness measurements and corrections, including sample images and a sample spreadsheet, can be found at http://www.haus-der-astronomie.de/materials/distances/street-lights

FULL ACTIVITY DESCRIPTION

This description begins with the basic version, where the teacher has already scouted a suitable location with standard-candle street lights and prepared the necessary software. Suggestions for more advanced versions are also given.

Preparations by the Teacher:

Find a street with suitable street lights. Lights are suitable when they are all of the same type or build, and whenever geometric effects do not dominate the measurement (flat, near-horizontal street lights for instance will probably be dominated by perspective/projection effects).

Image: Example for a lantern that appears approximately isotropical for a ground-level observer.

The street lights should shine as isotropically as possible; for practical purposes, all kinds of street lights that are not collimated (e.g. by an egg crate structure) should work.

Prepare a software pipeline for data-taking and analysis. The worked-out example, accessible via the link given below, uses Fitswork (http://www.fitswork.de/software/softw_en.php) to convert raw Canon images (.CR2) into FITS, preserving linearity. Different conversion methods are possible, many of them based on dcraw (https://www.cybercom.net/~dcoffin/dcraw/). For measuring object brightness, use ImageJ (http://imagej.nih.gov/ij/). This software has the advantage of also being of interest for astrophotography (e.g. as AstroImageJ, http://www.astro.louisville.edu/software/astroimagej/), so students might be able to re-use their software skills in other, more advanced projects.

For an advanced version of this exploration, scouting the location and finding a software solution can be left to the students, although some guidance is bound to be necessary.

Step 1: Exploring digital images

In this step, students explore the meaning of pixel values in a digital image. They are given the following guiding questions:

Using the software provided, examine images you have taken with the digital camera.

- What is the relation between pixel values and brightness?
- How can you capture the brightness of an object in the image?

This step should include the students taking test images of a light source and examining the images using their analysis software.

Let the students experiment with different exposures; they should discover that each pixel saturates at a certain brightness, so care needs to be taken with exposure times when taking images for brightness measurements: Saturated regions can introduce significant errors!

At the end of this step, students should be familiar with whatever software they or their teacher have chosen for this exploration. They should know how to convert raw images from their digital camera to FITS or another suitable format, and how to measure object brightness in their images (namely by something akin to the sum of pixel brightness for the pixel region that includes the object). Depending on the time available for the exercise, this step of the exploration can also include an experiment to test linearity. There are at least two possibilities for this. For the first kind of measurement, a light source (e.g. a shielded lamp or LED) is photographed with the digital camera using different exposure times, demonstrating linearity as exposure time is plotted against brightness. Alternatively, one can leave the camera setup unchanged and photograph one and the same light source, varying the source's distance from the camera. In that case, as long as linearity holds, one should recover the inverse-square law for the different distance-dependent values of image brightness. Non-linearity will lead to a deviation from this simple law.

As an activity that can take place in the classroom, and during daytime, either experiment can serve as preparation for the activity in the field, and allow the students to get to grips with handling the camera and analysis pipeline.

(If there is time, then the comparison of linearity measurements based on JPG images versus raw images transformed to FITS can vividly demonstrate why it is necessary to work with raw images!)

