EDUCATIONAL ACTIVITY
Atmospheric parameters changes during a Solar Eclipse

Authors:

- Mr. **Miguel Ángel Pío Jiménez**. Astronomer of the Institute of Astrophysics of Canary Islands.
- Dr. **Miquel Serra-Ricart**. Astronomer of the Institute of Astrophysics of Canary Islands.
- Mr**. Juan Carlos Casado**. Astrophotographer of starryearth, Barcelona.
- Dr. **Lorraine Hanlon**. Astronomer University College Dublin, Ireland.
- Dr. **Luciano Nicastro**. Astronomer Istituto Nazionale di Astrofisica, IASF Bologna.
- Dr. **Davide Ricci**. Astronomer Istituto Nazionale di Astrofisica, IASF Bologna.

Collaborators:

- Dr**. Eliana Palazzi.** Astronomer Istituto Nazionale di Astrofisica, IASF Bologna.
- Dr. **Emer O Boyle.** University College Dublin, Ireland.

1. Activity goals

In this activity we will study atmospheric changes, especially changes in temperature due to the decrease in solar radiation caused by the blocking of the disk of the Sun by the Moon during a total solar eclipse. For this, a weather station located in the totality band will be used.

Upon completion of the activity you will be able to:

- Describe the basic phenomenology of eclipses.
- Explain basic statistical analysis techniques and apply them to calculate the error on a result.
- Use the GLORIA eclipse web-tool to determine the thermal inertia during a solar eclipse.

2. Instrumentation

A weather station (Geonica Meteodata 2008CP, see Figure below) with sensors for measuring temperature (range -40 ºC to +60 ºC and error=0.1 ºC) and solar radiation (pyranometer, spectral range 305-2800 nm, temperature range -40ºC to +80 ºC, range 0-2000 W/m^2, error 5%) will be used for this activity. The students will have access to live data or to the database of archived data. A web-tool will be available to allow students to perform the activity.

Figure 0: Weather station (Geonica Meteodata 2008CP) and sensors.

3. Phenomenon

3.1 What is an eclipse?

In an eclipse, the observer's view of a celestial object is temporarily blocked due to the presence of another intervening object.

In the following we will consider eclipses occurring in the Sun-Earth-Moon system where the term eclipse applies to two very different phenomena:

1. A **solar eclipse** occurs when the Moon passes between the Sun and Earth, and the Moon fully or partially blocks the Sun. This can happen only at New Moon (Moon between the Sun and Earth) and if the Sun and the Moon are perfectly aligned as seen from Earth. In a total eclipse, the disk of the Sun is fully obscured by the Moon. In partial and annular eclipses only part of the Sun is obscured.

2. A **lunar eclipse** occurs when the Moon passes directly into the Earth's shadow. This can occur only when the Sun, Earth, and Moon are aligned exactly, or very closely, with the Earth in the middle. Hence, a lunar eclipse can only occur at Full Moon.

3.2 Conditions for eclipses to occur

Most of the time the Moon is above or below the plane of the ecliptic (the plane defined by the Earth's orbit around the Sun). For an eclipse to occur, the Moon has to be in, or very close to, the plane of the ecliptic and in New Moon phase (solar eclipse) or Full Moon (lunar eclipse).

