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# The greatest shadow on Earth

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**Abstract**
In a total solar eclipse, the Moon completely covers the Sun, casting a shadow several hundred km across the face of the Earth. This paper describes observations of the 14 November 2012 total eclipse of the Sun visible from north Queensland, Australia. The edge of the umbra was captured on video during totality, and this video is provided for teaching purposes. A series simple 'kitchen' experiments are described that demonstrate the 'sunset' effect seen on the horizon during a total solar eclipse and also the curved umbra seen in the sky when the eclipsed Sun is relatively close to the horizon.

*Keywords*: total, solar, eclipse, Daintree, Queensland, umbra, penumbra, Sun, Moon, blue, sky, sunset

## Introduction

A total solar eclipse is arguably the most spectacular astronomical phenomenon that can be seen with the naked eye. Solar eclipses are also useful for teaching science [1,2], and it is hoped that the information provided in this paper about the 14 November 2012 total solar eclipse in north Queensland will complement the existing body of eclipse teaching material.

In a total solar eclipse, the Moon completely blocks the Sun and casts a long shadow that reaches the Earth. Figure 1 shows an image of the shadow of the 26 March 2006 total solar eclipse over Turkey and Cyprus taken on the International Space Station (ISS).

Figure 1. Eclipse shadow over Turkey and Cyprus taken from the International Space Station (ISS) of the 26 March 2006 total solar eclipse. (Credit: NASA).

It is remarkable that ratio of the diameter of the Moon to that of the Sun is exactly the same as the ratio of the distances between the Earth and Moon and the Earth and Sun, i.e. about 1:400. This means that when the Moon lies directly between the Earth and Sun, the Moon is a perfect fit to the Sun, enabling details of the solar atmosphere to be revealed, even to the naked eye.

No other moons of the solar system are such a perfect match to the Sun. For example, Mars has two tiny moons, Phobos and Demos only a few km across, which orbit Mars much closer than the Moon does the Earth but are too small to totally eclipse the Sun. Some other moons, for example Io and Titan, totally eclipse the Sun but are much larger than the disc of the Sun. Figure 2, shows a total eclipse of the Sun on Jupiter. Anyone on Jupiter within the shadow of Io would see the black disc of Io as over four times the diameter of the Sun. However, only a fleeting glimpse of the solar atmosphere would be seen at the edge of the Sun immediately before and after totality, since most of the time the disc of the Sun would lie deep within the shadow of Io.

