Black Holes in My School

How do we detect stellar mass black hole candidates?

Orientation Phase

Orienting and Asking Questions

Figure 1.

Do you know what a Black Hole is? I am sure you heard a lot about it but what are these intriguing objects? Can you describe in your own words what you think they are, where can we find them and how do we detect them?

Discuss with your classmates and write down your ideas.

I am sure you heard about the first ever image of a Black Hole taken with the *Event Horizon Telescope* (Fig 2), obtained on April 2019. As you can see in this image, the observation came very close to what was expected. This means that our theoretical models are very close to reality! But we are still very far from really understanding what these amazing objects are.

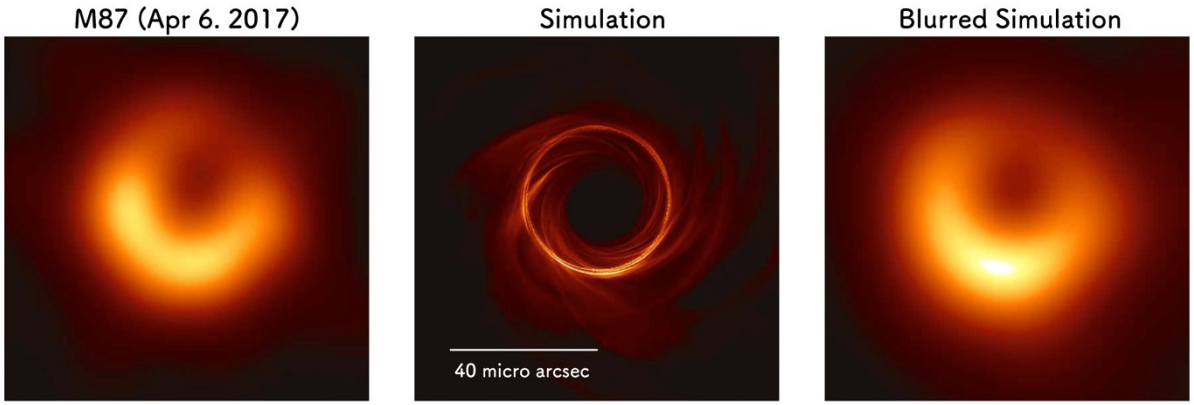


Figure 2. *(Left) The observed image of an accretion disc around the super massive black hole in the centre of the galaxy M87. (Centre) The simulated image based on a general relativistic magneto-hydrodynamical simulation. (Right) The model adapted to the observational resolution*

Black holes can be found as massive companion objects of stars, or in the centre of galaxies, or even as sole navigators of our Universe (as some recent investigation indicates). It is very challenging to observe them since one of their main characteristics is that they don't emit or reflect light! We can only find them via indirect evidence, while studying the possible impact that they cause in surrounding material (gas, dust, stars, etc.).

So how about diving into their world and get to know them a little bit better?

Provide Contact with the content and/or provoke curiosity

We presented above an image of what we think is a black hole in the centre of M87 galaxy located at a distance of 55 million light-years from Earth. The current estimates for its mass is of the order of 6 x 10^9 solar masses.

But there are black holes with much smaller masses. In this activity, we are interested in the so called Stellar Mass Black Hole candidates.

If you are curious and want to learn more about the essence of black holes, have a look at the following *An Introduction to Black Holes* (link).

Teacher Guidelines:

Exploratory Phase

Question or Statement

Define Goals and/or questions from current knowledge

In this image we present the masses of (stellar) black hole candidates that have been found so far.