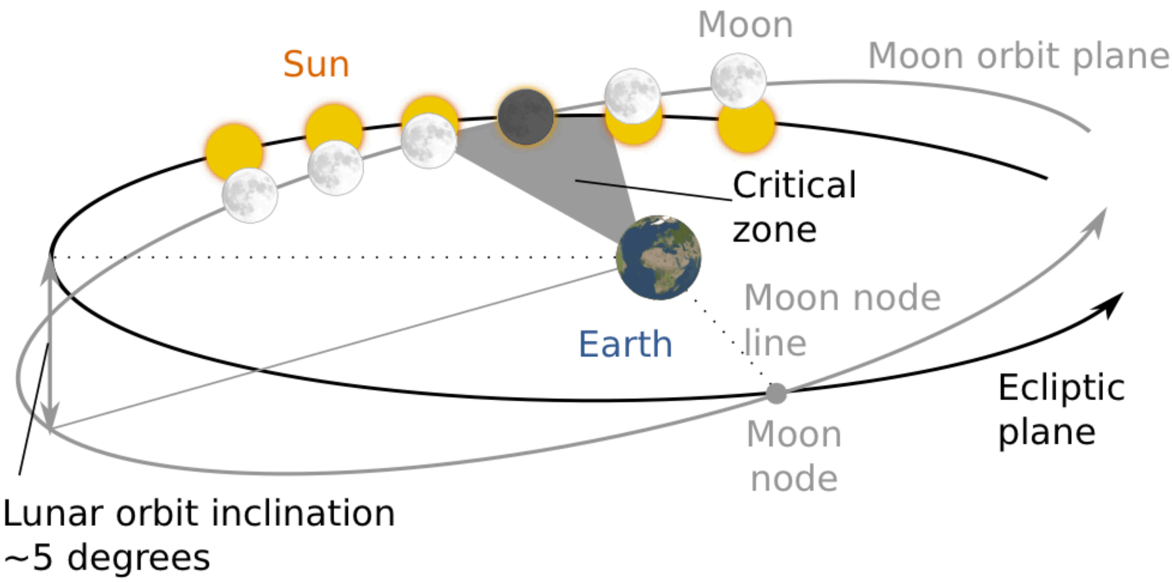

Figure 1: The ecliptic plane and the Moon's orbit. The "critical zone" indicates a strip in which an eclipse may occur. (Diagram starryearth.com). The "Moon node line" refers to the line joining the centre of the Earth to the point where the Moon's orbit intersects the ecliptic plane.

The conditions in which solar eclipses can occur, happen two or three times a year - every 173.31 days - in the so called **eclipse seasons**. The **eclipse year** is the time between two alignments of Sun, Moon and Earth and it is 346.62 days. During this time two eclipse seasons happen.

The Moon's orbital node lines (Fig. 1) don't have a fixed orientation, but rotate by about 20° per year, going through one full turn in 18.6 years. This means that the dates on which the eclipses happen change each year. For example the eclipses of 2001 were in the months of January-February, June-July and December, the eclipses of 2003 were in May and November and those of 2006 in March and September. The movement of the orbital nodes means that the eclipses occur throughout the ecliptic. Figure 2 shows the umbral and penumbral zones on Earth during a total solar eclipse.

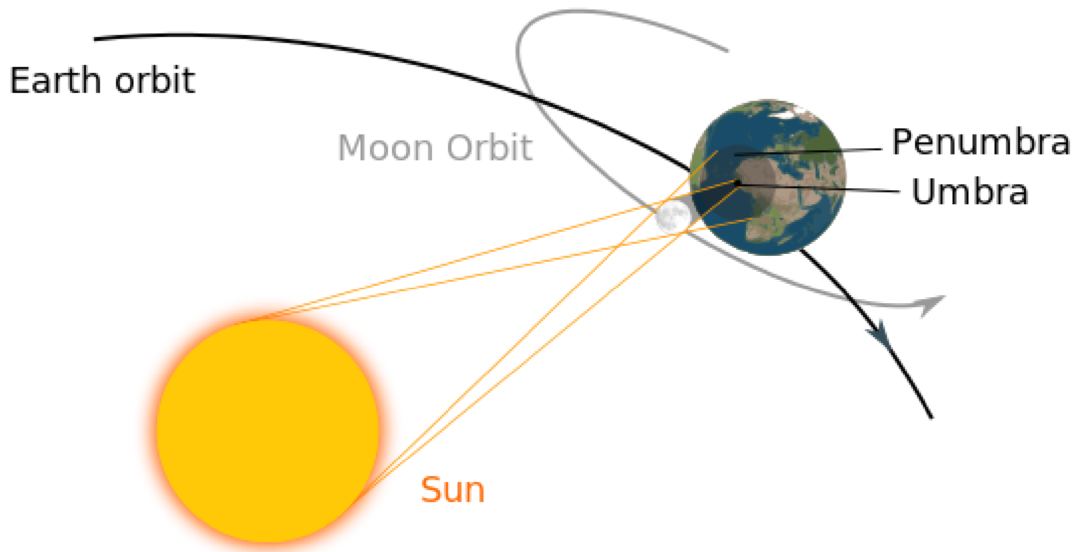

Figure 2: Diagram of the umbral and penumbral zones in an eclipse.