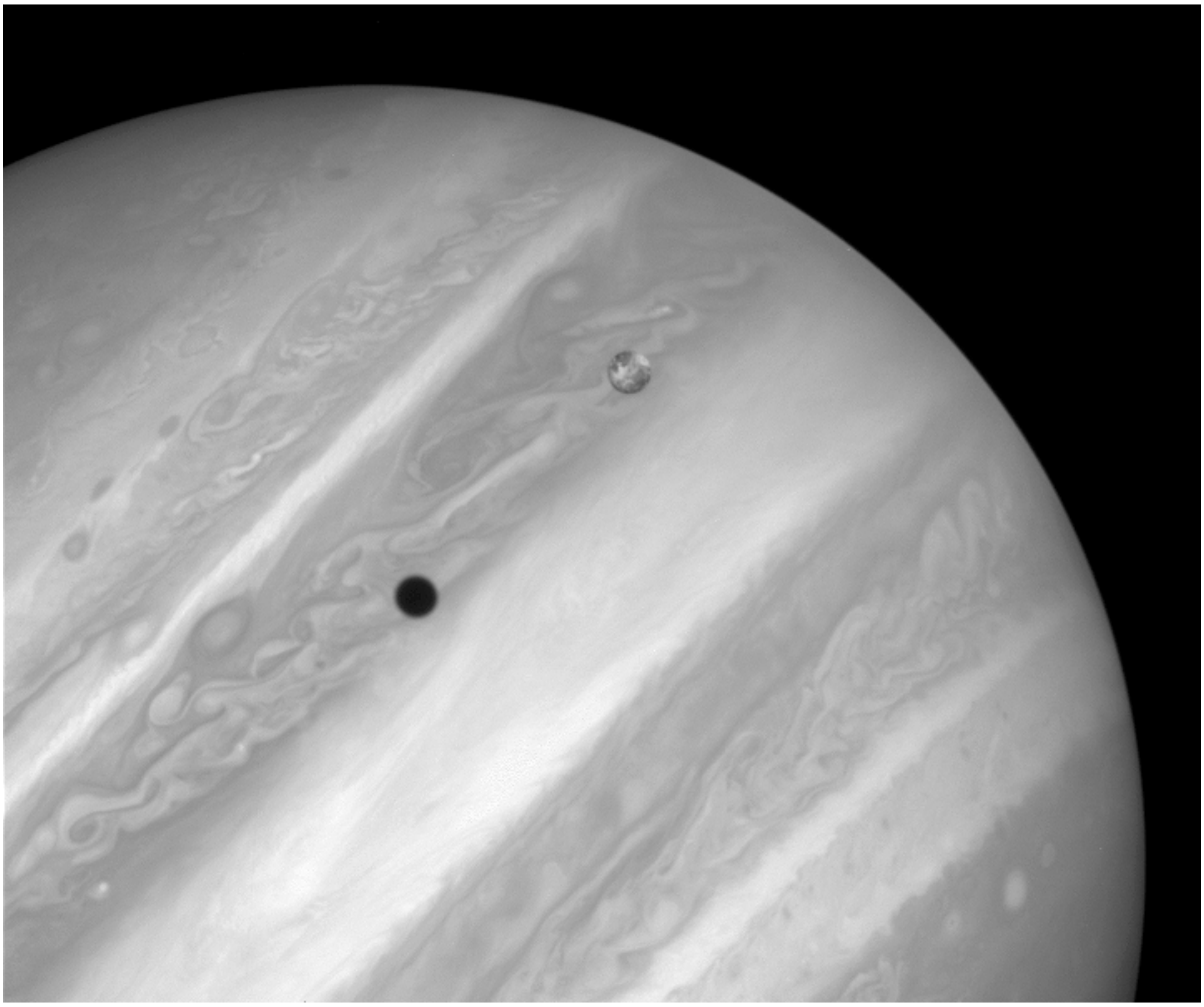

Figure 2. A total solar eclipse on Jupiter caused by the Jovian moon Io. (credit: J. Spencer (Lowell Observatory) and NASA/ESA)[1].

Since the diameter of Sun is 400 times larger than the diameter of the Moon, the Moon casts a cone shaped shadow known as the *umbra*, which is Latin for shadow, which has been transliterated, for example, into the English word *umbrella*. The umbra of the 14 November 2012 eclipse was 140 km across at right angles to the direction of the eclipse path on the surface of north Queensland. Outside the umbra the Sun is partially eclipsed and so this region is called the *penumbra*, or literally *part shadow*, from the Latin *pen* meaning part – as in *pen*insular, or part island. The penumbral region of the November 2012 eclipse extended several thousand km on either side of the umbra. For example, totality was observed in the vicinity of Cairns, but over 2000 km away in Adelaide only 42% of the surface area of the Sun was covered by the Moon. (More information about the 14 November 2012 eclipse can be found at these websites[2]).

[1] http://www.spacetelescope.org/images/opo9630a/

[2] astro.ukho.gov.uk/eclipse/0312012/; eclipse.gsfc.nasa.gov/SEmono/TSE2012/TSE2012.html

The 2012 eclipse umbra only covered a tiny fraction of the surface of the Earth. If the Earth was modelled as a standard NBA basketball with a circumference of 75 cm, the umbra would be a dot just 2.6 mm in diameter.