Step 2: Street light measurements in the field

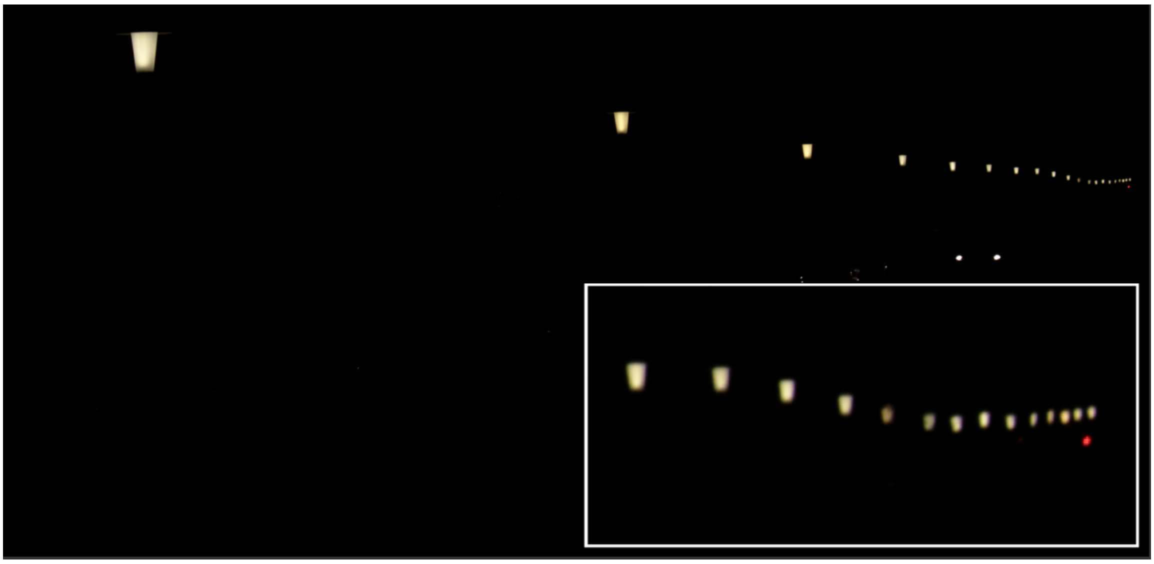


Image: Line of street lights receding about 600 meters into the distance. Inset: Zoomed-in image of the most distance of lights.

In this step, students go to the location chosen by the teacher (are their main targets) in suitably dark conditions (evening/night) and take an image or images of the row of street lights that are their main targets. Different strategies are possible. In the worked-out example, you can find all street lights in one image. Alternatively, one could take one image per street light, centring each light source in the image used to measure its brightness. (This amounts to a field trip in the night-time; teachers should make sure to take appropriate precautions to ensure their students' safety.)

Drawing on what they learned in Step 1 about saturation, students should take images at different exposure times (or, alternatively, different ISO values and aperture values) so as to be sure to obtain at least one image that is not saturated. For one street lamp (typically the nearest!), the distance to the camera should be measured directly, e.g. using measuring tape or a laser distance measuring device. This distance will be used to calibrate the standard candle measurements.

Step 3: Image analysis

Once the image or images used for measurement have been taken, they can be analysed. In the worked-out example, this is done by converting the images into FITS images and then measuring the brightness of those areas of the image that contain the various street lights. Under suitably dark conditions, background brightness should not play a significant role in the measurements. If backgrounds are bright, or if the students suspect this to be a significant source of error, suitable selection tools should be used to ascertain that the areas used for brightness measurements only contain contributions from the street lights. When background brightness is not a problem, as in the worked-out example, lamp brightness can be measured using simple rectangular or elliptical selection tools. Measured values should be tabulated, for instance in a spreadsheet (such as Microsoft Excel, OpenOffice Calc or Google Sheets). The values are not in any of the usual physical units, but since they have been measured in the same way, they should be in the same (unusual) units, allowing for the calculation of ratios. Using the reference street light, whose distance has been measured directly, as well as the inverse square law for intensity, the (standard candle) distances of the other street lights can now be calculated.

Step 4: Cross-check

In astronomy, we need to cross-check different methods of distance determination against each other in order to probe their validity. In the street light example, there are various ways for alternative (and more direct) distance measurements for comparison.

When street lights are aligned alongside a straight road, direct measurement of the distances between the street lights, and from two of the street lights to the location of the camera, will yield sufficient information to calculate (using simple linear equations) each street light's distance from the camera.

Direct measurements are the most easily understood, but have a disadvantage in terms of timing: Those direct measurements should not be made at the same time as the field work in Step 2 (as this might leave students wondering why they need to make the standard candle measurement at all, or cause them to conflate the measurements). Having two separate field measurements, however, means a considerable investment in time and, possibly, logistical planning.