3.3 Number of eclipses per year

The minimum number of eclipses that occur each year is four - two solar eclipses and two lunar eclipses. The maximum possible number of eclipses per year is seven, and only rarely happens. The following combinations are possible:

- 5 solar eclipses and 2 lunar eclipses
- 5 lunar eclipses and 2 solar eclipses
- 4 solar eclipses and 3 lunar eclipses
- 4 lunar eclipses and 3 solar eclipses

3.4 Types of solar eclipse

There are different types of solar eclipse, depending primarily on the length of the Moon's shadow and the Moon's distance from Earth. These are illustrated in Fig. 3.

1) Partial eclipse: Only the Moon's penumbral shadow reaches the Earth's surface (see Fig. 3, position C). These eclipses always occur at high latitudes (north or south).

2) Annular eclipse: The Moon is too far from Earth for its umbral shadow to completely cover the disk of the Sun, but it still blocks out most of the Sun light, leaving only a ring of light visible (Fig. 3, position B).

3) Total eclipse: In this case the Moon is sufficiently close to Earth for its penumbral shadow to reach Earth, perfectly blocking the complete disk of the Sun (Fig. 3, position A).

It is worth pointing out that solar eclipses are seen on Earth only because of the happy coincidence that, at some times during the year, the angular sizes of the Moon and Sun are identical. Hundreds of millions of years in the past, the Moon was too close to the Earth to precisely cover the

Sun as we can now observe. Tidal forces cause the orbit of the Moon around Earth to increase by about 3.8 cm each year and in just under 1.4 billion years, the distance from Earth to the Moon will have increased by 23,500 km. After that, the Moon will no longer completely cover the Sun's disk as seen from Earth. Therefore, the last total solar eclipse on Earth will occur in about 1.4 billion years from now!

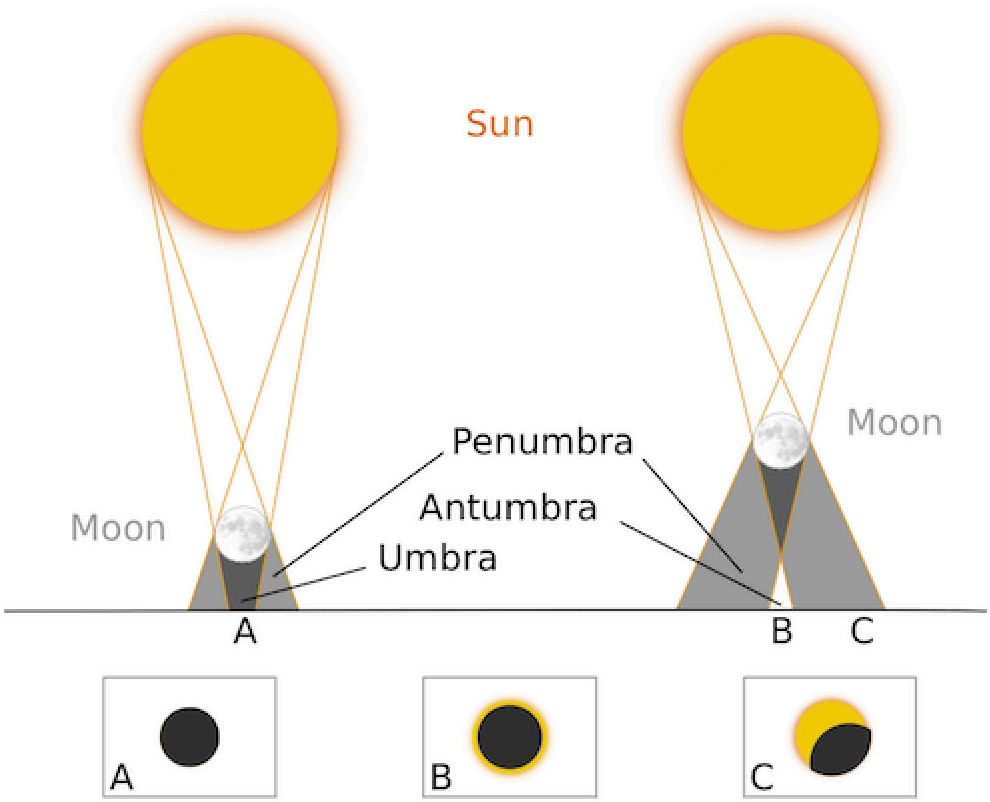

Figure 3: Diagram showing eclipse types depending on the relative position of the Moon with respect to Earth. When Earth is in region (A), a total solar eclipse is seen; in (B) an annular eclipse is seen, while in (C) a partial eclipse is observed.