A total eclipse of the Sun is a complicated dance as the Earth and Moon continuously change position with respect to the Sun, and the Earth rotates on its axis. At any given location, a total eclipse of the Sun is a very rare event occurring only about once every two centuries or so. In contrast, although total lunar eclipses are about as rare as total solar eclipses, when they do occur they can be seen from half the surface of the Earth at the same time, i.e. anywhere on the night side of the Earth. Total lunar eclipses can last for more than one hour, whereas the maximum for a total solar eclipse is only 7 min.

Another difference between lunar and solar eclipses is the difference between partial and total eclipses, what we might call colloquially the 'wow' factor. A partial lunar eclipse is nearly as spectacular as a total lunar eclipse, but that is not the case for solar eclipses; 100% coverage of the Sun is required for the solar atmosphere to be revealed in all its glory. On 14 November 2012, a 98% eclipse was observed in Darwin in the Northern Territory (NT), Australia, but not many eclipse enthusiasts (often referred to as *umbraphiles*) went to the NT instead of Cairns. The Sun is about 500 000 times brighter than the full Moon and therefore in a 98% eclipse, 2% of the surface area of the Sun remains uncovered, which is 10 000 times brighter than the full Moon! In a similar fashion, annular eclipses, in which the Sun forms a bright rim around the Moon, do not attract the same attention as total solar eclipses.

**The QUT expedition to the Daintree to observe the 14 November 2012 eclipse**

All of the authors of this paper were part of a team who travelled to the Daintree region north of Cairns in Queensland to observe the eclipse and investigate the effect of a total solar eclipse on birds; for example, would there be a second dawn chorus? The base camp was the Daintree Rainforest Observatory (DRO) run by James Cook University[3]. Acoustic sensors were placed at DRO and various inland and coastal sites in the vicinity of Cape Tribulation. A GoPro camera was placed on a crane at DRO and set to acquire images every 10 seconds from just before dawn until after the eclipse. Another GoPro camera was positioned on a nearby beach pointing eastwards. Both these of videos are available in supplementary material.

Prior to this expedition there was anecdotal evidence that birds and other wildlife are affected by total solar eclipses. However, the 2012 eclipse was the first time a total solar eclipse was observed from a tropical rainforest with instruments capable of recording long sequences of acoustic data.

At DRO, the eclipse began at 5:43 am, only a few minutes after sunrise at 5:39 am. It took about one hour for the Moon to cover the Sun. Totality occurred between 6:39 and 6:41 when the Sun was between 14 and 15° above the horizon. The team monitored the eclipse by eye using eclipse shades. As the Moon passed across the face of the Sun the landscape gradually

[3] www.jcu.edu.au/canopycrane/

dimmed and became similar in brightness to the predawn sky. Shadows also became noticeably sharper due to the Sun becoming a smaller light source. All shadows in sunlight have a penumbral region which softens the edges, but during a solar eclipse the penumbral region becomes narrower and hence shadows appear sharper. A few seconds before totality the light level reduced very quickly, about as quick as turning a dimmer switch on an electric light. The solar atmosphere, or corona, leaped into view and a red solar prominence could be clearly with the naked eye on the dark edge of the solar disc. The diamond ring effect was also observed. At the end of totality, 90 s later, the brightness of the Sun increased as quickly as it had dimmed. The Moon left the Sun at 7:44 at an elevation of 29°.

Figure 3. GoPro image of the eclipse during totality. Note the circular shape of the intersection of the umbra with the atmosphere and the red sunset effect. (Image available for download in supplementary material).

The GoPro camera on the beach captured the intersection of the umbra with the atmosphere (figure 3). A red horizon was also observed, caused by the scattering of light shining into the umbra from the penumbral region [3].  In the supplementary beach video the edge of the umbra is seen traveling from left to right, i.e. north to south.

Figure 4. Photo showing the boundary between the umbra and penumbra at the end of totality.

Figure 4, also taken from the beach GoPro camera, shows the actual edge, or 'terminator' of the umbra, which was probably the first time that the edge of the umbral shadow was recorded so clearly. The eclipse occurred early in the morning when the Sun was just 14° above the horizon and so the conical umbra intersected the atmosphere at a shallow angle.