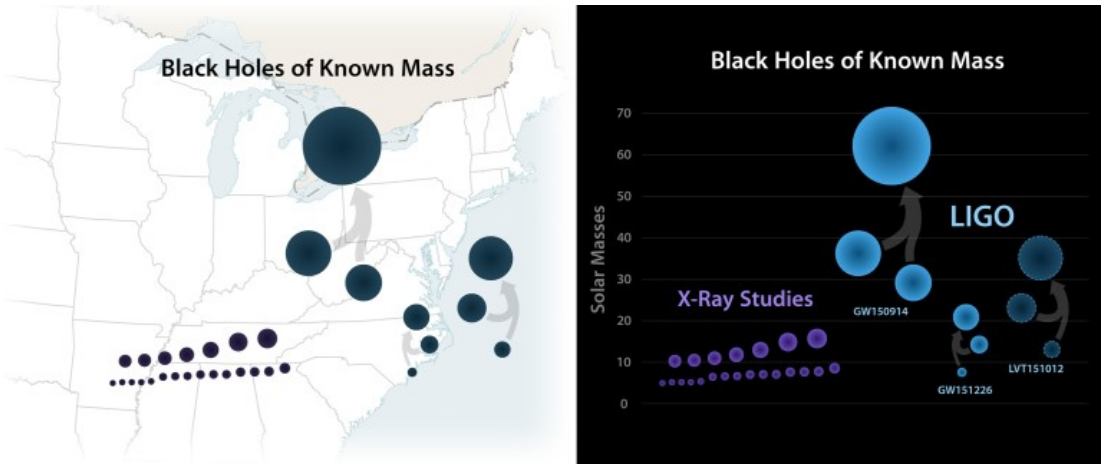


Figure 3. *Source: https://writescience.wordpress.com/tag/black-holes/*

But how can we determine the mass of such objects in the universe?

Astronomers try to detect them when they are part of a binary system: a system composed of a regular star and a compact object. Observations of the behaviour of the stars give us data that, after being analysed, allows us to determine the mass of the compact object. Depending on the result, we can claim (or not) that they are good black hole candidates.

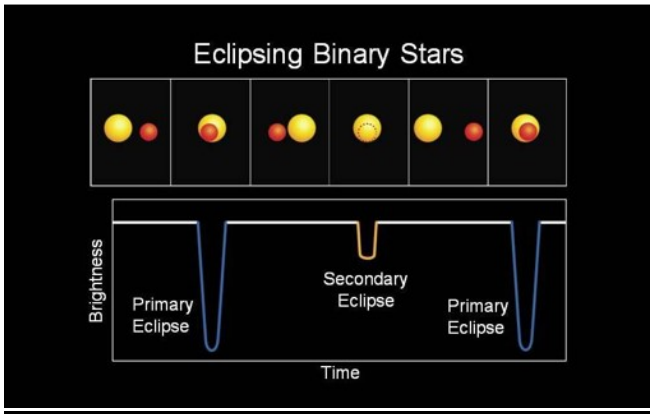
There are other ways to determine the mass of stellar black hole candidates. For instance, using luminosity versus temperature of stars. And the ultimate technique for determining the mass of a black hole is via the measurements of gravitational waves! But that is a topic for another lesson.

In this activity, you will follow the steps taken by astronomers to detect a strong stellar mass black hole candidate named **XTE J1118+480**.

Generation of Hypothesis or Preliminary Explanations

To detect a stellar black hole candidate in a binary system, we need the orbit elements of the visible star. Since we can't actually see its movement, we infer it by observing the change in brightness of the star to detect its periodicity. Once we have the orbital period, Kepler's Law can be used to estimate the mass of the compact companion.

Evidence



The picture above shows a model of an eclipsing binary and the expected light curve (brightness vs time graph). Discuss with your colleagues what is depicted here and why the light curve has this shape. Would you be able to determine the orbital period of the star?

Plan Investigation

You have access to images of the sky where our stellar mass black hole candidate **XTE J1118+480** is.

Download the 62 different images you will analyse here. (link)

First you will have to identify the binary system. Remember that it is not visible, so you have to build light curves and analyse them to look for characteristics of the light curve of a binary system.

Having identified the binary system, the orbital period has to be determined so that the mass of the companion can be estimated.

In the set of images, there is a refence image (the "finder"), identifying the stars we are interested in:

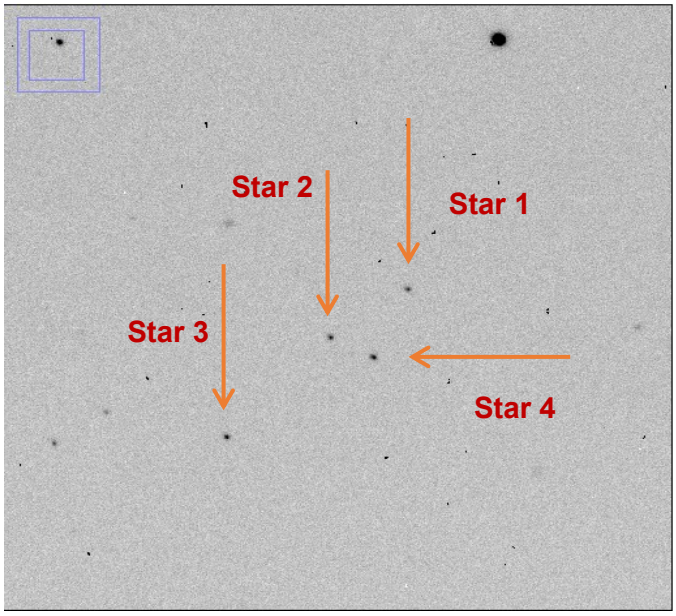


Figure 1 *Image identifying the stars to be studied. This is an image taken with the Faulkes Telescope of the region where the black hole candidate XTE J1118+480 is.*