3.5 How the eclipses appear

Partial eclipse: During a partial eclipse there are two points of contact. The first point is the moment of contact between the discs of the Sun and the Moon, which marks the beginning of the phenomenon. As the Moon continues along its orbit, an increasing fraction of the solar disk is covered, until the maximum, after which the shadow departs from Earth's surface and the full disk is visible again.

The **magnitude** of an eclipse is the fraction of solar diameter covered by the Moon (Fig. 4). The magnitude can be expressed both in percentage and decimal fraction (60% or 0.60). The term "**obscuration**" refers to the fraction of the solar surface covered by the Moon (Fig. 4).

VERY IMPORTANT EYE SAFETY: In a partial eclipse, the Sun is still very bright, so normal precautions apply to observing the Sun in that case.

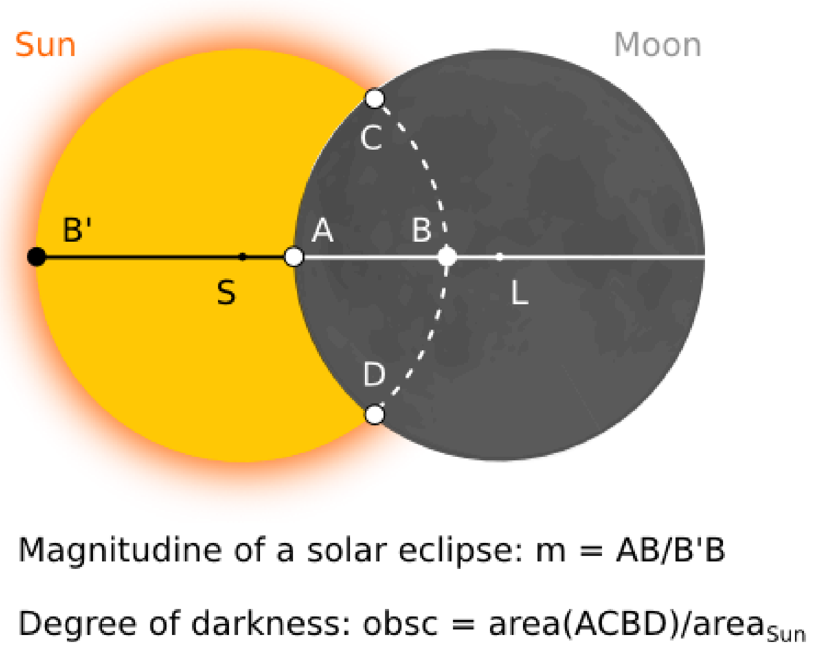

Figure 4: Magnitude and dimming of a solar eclipse. The magnitude expresses the fraction of the Sun's diameter hidden while the dimming is the fraction of the Sun's surface that is overshadowed.

Annular eclipse: An observer of an annular eclipse will see four moments of contact between the solar and lunar discs. The **first contact** is the moment when both disks appear to touch. Slowly, in a process that takes about an hour and 30 minutes, the lunar disk appears to fully cover the solar surface; this is the **second contact**. Then the central or **annularity** phase, culminating in **third contact** of the event begins. This phase, can reach about 12 minutes and 30 seconds. The **fourth contact** refers to the end of the eclipse.

Total Eclipse: A total eclipse also has four contacts. The first contact and the preceding stage are similar to those in an annular eclipse. But now, before second contact, the observer will see a dramatic change in light. Atmospheric parameters such as temperature and relative humidity are also changed.

If the observer is located in a high place with a good view of the distant landscape, the moon's shadow can be seen approaching the western horizon at high speed. At the instant of the second contact it produces a **diamond ring**, a brightness which happens at the point when the sun is almost completely hidden. But before the last portion of the sun disappears, because of the rugged terrain of the edge of the lunar disk, luminous fragments of light, called **Baily's beads** (Fig. 5) can be seen. Then suddenly the outer atmosphere of the sun (the solar corona) appears (Fig. 6). In the first few seconds some of the sun's chromosphere (gases) can be seen as a thin arc of intense red color with bright bumps. These quickly disappear after the advance of the lunar disk (Fig. 7).