This was also the first time that wide-angle high definition video cameras were used to collect time lapse photographs of the landscape during a total solar eclipse. The HD GoPro camera was introduced in October 2011, after the previous total solar eclipse, which occurred on 11 July 2011. The last total solar eclipse in Australia occurred on 4 December 2002 in Ceduna, South Australia. Normally, during a total solar eclipse, cameras tend to be focussed on the Sun and not the horizon, and therefore the reddening of the horizon tends not to be recorded.

During a total solar eclipse, the sky above the eclipse becomes bluer than the regular blue sky, which can be seen in figure 4 on either side of the 'terminator'. If the image (available in supplementary material) is loaded into an image analysis program such as ImageJ (freely available for Mac, Windows and Linux[4]) and the cursor moved around the sky it will be seen that the blue/red ratio is higher on the umbra side (right) compared to the penumbra (left).

[4] rsbweb.nih.gov/ij/

The eclipse of 14 November 2012 can be simulated using a planetarium program called *Stellarium*[5]. Use the location icon at the top of the icon bar on the left of the screen to set the location to Cairns and the date/time icon immediately below the location icon to set the date to 14 November 2012. Use the arrow buttons on the right of the horizontal icon bar at the bottom left of the screen to run the eclipse forwards and backwards. The eclipse terminator is not simulated on *Stellarium*.

**Effect of the eclipse on birds**

Details of the effect of the eclipse on birds will be presented in other papers. However, for the sake of interest the results are briefly summarized here. Between sunrise and totality, a period of about an hour, birds were seen swooping and diving above the forest canopy breakfasting on insects. Some birds came very close to the ground near the film crew and observing team. The birds went quite during the 90 s of totality and then started a second dawn chorus as the Sun emerged from the behind the Moon and started feeding again. A film about the expedition can be viewed at[6]. (If the video cannot be found type "Second Dawn QUT" into YouTube).

**The geometry of the umbra**

When standing on the surface of the Earth, the umbra comes from behind when looking in the direction at the Sun. The shadow moves in the same direction as the Earth, i.e. from east to west, but travels faster than the rotation of the Earth. The geometry of the 14 November 2012 umbra is shown in figure 5.