You are probably thinking. Why do I need 4 stars? That is a very relevant question. The issue is the following: when we observe a star with a ground telescope, we have the Earth's atmosphere between us and the desired target. The atmosphere turbulence affects the quality of the image and can introduce variations to the apparent brightness of the star. These changes of values are not real. However, the atmosphere will affect all the starts around the object in more or less the same way. So, if you measure the variation in other stars (that we know don't have intrinsic variation) we will know how much of the variation is due to the atmosphere and how much is the real variation of the object to be studied.

To handle these images, you will use **SalsaJ** (Such A Lovely Software for Astronomy in Java), an astronomy image processing software that will enable you to reproduce the variation in brightness - the light curve - of this object.

Image Analysis - SalsaJ software

You can find SalsaJ here. Install it on your computer.

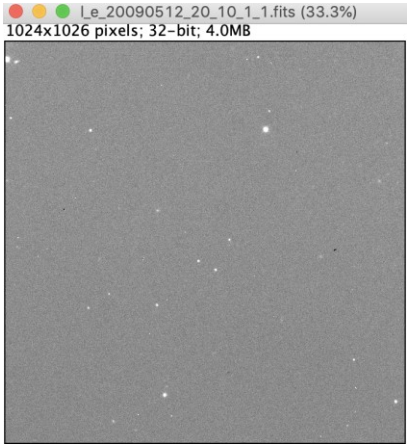
Measuring Brightness

The technique of measuring the brightness of objects is called photometry. It encompasses much more than just measuring the number of photons that reaches us from a certain object. If you want to know more, have a look at:

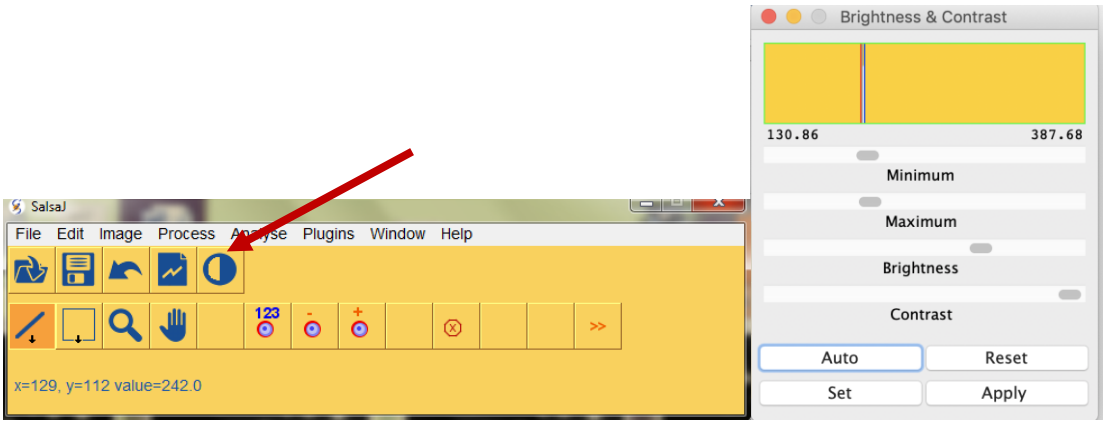
- An introduction to photometry (link)

Let's start our investigation!

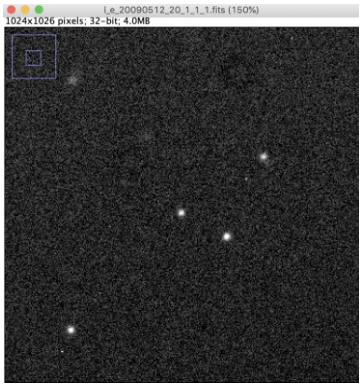
- Open SalsaJ
- Use (**Open**) to open an image, e.g. l_e_20090512_20_1_1_1.fits