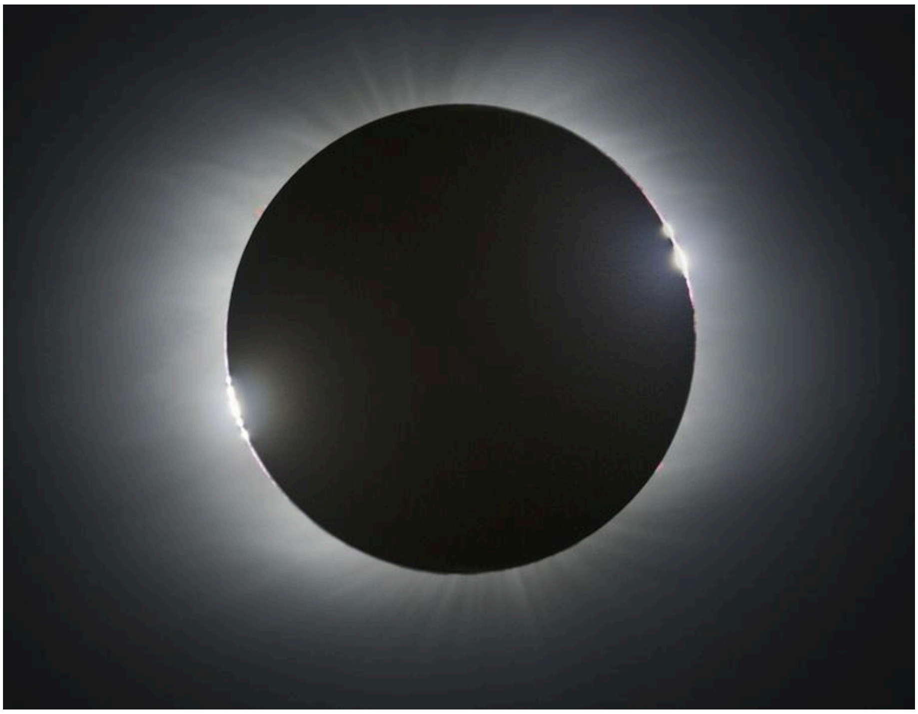

Figure 5: Composition of images showing the second and third contacts, Baily's beads, bumps and inner corona in the solar eclipse of July 22, 2009, near the city of Chongqing, China in the Shelios 2009 expedition. (Photo J.C. Casado / starryearth.com).

The solar corona (Sun's outer atmosphere), an intense pearly white colour, shows structures that follow the arrangement of the magnetic field of the Sun. It is not normally visible because it is about 100,000 times less intense than the Sun light. In the centre is the lunar disk, now seen in silhouette. The shape and brightness of the corona depend on where the Sun is in its 11 year cycle. At solar maximum the corona has radial symmetry (Fig. 6 right), while at its minimum the coronal feathers are asymmetrical (Fig. 6 left).

3.6 Visibility and duration

Total solar eclipses are not as uncommon a phenomenon as might be thought. However, because the shadow of the Moon is narrow, they are only visible in a relatively small band on Earth's surface, and are observed at a specific point on the Earth's, such as a city, only once every 375 years on average. It is therefore necessary to make long journeys to be in the band of totality and to witness the entire event. On average, a total eclipse will last about 3 minutes with the longest lasting up to 7 minutes 30 seconds.

Figure 6: Left. Picture of the total solar eclipse of August 1, 2008 from Novosibirsk, Russia in Shelios 2008 expedition. Combination of 67 digital images showing long stretches of the corona, bumps, Earthshine and stars. Right. Picture of the total solar eclipse of November 23, 2003 taken on board an aircraft flying over Antarctica in Shelios 2003 expedition. Photos and processing: J.C. Casado / starryearth.com.

Figure 7: Baily's Beads and solar chromosphere at second contact of the eclipse of November 13th, 2012 observed in Cairns, Australia (Credit J.C. Casado, gloria-project.eu).