Alternatively, the cross-check can be made online, using available online maps (such as Google Maps or Open Street Map, https://www.openstreetmap.org/). Distance measurements can be either made in the classic mode of Google Maps or by taking a screen shot and measuring distances in image processing software such as Adobe Photoshop or Gimp (http://www.gimp.org/). In parallel with the standard candle analysis, it makes sense to use these tools to determine the street lights' relative distances from the camera; the reference street light can be used to convert this to linear distances.

The results should be plotted to check the validity of the method, comparing directly measured and standard candle values for the various street lights.

Step 4 (advanced): Error sources

When standard candle distances for the street lights and their directly measured counterparts are plotted against lamp number (or each other), the result will not quite be a straight line.

In advanced versions of the exploration, students are invited to think about the reason(s) for these deviations.

Students should realise that some of the deviations are random - that both imaging and measurement is likely to introduce small errors that can go in either direction.

Two kinds of systematic errors are particularly important, as they have analogues in astronomical distance measurements, and as they are reasonably likely to occur in the street light exercise.

The first systematic error comes from the limitation of the standard candle assumption. While street lights of the same type are likely to be very close in brightness, there are probably some intrinsic variations. For instance, there might be aging effects of the light source used. In astronomy, we cannot visit our standard candles to directly measure their intrinsic brightness; this necessitates systematic tests using alternative methods of distance measurement to determine whether or not standard candle candidates of a certain type show variations depending on various measurable candidate quantities (e.g. for supernovae Ia, peak brightness variations that correlate with the shape of the light curve).

In the street light exercise, students can instead try to measure intrinsic brightness variations directly, e.g. by walking up to the various street lights and taking images of them from some standard distance under some standard angle (for readers who are familiar with the astronomical magnitude system of measuring brightness: an image taken at a standard distance corresponds to defining an absolute magnitude).

The second systematic error occurs whenever a part of a light source is obscured from the perspective of the observer. Street lights can be blocked by branches or leaves, or by dirt on the street light itself; astronomical objects can be situated behind clouds of gas and dust, leading to extinction phenomena. This systematic error will always make the source appear less bright; it should be investigated whenever a street light brightness measurement gives a value that is unexpectedly low, corresponding to a standard candle distance that is unexpectedly large. In some cases, the obscuration can be found out and documented, or even corrected for. In the worked-out example, an image taken at greater magnification showed leaves obscuring part of a street light that had been measured as surprisingly dim. From the zoomed-in image, the fraction of obscuration could be determined, and a corresponding brightness correction applied.

CURRICULUM

Great Britain:
EdExcel GSCE Qualifications for astronomy 5AS01, Topic 3.3. of Unit 1

Scotland:
Higher Physics curriculum area ‘Our dynamic universe’, unit ‘The expanding universe’

Germany:
Astronomy curriculum in Mecklenburg-Vorpommern, sections 7.1 and 7.6; 9th

grade astronomy curriculum in Saxony-Anhalt topic 5, 10th grade astronomy curriculum, and grades 11/2 Kurs 2; Thuringia 10th grade astronomy, Themenbereich 3.2 and 3.1; Bavaria, grade 12 physics with astronomical topics, PhAst 12.4 and 12.5.

ADDITIONAL INFORMATION

The most exciting results obtained by using supernovae of type Ia is recounted in the 2011 Nobel Lecture by Brian Schmidt: https://www.nobelprize.org/nobel_prizes/physics/laureates/2011/schmidt-lecture.html

In-depth information about standard candle measurements such as the ones demonstrated in this activity can be found in astronomical text books:

- de Grijs, R. 2011: An Introduction to Distance Measurement in Astronomy. Wiley & Sons.
- Webb, S. 1999: Measuring the Universe: The Cosmological Distance Ladder. Springer: Berlin, Heidelberg, New York.

CONCLUSION

Using streetlights as standard candles can help students understand astronomical standard candles as well as their possible error sources. As a practical activity, it can serve to introduce students to digital image processing and serve as a stepping stone for later activities involving astrophotography, in particular those dealing with photometry.

CITATION

Pössel, M., 2016, *Street Lights as Standard Candles*, astroEDU, doi:10.14586/astroedu/1535