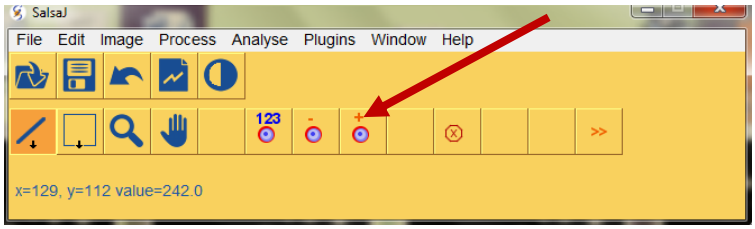
- You can use and play with the brightness and contrast to be able to see better the 4 stars in the image

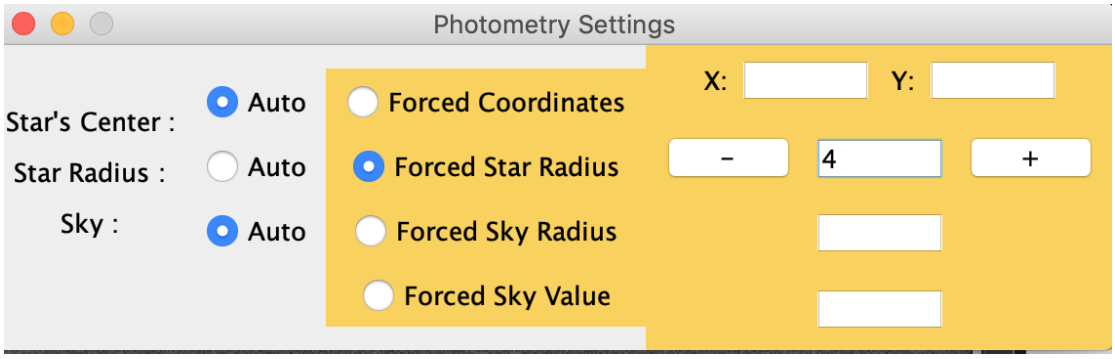


- The image can be zoomed in using the (**Magnifying glass**)
- Use (**Scrolling tool**) to select the region where the stars are. In general, they are at the centre of the image.

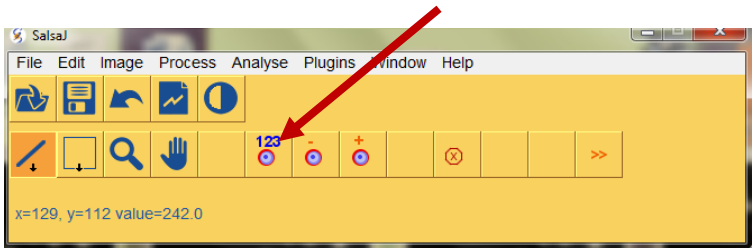


- To do the photometry, you need to define the parameters for your measurements. More specifically, the radius of the aperture that contains each star. All the stars, except our Sun, are very far away from us, thus they behave like point sources. When their photons cross our atmosphere, they are deviated in various directions (this is why we perceive stars as twinkling) and the images will show stars with a certain radius. The more turbulent the atmosphere the larger apparent radius. But the atmosphere affects equally all the stars in the image. (Sometimes it is necessary to determine the adequate radius for each image, especially if the conditions vary significantly throughout the observations. In our case, that is not necessary, and we will use the same radius value for all the images.)
- Open (**Photometry Settings**) and force star radius to 4. This value has already been tested and works well for our purpose.