4. Performing the activity

4.1 Calculation of the thermal response of the atmosphere from atmospheric measurements in a total solar eclipse

An interesting effect that occurs during the course of an eclipse, more remarkable in a total eclipse, is the decrease of the environmental temperature due to the decrease of the solar radiation or ambient brightness (see Ref. 8). The interesting thing is that the phenomenon does not occur instantaneously when the sun is completely covered (maximum eclipse or second contact), but is an effect that occurs after a time ranging from 2 to 20 minutes.

This time delay depends on many factors, such as the time of day when the eclipse occurs, the presence of nearby bodies of water such as a lake or ocean, proximity to wooded areas etc., but it is easily measurable. The time at which the minimum intensity of light occurs, coincident with the maximum eclipse (second contact) must be noted. Then, the time at which the temperature is a minimum is also recorded. The thermal response of the atmosphere or the *atmospheric thermal inertia* is the time interval between these two minima.

The following exercises (Method 1 and Method 2) can be used to estimate the thermal response of the atmosphere.

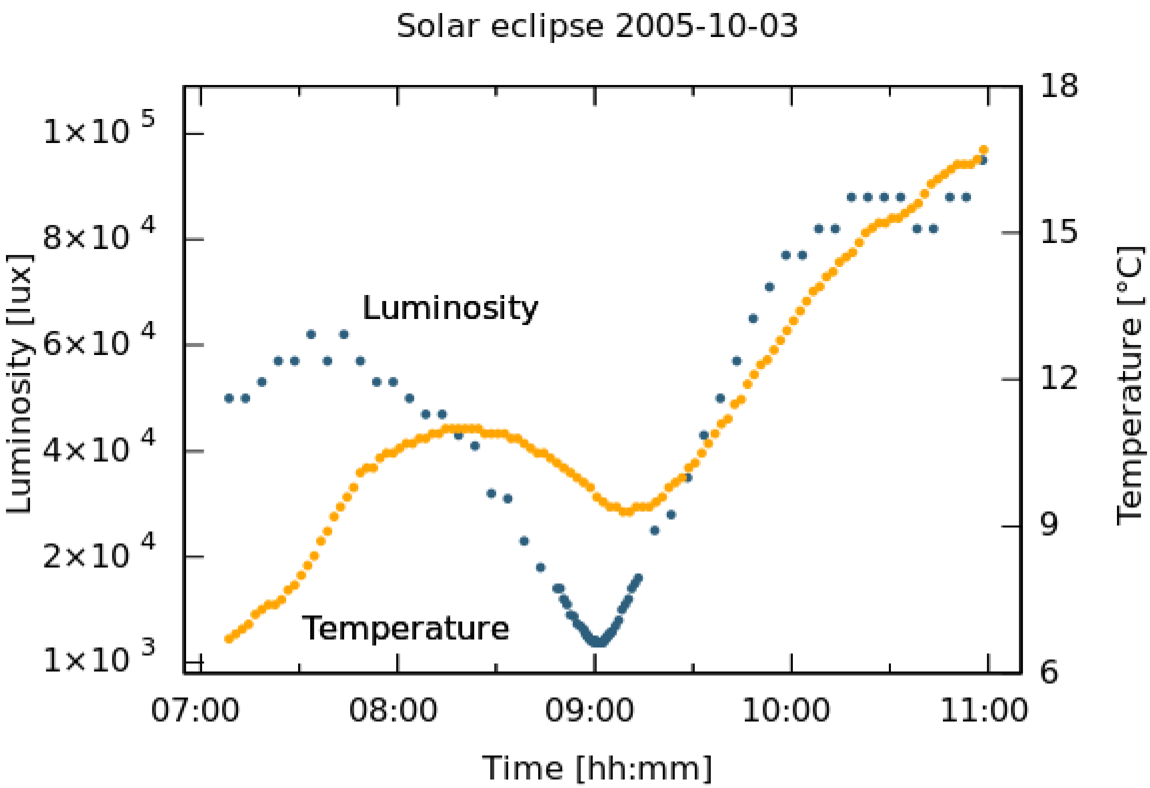

Figure 10: Representation of the drop in solar radiation or luminosity (blue) and temperature (yellow) as a function of time produced during the annular eclipse that occurred in October 2005.