[5] www.stellarium.org

[6] https://www.youtube.com/watch?v=Mgp60m28l-Y

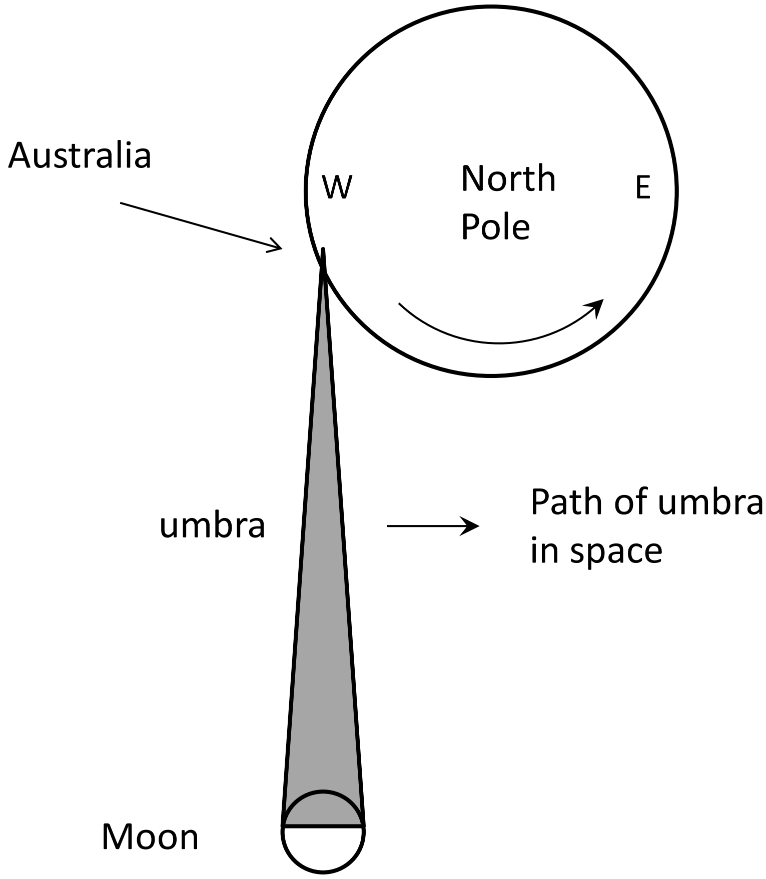


Figure 5. The cone of the umbra sweeps from west to east and moves faster than the rotation of the Earth.

Eclipse umbra are conical in shape and very ‘sharp’. If the umbra were modelled as a needle 10 cm in length, the ‘Moon’ end would be 1 mm in diameter and the ‘Earth’ end just 0.3 μm in diameter –extremely sharp! If an eclipse occurs when the Sun is close to the horizon, as it was on the 14 November 2012, the intersection of the shadow with the atmosphere, when viewed in the direction of the Sun, is circular, as shown in figure 6. Note the similarity with the photograph of the shadow in figure 3. Figure 7 shows a lateral view of the umbra.

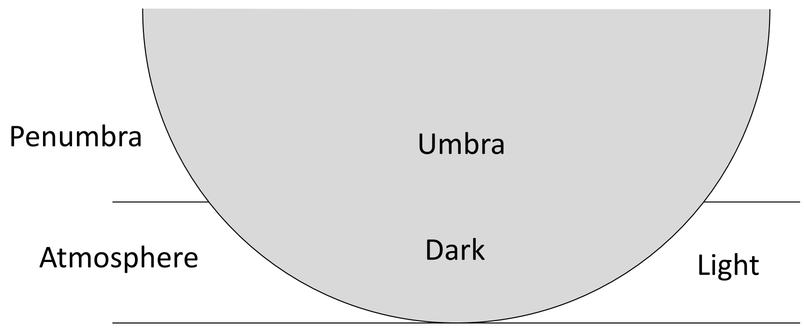


Figure 6. Cross sectional view of the umbra as seen during totality when looking in the direction of the Sun. Note the similarity to figure 3.

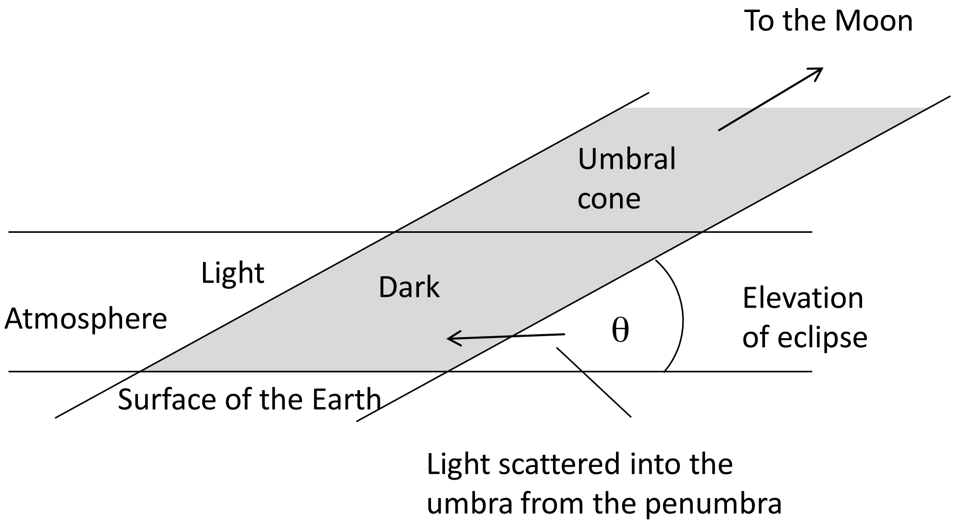


Figure 7. Side view of umbra. Scattering of light into the umbral zone from the penumbral region produces the red sky effect during a total solar eclipse. Although the shadow is cone shaped, on the scale of the thickness of the atmosphere the sides are nearly parallel.