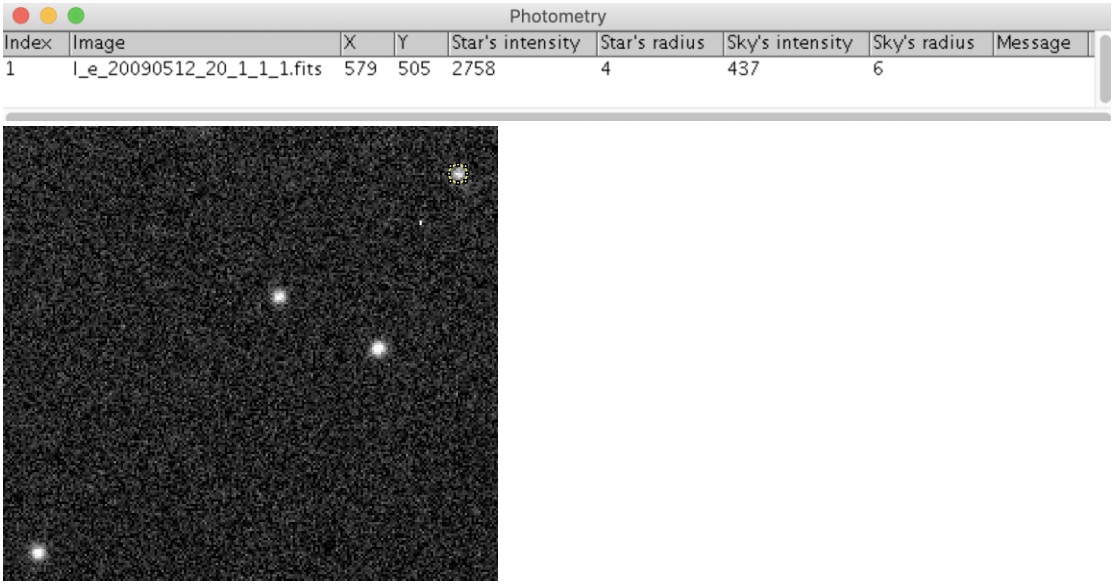


- You can now proceed to measure the brightness of each star by selecting (**Photometry**) and then clicking in each star.

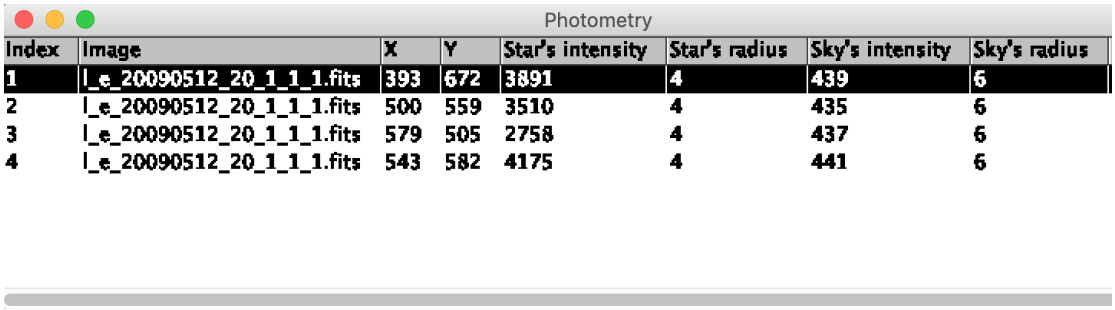


- When you click for the first time, a box will appear.

- When you click in each star, a small yellow circle will appear around it as you can see below and the value of the measurement will appear in the box.



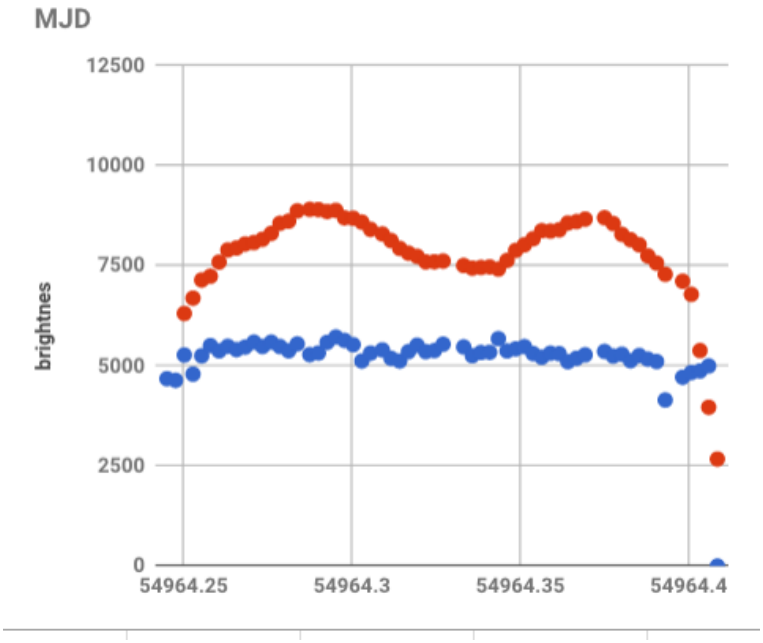
- You will be able to see all your measurements in the box. This will be very useful as you will need to copy this values to the spreadsheet given in this lesson. You will be measuring the 62 imagens. And in each one of them, you will measure the brightness of the 4 stars. So make sure you are consistent and measure them in the same order in all the images.
- For the image l_e_20090512_20_1_1_1.fits these are the results you should obtain:



Perform Investigation

Obtain the photometry for the 4 stars of all images and copy the values to this spreadsheet (link). It is already prepared to build the light curves of the 4 stars.