4.1 Weather data

During the broadcast of the event, the weather station will periodically save (about every 5 seconds) the values for each of the variables discussed earlier, so that they can be accessed at any time from the GLORIA website (www.gloria-project.eu). A web tool (www.gloria-project.eu/eclipse-meteo/, Fig. 11) is provided to enable detailed examination of the data in any time interval requested. For example, time intervals can be selected from different moments during the eclipse. Values of temperature and solar radiation intensity will be plotted on a graph, along with the errors on these values. The interval can be changed (“zoomed in”), so that more detailed data can be plotted in a particular time interval, to get more accurate determinations of the minimum values for the radiation intensity and temperature.

After selecting the data and making the graphical representation, the "*atmospheric thermal* *inertia*" can be calculated as before.

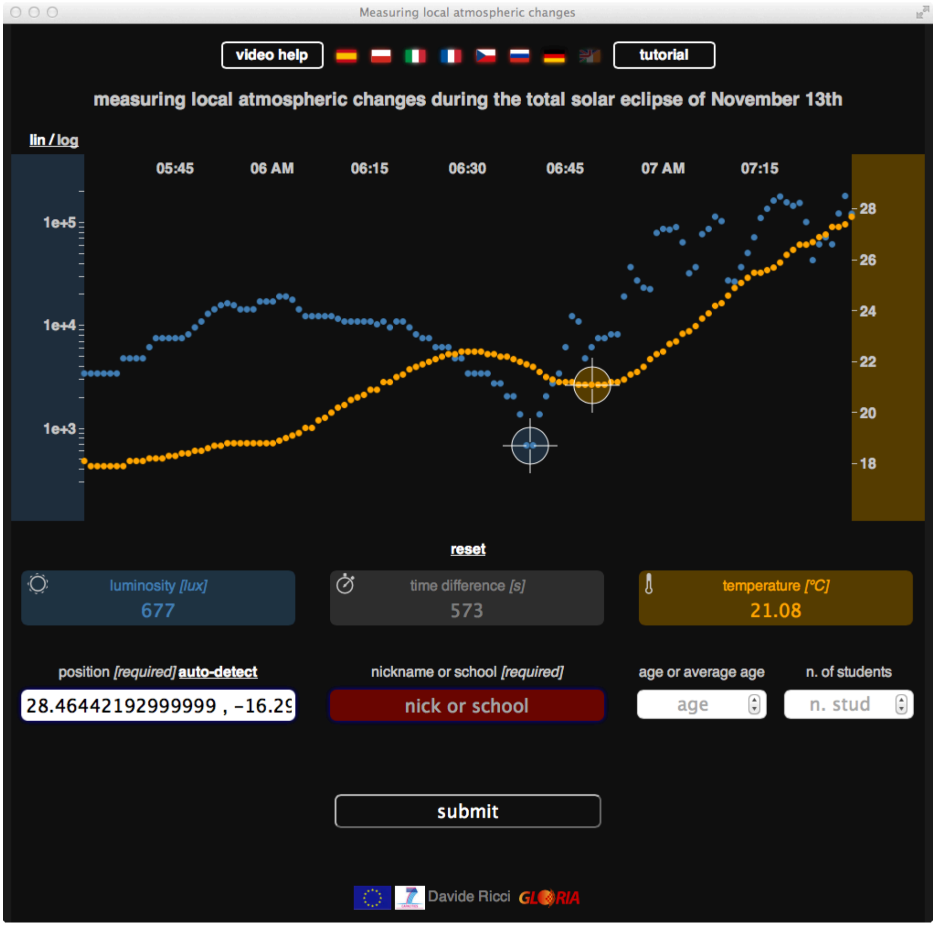

Figure 11: Representation of the fall in solar radiation or light (blue) and temperature (orange) versus time, produced during the total eclipse of November 13, 2012. The data are shown with the GLORIA web tool (www.gloria-project.eu/eclipse-meteo/). The time difference between the temperature and light minimum in this case was 573 seconds.

4.2. Measurement error

Any measurement of a physical quantity, such as temperature, has an error associated with it. When the error is small, or the measurement is not being used for scientific purposes, typically it is omitted for simplicity. The ideal is that a measurement gives both an 'accurate' and a 'precise' result. By 'accurate' scientists mean that the measured value is close to the actual value (within the error) and the term 'precise' means that repeated measurements can reproduce the same result (again, within the error).