The minimum average speed of the umbra across the Earth can be calculated using the great circle (geodesic) distance between the beginning and end of the eclipse path. The great circle distance is the shortest surface distance between two points on a sphere. (Airlines often use great circle routes for long distance flights). In the case of the 14 November 2012 eclipse, the start and finish points of the eclipse were E 133 05.2 S 11 26.2 and W 79 57.8 S 29 32.6. The great circle distance between these two locations was calculated as 9520 km using a great circle distance calculator on the internet[7]. The start and finish times were 20 36.1 and 23 47.4 (UT) respectively, corresponding to a duration of 3 h and 11 min. Therefore the average speed of the umbra was 2990 $kmh^{-1}$, or 0.83 km $s^{-1}$. An eclipse path cannot be shorter than the geodesic, and so for a path longer than the geodesic the average speed will be higher.

[7] http://williams.best.vwh.net/gccalc.htm

It is interesting to note that the only aeroplane capable of viewing a total solar eclipse for longer than the maximum seven min is the Lockheed SR-71 Blackbird, which has a range of 5400 km and cruising speed of 3530 km per hour. However, the Blackbird ceased operations in 1998 and so currently no aircraft exists fast enough to keep up with a total solar eclipse.

**The sunset effect during a total solar eclipse**

Figures 3 and 4 show a red sunset-like horizon during the Nov 14 total solar eclipse. The reason why sunsets appear red is because blue light is scattered more than red light by the atmosphere, which is also why the sky appears blue during the day. Scattering also explains why the sky is bright for an hour or so after sunset and before sunrise. For example, the western horizon is still fairly bright 15 min after sunset, which indicates that close the Equator the indirect sunlight is scattering through about 400 km of atmosphere, much greater than the width of the umbra in a total solar eclipse. (The circumference of the equator is about 40 000 km, so in 15 min a point on the Equator will travel about 40 000/96 km which is approximately equal to 400 km).

On an airless body such as the Moon the landscape would become completely dark as soon as the Sun sinks below the horizon. In a total solar eclipse, the atmosphere beyond the umbra is illuminated by the Sun, and some of this sunlight is scattered into the umbral region. However, this light has to travel through a similar thickness of air that direct sunlight passes through at sunset. Hence there is a sunset effect at the horizon during a total solar eclipse.

**Eclipse experiments that can be performed in the classroom or at home**

A simple experiment that illustrates why sunsets are red and the sunset effect that occurs during a total solar eclipse can be performed in the class room, or at home in the kitchen. The experiment described here was performed by one of the authors (SH) in the home kitchen. A clear plastic container was filled with water and a few drops of milk added to make the water cloudy. A beam of light from a LED torch was shone through the container and the scattering of blue light was observed (figure 8). When the bulb was viewed through the container a sunset effect was seen (figure 9). The sunset effect is seen more clearly with a LED 'bulb' since the light emitted by an LED contains more blue compared to an incandescent bulb, and therefore the scattering effect is greater.