You should have a result like this one:



Analysis and Explanation

Analysis: Analyse evidence to discover a possible answer

Analyse the light curves, discuss with your colleagues and try to identify one of the stars as a binary system. Write down your arguments.

Try to figure out what is the period of this binary system by modelling the curve and finding the best fit. But first you have to convert Julian Date to calendar date and hours and minutes. You can use the following calculator: https://www.aavso.org/jd-calculator

Explanation: Formulate an explanation based on the analysis of your evidence

Now that you have an estimate of the orbital period of the star, you can reproduce the calculation of the minimum mass of the black hole candidate you are studying.

Use the formula to determine the limit mass of the compact object

$$f(M) = \frac{{M_1}^3 \sin i^3}{(M_2 + M_1)^2} = \frac{P{K_2}^3}{2\pi G}$$

(where M_1 and M_2 are the masses of the compact object and the companion star respectively, P the orbital period, i.e., the time it takes for the star to complete an orbit, G is the universal gravitational constant, i is the inclination of the orbital plane of the system with the line of sight of the observer and K_2 the radial velocity of the visible star)

The radial velocity of the visible component of this system was determined to be ~ 700 km s^{-1} , (http://adsabs.harvard.edu/abs/2001ApJ...556...42W).

Be careful with the units – for instance, your orbital period has to be in seconds.

Give your result in solar mass units using M_{sun} = 1.9891 × 10^{30} kg.

What can you say about the candidate? Does it have enough mass to be considered a strong candidate?

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

Scientists already know the period of this object:

P = 4.08 hrs = 0.17 days= 14 688 s.
(http://adsabs.harvard.edu/abs/2001ApJ...556...42W).

The image data range from MJD = 54964.24506 to MJD= 54964.40856, which is almost a full period of (0.1635)!

Using the formula to determine the limit mass of the compact object:

$$f(M) = \frac{{M_1}^3 \sin i^3}{(M_2 + M_1)^2} = \frac{14\,688\ s * 700^3 * 10^9 m^3\ s^{-3}}{2\pi\ x\ 6.67384 * 10^{-11} \mathrm{m^3\ kg^{-1}\ s^{-2}}}$$

And using solar masses as unit, M_{sun} = 1.9891 × 10^{30} kg

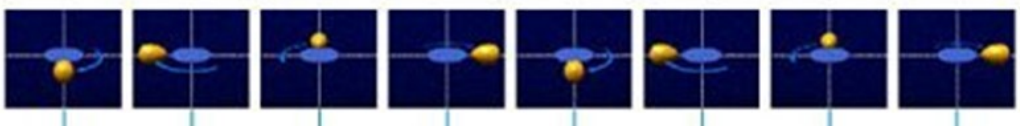
$$f(M) = \frac{{M_1}^3 \sin i^3}{(M_2 + M_1)^2} = 1.2 * 10^{31}\ kg \sim 6.1\ M_{sun}$$

This is a wonderful result – a very good candidate to a stellar black hole!

How does your result compare with this one?

"*Et voila*", you have replicated the work of scientists who investigated this specific black hole candidate!

Research a little bit more about this very interesting object. You can use the World Wide Telescope (http://www.worldwidetelescope.org/webclient/) to do your research. You can find the place in sky where it is located, and several sources of information related to it. Just use the search function and click in the proposed object. Using the right side of the mouse and clicking on the object a box with more information will appear and if you click on the information you will be driven to the Chandra X-ray observatory where more information can be found.



Now explore a bit more about Stellar Mass Black Hole Candidates and try to find out common and different things related to the candidate you have analysed and other candidates. You can start with this interesting site:

http://blackholes.stardate.org/objects/type-stellar-mass.html

Play a little bit with the mass of the black hole:

http://hubblesite.org/explore_astronomy/black_holes/encyc_mod3_q14.html

(click in Cosmic Wonders and then in the Black Holes article)

A bit more technical information can be found here:

https://en.wikipedia.org/wiki/Stellar_black_hole#Candidates

What can you conclude after getting to know about these other black hole candidates?

Communicate

Communicate and justify your explanation

Gather all your information and data collected and write a report with all the steps of your investigation.

Well done! You are now a black hole scientist!

Reflect

Reflect on what you have learned from the learning process

Review your learning process while studying **XTE J1118+480**:

- What are the main concepts that you have learned?
- Which competencies did you improve or acquire?
- How do you feel about the activity?
- What would you do differently?
- What would you like to know more about Black Holes?