There are two types of error in a measurement: **"systematic"** and **"random"** error. The first one causes biases in the measurement of a quantity and when a number of separate measurements are averaged, the final value differs significantly from the actual value of the parameter being measured, affecting the accuracy of the result. The causes of a systematic error are numerous. For example, bad calibration of the instrument used for the measurement (incorrect zeroing). They can also be non-constant but related to the value of a different quantity. For example, a metal ruler can change its length because of a change of temperature in the room. Systematic errors can be difficult to detect, even for experienced research workers and are not considered further here.

On the other hand, random errors are governed by the laws of the statistics. Although their treatment can be very complex, the basic rule is that as the number of measurements of a quantity increases, the uncertainty on the measurement decreases. Therefore, the precision of the measurement can be improved through repeated measurement and the application of some basic statistics.

Let's consider the case of the thermometer and the measurement of the atmospheric temperature. When we hear about air temperature from the TV news or read it in the newspaper, no mention is made about the error of the value or even if it corresponds to a single measurement or to an average of several ones. Given that integer values are typically reported (e.g. “the temperature in Madrid today was 30 °C”), we guess that the “uncertainty” on the figure is ± 0.5 degrees. This is OK for the use we make of such information. However when the temperature measurement is being used for industrial or scientific purposes, much more precise measurements might be required. For example, a precision of 0.1 or even 0.001 degrees might be necessary to monitor the temperature every second in a scientific experiment. But then how is the error on each single measurement estimated, or that of the average of the temperature measurements taken, for example, over one minute?

Single measurement: Let's assume a digital thermometer is being used that displays the temperature with two digits after the decimal point (e.g T=20.00 °C). A (single) “measured” temperature of 20 °C would then have an error of ± 0.01 degrees. So the measured temperature is written as 20.00 ± 0.01 °C, which means the actual temperature is most likely to be in the range [19.99 - 20.01] °C.

Averaging: If we make many independent measurements of the temperature, then statistical methods to improve the precision of the measurement can be applied and the error on the measurement reduced. The golden rule is that if we make N estimates of the temperature, the error on average temperature will be reduced by the square root of N compared to that of a single measurement. For example, say there are 5 measurements of temperature as follows: 20.01 ± 0.01 °C; 20.01 ± 0.01 °C; 20.02 ± 0.01 °C; 19.98 ± 0.01 °C; 19.99 ± 0.01 °C. The average temperature is simply the sum of values divided by 5 (i.e. 20.002 °C). The error on this mean value is now $0.01/\sqrt{5}$ = 0.004 °C. Therefore, by making 5 separate temperature estimates, the error is reduced from 0.01 °C to 0.004 °C and the final result is quoted as T=20.002 ± 0.004 °C.

When averaging measurements with random (or "independent") errors, which means that the error in each measurement is not related in any way to the others, the error reduces as discussed above. The calculation of the final error is done using the error propagation law "of the square root of the sum of the squares of the errors":

$$< Error > \ = \sqrt{(err_1^{\ 2} + err_2^{\ 2} + ... + err_N^{\ 2})/N}$$

In most cases it is reasonable to assume that the errors are a fixed fraction of the measured values. Let's call this fraction ***f***. Then we can simplify the formula as follows:

$$f_{new} \ = \ f * \sqrt{N}/N \ = \ f\,/\,\sqrt{N}$$

For example for N = 16, the fractional random error is reduced by a factor 4. Notice that this is a "Sum and Difference Rule". This means that if the operation performed on the measured data is a difference rather than a sum, the errors still combine as shown in the above <*Error*> formula (i.e. errors do not magically disappear if you are taking the difference of two quantities, both of which have errors associated with them, to get your result). We will use this concept in the activity.

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   The wider literature on the subject is in English:
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Finally note the NASA Technical Publication, published some eighteen months before each annular or total eclipse. Collect maps, charts, forecasts and information on general and local circumstances of the eclipse in question. For more information contact Fred Espenak, NASA / GSFC, Code 693, Greenbelt, MD 20771 (USA) or via e-mail: espenak@gsfc.nasa.gov