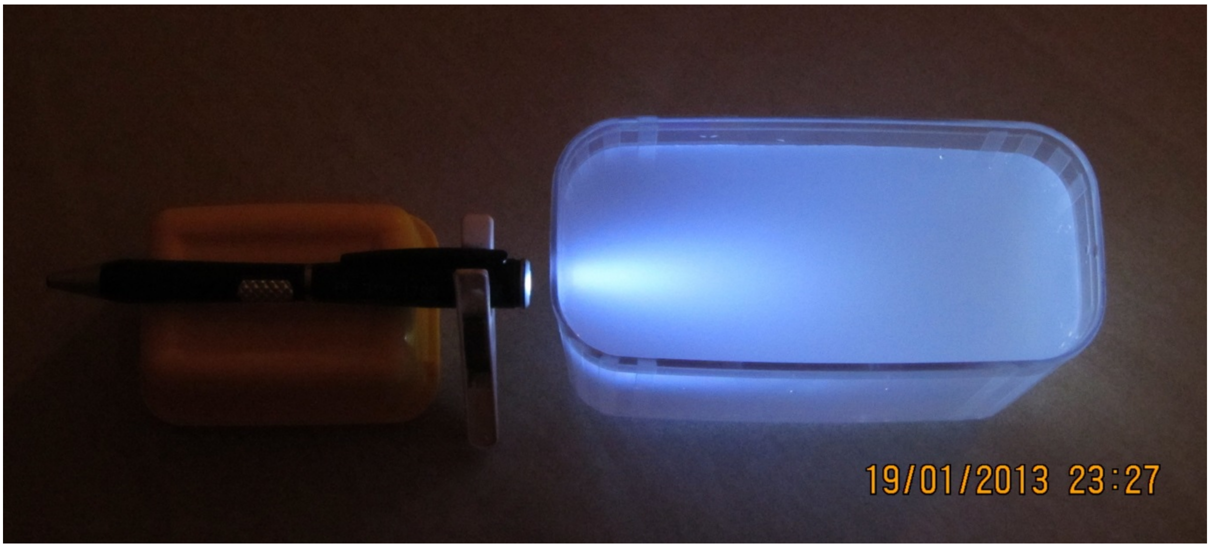


Figure 8. Blue light scattered from a LED torch beam.

Only a small drop of milk is required. If too much milk is added the setting ‘Sun’ cannot be seen. If this is the case, tip some water out and add fresh water until the bulb can be seen. Milk is a good scatterer since it is white and so does not contribute an excess amount of blue or red to the beam.

Figure 9. Photo of the LED bulb observed through milky water. Note the red light around the LED simulating a sunset.

Another experiment can be performed, which is directly relevant to the sunset effect seen during total solar eclipses. In a darkened room, if an LED torch is shone horizontally through a tall glass with vertical sides (figure 10), close to the top the beam appears blue, but it becomes redder as the beam descends. In this model, the beam of light is equivalent to the illuminated atmosphere surrounding the umbra.

An LED torch and transparent container with milky water can also be used to demonstrate the umbra. This can be done by sticking a piece of tape, smaller than the width of the LED torch beam, onto the side of the container and directing the beam onto the sticker. The shadow of the sticker will be seen in the milky water, in essence a miniature version of the shadow seen in figure 3.

The experiments described are suitable for performing in front of a class, but could also be set as homework. If set as homework, students could be assigned marks for innovative ways of setting up the experiment, and use their mobile phones or tablet computers to photograph their experiments.

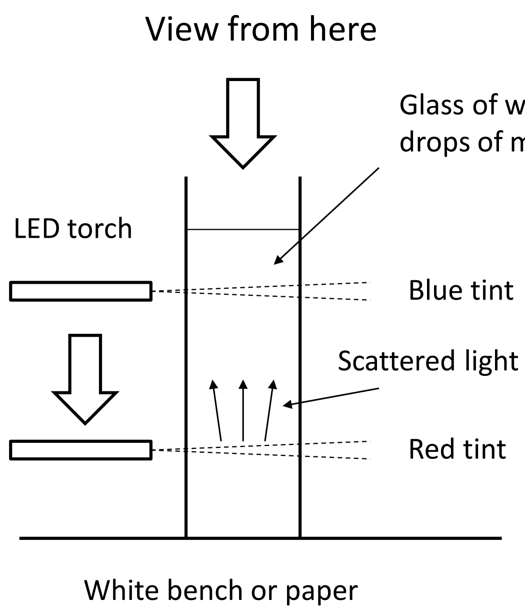


Figure 10. Schematic diagram of experiment to demonstrate the sunset effect during a total solar eclipse.

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